The effects of magma intrusion on localized stress distribution and its implications for coal mine outburst hazards

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A B S T R A C T
Magma intrusions into coal seams are common throughout the world. The high temperatures and pressures induced by magma intrusion can alter the properties of coal, including its rank, mechanical properties, cleat and pore structures and adsorption-desorption behaviors. Because the thermal properties of magma intrusions also affect localized in situ stress distributions, both the alteration of coal properties and changes in stress distribution can directly influence coal seam gas outburst disasters. This phenomenon was recently observed and confirmed by several outbursts in the Haizi coal mines of Huaibei, China. In this paper, the processes and mechanisms of this magma intrusion are comprehensively analyzed based on an integrated data set including previously published geological data, in-house laboratory tests, and field observations. The results demonstrate that there is an intrinsic relationship between the intrusive sill and the subsequent in situ stress distribution. These data suggest that the magma intrusion in the Haizi coalfield originated as a crust-mantle type controlled by magmatic underplating; later transported mantle-derived magma successively along the Tanlu Fracture Belt, the Subei Fault, and the Daliujia Fault; and finally intruded into the coalfield as a thick sill. By comparing the lithologies of the coal seam roof and floor, as well as the distances between key coal seams (No. 3 and No. 7), it was discovered that the magma intrusion that entered the No. 5 coal seam was also associated with erosional effects. The squeezing that occurred during this intrusion changed the in situ stress distribution within the region, which increased along with the increasing thickness of the overlying sill. Therefore, the increased in situ stress also caused an increase in the outburst risk of the underlying coal seam, a conclusion that was verified by measuring the quantity of drilling cuttings on working faces as well as onsite outburst events.

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1. Introduction

The process of coalification generates coal seam gas, which is predominantly methane; the characteristics of this process are controlled by the geological history and evolution of a given region (Moore, 2012). Magma intrusion is a common phenomenon that has been observed in coal sedimentary basins in major coal-producing countries throughout the world (Wang et al., 2014a), Coalfields in China are complex geological structures that are known to have undergone multiple periods of coal accumulation. Magmatic thermal metamorphism strongly affects coal metamorphism zonation (Gurba and Weber, 2001; Cooper et al., 2007; Jiang et al., 2010; Yao et al., 2011); this occurs when magmatic intrusions provide a high temperature and pressure paleo-environment for original coal seams, which accelerate the thermal maturity of coal and form coal metamorphism zones (Barker and Pawlewicz, 1995; Fjeldskaar et al., 2008; Wang et al., 2014b). Of the multiple known periods of magma intrusion in China, the Yanshanian period is the most active; its magmatic intrusions encompassed a wide range of sizes, magmatic properties, and patterns of intrusion, which varied in their type, depth and location. This period thus greatly controlled the characteristics of surrounding rock masses (Yang, 1996). Igneous rocks are dense and hard and have very good structural integrity. The occurrence, size, and distribution of these intrusive rocks thus play an important role in controlling the safety of nearby coal mining activities (Wang et al., 2013). The two main types of intrusive bodies in coalmines are sills and dykes. These thick, hard magmatic sills, if located in an overlying stratum, can create unsafe mining conditions in underlying coal seams by affecting their metamorphic zonations, pore structures and adsorption-desorption behaviors. The ultra-low permeabilities of sills also allow them to act as a reservoir seal of the
underlying coal seam, thus directly influencing gas occurrences and outburst disasters (Gudmundsson and Lotveit, 2012; Wang et al., 2014a, 2014b, 2014c; Xu et al., 2014; Zhang et al., 2015). Therefore, constraining the zone of magma intrusion is one of the key parameters for controlling abnormal gas occurrences and outburst disasters (Anderson, 1995; Faiz et al., 2007; Saghafi et al., 2008; Sachsenhofer et al., 2011; Wang et al., 2014b).

It is well known that gas-coal outbursts are triggered by the combined effects of ground in situ stress, gases, and the physical properties of coal (Paterson, 1986; Cao et al., 2001; Peng et al., 2012). Overlying sills can influence the properties of underlying coal layers and their in situ stress distributions. Previous workers have studied the thermal evolution, thermal metamorphism, and trap effects caused by these overlying sills (Wang et al., 2013; Wang et al., 2014a, 2014b; Xu et al., 2014; Zhang et al., 2015) and have determined that coal outburst indices progressively increase with an increase in the thickness of the overlying sill. It has also been noted that the outburst index increases with decreasing interval space between the sill and coal seam. Further work has observed that gas contents and virgin gas pressures are commonly high in coal seams located under thick sill rocks, because their micro-pores are well developed and their sorption capacities are very high (Wang et al., 2014a). Therefore, coal seams located under sills are commonly more prone to coal/gas outbursts. Because of these geological conditions and the soft and tectonically damaged state of the coal body, compressive squeezing may occur during magma intrusion, thus changing the localized in situ stress field of the underlying coal seams.

A variety of previously published field and laboratory studies have determined that ground stress plays an extremely important role in causing coal and gas outburst accidents (Brown and Hoek, 1978; Shepherd et al., 1981; Zhou et al., 2005; Liu and Harpalani, 2014). Whether occurring during the geological evolution of the coalfield or during active mining operations, the redistribution of stress can lead to the modification of the geological environment, which strongly affects gas migration. Therefore, ground stress is one of the key factors controlling the occurrence of coal/gas outburst disasters (Meng et al., 2011; Cheng et al., 2013; Guo et al., 2014). As a sill squeezes into a virgin coalfield, the local stress field is passively modified and redistributed. The localized modification and redistribution of stress tends to induce a complex stress profile with an uneven stress distribution on the coal seam, which can potentially increase the risk of coal/gas outbursts (Zhang et al., 2015). In this study, we chose the Haizi coal mine, which contains a 120-meter-thick overlying sill, as a case study. We collected both field and laboratory data (including geological data inversion), measured in situ stress data, performed statistical analyses on the index of drill cuttings quantity (S), and validated site cases. Based on these data, we were able to systematically analyze the processes of intrusion and ground stress transformation due to the sill in order to better understand the mechanisms of outburst disasters in the underlying coal seams. The findings of this study provide a theoretical basis for classifying mine gas disasters and lay the foundation for future potential disaster prevention and mitigation.

2. Geological setting of the Haizi coal mine

The Haizi mining field is located north of the Linhuan mining field in the Huaibei coalfield, China. The Huaibei coalfield is located in the southeastern margin of the North China plate, east of the depression of Yuhuai. This coalfield lies in the Xu-Su arcuate tectonic circle, in which the concave side of the arcuate structure has become a stress concentration zone due to undergoing compression, and is therefore ideal for gas storage (Han et al., 1993; Jiang et al., 2010; Wang et al., 2014c). Folds and faults are well developed in the Linhuan mining field, in which there are four outburst coalmines: Haizi, Yangliu, Yuandian and Qingdong. The Haizi coal mine is a mine featuring typically complex geological structures, such as an EW-trending monoclinal structure

Fig. 1. Regional structure outline, sill distribution and composite columnar in the Haizi coalfield. (a) Regional structure outline of the Anhui province boundary; (b) Sill distribution and sampling locations; (c) Geological columnar composite.
surrounded by the Damajia Fault (which is NE-trending), the Daliujia Fault (NNE-trending), and the Wufang Fault (NEE-trending), as shown in Fig. 1. Coal seams no. 3, 4, 7, 8, 9, and 10 coal seams are all mineable; of these, Nos. 7, 8, 9, and 10 are primary mineable coal seams with classified outburst risks. Coal seams Nos. 5 and 6 are more poorly developed; these seams are not economically mineable, are thin, and feature unstable geological conditions. The No. 5 coal seam contains a thick, widespread magmatic sill in the middle and western parts of the mine, which poses a safety concern for mining activity. According to geological exploration data, more than half of the mining field has been intruded by magma. The thicknesses of these sills gradually decrease from northwest to southeast, although this trend is mutated near the mine exploration line 19, where there is a slight fold. West of line 19, measured sill thicknesses range from 140 to 170 m but are smaller in the east. The sill is approximately 55 m away from the No. 7 coal seam, and nearly 170 m away from the No. 10 coal seam (Fig. 1).

3. Processes and mechanisms of magma intrusion

3.1. Magma intrusion processes

Regional strata in the Huaibei coalfield have undergone multiple stages of evolution and multiple episodes of metamorphism throughout recent geologic history (Han et al., 1993; Jiang et al., 2010). During the Indosinian and Yanshanian orogenies, increased tectonic activity created many large fractures during the formation of coal-bearing strata. A mesh of fracture networks was also formed by interweaving NNE-trending and EW-trending fractures, among which the Tanlu fracture belt (NNE-trending), Subei fracture belt (EW-trending) and Fengwoo fracture belt (NNE-trending) are connected and likely control the movement and distribution of magma in the area (Fig. 1a). The Tanlu fracture belt is located in the eastern margin of the Huaibei coalfield, which has recorded different strike-slip distances and cutting depths during the processes of its formation and evolution. The evolution of this fracture belt is shown in Fig. 2: in the Late Triassic (specifically in the Late Indosinian period, 230–208 Ma), the length of the Tanlu was less than 1500 km, its cutting depth was approximately 15–20 km, and its largest left-lateral strike-slip distance was ~430 km. Data describing the extensional and deepening behavior of the Tanlu during the Jurassic Period (208–135 Ma) are not well known. In the middle Cretaceous-Paleocene (Sichuan period, 135–52 Ma), the Tanlu appeared to be a slightly dextral strike-slip normal fault, with a strike-slip distance of less than 100 km and a cutting depth of approximately 30–40 km. Finally, during the Miocene to Pleistocene (Himalayan Period, 23.3–0.73 Ma), the Tanlu appeared to function as a left-lateral strike-slip normal fault with a strike-slip distance of 50 km and a cutting depth of greater than 50 km (Wan, 1996). The Subei fault is a normal fault that cuts and controls the region’s Tertiary strata; it is approximately 240 km long and 4–6 km wide, with a fall drop height of greater than 1000 m. The Daliujia Fault is located in the western boundary of the Haizi coalmine and has a fall drop height of 300 m. It is considered to be one component of the NNE-trending Fengwoo fracture belt and is connected to the Subei fracture belt in the deep well field.

The most active period of magma intrusion in East China was that of a hypabyssal magma intrusion that directly influenced coal measure metamorphism in the region. The Yanshanian Period featured four periods of magma intrusion (Han et al., 1993); intermediate and acidic rocks were formed during the first three periods from the aforementioned crust-mantle-derived magma, and basic and ultrabasic rocks were formed during the fourth period from the mantle-derived magma (Xu and Qiu, 2010). The sill in the Haizi coalmine mainly comprises diorite and diorite porphyry, indicating that it is intermediate to intermediate-acidic in composition and that it was derived from the crust-mantle through the effects of magmatic underplating. By comparing these data with the known depth of the Moho interface near the Tanlu Fault in North China (approximately 34–36 km) (Liu, 2007), the history of the fault’s evolution, as well as the processes of magma intrusion, can be described as follows:

First, when the cutting depth was too shallow to reach the Moho interface, magma from the mantle was unable to directly upwell through the Tanlu Fracture Belt, and instead intruded along the bottom of the crust and melted the crust to form a new magma source. Under the effects of this magmatic underplating, magma gradually upwelled to a certain distance before being injected along the Subei fault and then intruding into the Haizi coal mine along the Daliujia fault. In the Late Yanshanian, the cutting depth of Tanlu was able to reach the Moho interface, allowing mantle-derived magma to directly upwell along the Tanlu Fracture Belt and then to follow the same intrusive path. There is extensive observational evidence indicating that when a vertically upward-propagating dyke meets a stress barrier or stiff strata, the dyke is often deflected into a sill (Gudmundsson, 2006; Gudmundsson and Philipp, 2006; Gudmundsson, 2011). Here, the existence of EW-trending fractures (the Subei fault) and NNE-trending fractures (the Daliujia fault) demonstrate that the maximum principal compressive stress changed from vertical to horizontal in the Haizi mining field, which is one of the conditions needed for sill emplacement.

![Fig. 2. Evolution of cutting depths of the Tanlu fault.](image)
In the Huaibei coalfield, NNE-trending fractures are interwoven with EW-trending fractures, forming a mesh of fracture networks. Magma was injected along the Tanlu and Subei faults, in addition to being intruded into the No. 5 coal seam in the Haizi mining field. This latter intrusion occurred along the Daliujia fault and progressed upwards before the magma’s upwelling was stopped by a stress barrier, as is shown in Fig. 3. The additional presence of many soft layers in the Haizi mining field, where most rocks include alternating soft and stiff layers, also probably helped to generate sills (Gudmundsson, 2011; Wang et al., 2014a).

3.2. Mechanisms of magma intrusion

Generally, magma squeezing and magma erosion are the main mechanisms by which magma intrudes coal measure strata. If we assume that magma squeezed into the strata without any associated large-scale erosion, the lithologies and thicknesses of the floor and roof below and above the coal seam would be similar in a local region within the coal mine. This hypothesis can be tested using two common geological methods: first, by comparing the lithology and thickness of the coal seam roof and floor, and second, by comparing the distances between key strata and coal seams.

3.2.1. Comparing the conditions of the coal seam roof and floor

Table 1 lists all surface borehole data, including lithologies and thicknesses of the strata in the roof and floor; variations in these data are shown in Fig. 4.

Results demonstrate that the first rock stratum in direct contact with the sill in the roof is mainly sandstone, with a thickness of approximately 5.4–16.2 m; the second rock stratum in the roof is mudstone, with a thickness of approximately 5.0–10.8 m. The first and second rock strata
in the floor are mainly mudstone (3.5–8.8 m) and packsand (6.25–12 m). Although thicknesses and lithologies vary slightly between several boreholes with different sill thicknesses, the data are broadly similar, suggesting that the intrusion of magma did not erode certain strata and therefore that the most likely manner of intrusion was magma squeezing.

3.2.2. Comparing the in situ distance between key coal seams

Geological data from the Haizi coal mine show that coal seams No. 3 and No. 7 can be found in most regions, and can therefore be considered key strata for determining sill conditions by measuring relative distances, as is shown in Fig. 5.

These equations are shown as follows:

\[
\begin{align*}
H_{37} & = H_3 - H_7 \\
H_{37} & = H_{37} - H_{\text{ sill}}
\end{align*}
\]

In these equations, \(H_{37}\) is the absolute distance between the No. 3 and No. 7 coal seams, in meters; \(H_{37}\) is the relative distance between the No. 3 and No. 7 coal seams without the sill (m); \(H_3\) is the floor elevation of the No. 3 coal seam (m); \(H_7\) is the roof elevation of the No. 7 coal seam (m); and \(H_{\text{ sill}}\) is the thickness of the sill (m).

The spacing between the two coal seams is very similar in local regions during periods of geological history without large geotectonic movements. If magma intrudes and erodes certain strata, this absolute distance will not be changed, but if sills are instead squeezed into strata, this absolute distance will be changed by an amount proportional to the thickness of the sill but the relative distance will remain constant. Following this principle, we collected geological data from a series of surface boreholes located in positions with different sill thicknesses (Table 2). Absolute and relative distance variations are shown in Fig. 6a and b.

Data presented in Table 2 and Fig. 6 demonstrate that the distance between the No. 3 and No. 7 coal seams increases with increasing thickness of the sill. In contrast, the relative distance remains roughly constant at ~250 m, which is nearly equal to the absolute distance between the No. 3 and No. 7 coal seams in regions without the sill. Taken in total, these results strongly suggest that the main mechanism of magma intrusion in this region is that of magma squeezing.

4. Distribution characteristics of the in situ stress field under the magmatic sill

Tectonic activity likely directly influences in situ stress. Therefore, it is likely that the distribution of this in situ stress could vary with different thicknesses of the magmatic sill. This hypothesis can be directly tested using the acoustic emission (AE) method and indirectly tested by determining the quantity of drilling cuttings (S).

4.1. Results and analysis of the AE method

The AE method is commonly used to directly measure in situ stress, and calculates stress history based on the Kaiser Effect of rock materials (Seto et al., 1999; Brady and Brown, 2005; Shkuratnik et al., 2007). In this method, AE signals of samples under directional uniaxial compression are received by auxiliary computer; these emissions increase until the stress reaches a critical value, which is equal to the original stress.
that was placed on the samples. Five samples were collected from regions of different sill thicknesses (0 m, 22 m, 60 m, 85 m and 145 m); the locations of these samples are shown in Fig. 1 (b) and Table 3.

To calculate the space’s primary stress, samples are always collected in six directions, namely, X, Y, Z, X45°Y, Y45°Z, and Z45°X (Fig. 7a, Li et al., 2011). In deep rock strata, we collected samples at the head of the working face by using a compass to locate and label the inclination direction, and then used only three directions for subsequent calculations (Fig. 7b, Li, 2006).

For a test loading system, we used a 100 kN test machine. The corresponding curves of AE-time and cumulative number-time were recorded by the domestic AE-4008 type four channel AE parameter tester. Results of these analyses are shown in Table 4.

In Table 3, \( \sigma_1 \) is the normal stress parallel to the direction (X), in MPa; \( \sigma_2 \) is the normal stress perpendicular to the direction (Y), in MPa; and \( \sigma_3 \) is the normal stress at the 45° direction (Z), in MPa (Fig. 7b).

The different stress values and directions of maximum horizontal principal stress for each measured point can be calculated using the following formulas (in which normal compressive stress is expressed as the positive direction) (Brady and Brown, 2005; Li, 2006; Li et al., 2011):

\[
\begin{align*}
\sigma_\gamma &= \gamma H \\
\sigma_{T, \max} &= \sigma_{h, \max} - \lambda \sigma_\gamma \\
tg 2\phi &= \frac{\sigma_1^2 + \sigma_2^2 - 2\sigma_1 \sigma_2}{\sigma_1^2 - \sigma_2^2} \\
\sigma_{h, \max} &= \frac{\sigma_1^2 + \sigma_2^2 + \sqrt{2} \sqrt{(\sigma_1^2 - \sigma_2^2)^2 + (\sigma_1^2 - \sigma_2^2)^2}}{2} \\
\sigma_{h, \min} &= \frac{\sigma_1^2 + \sigma_2^2 - \sqrt{2} \sqrt{(\sigma_1^2 - \sigma_2^2)^2 + (\sigma_1^2 - \sigma_2^2)^2}}{2} \\
\sigma_{h, \text{avg}} &= \frac{\sigma_{h, \max} + \sigma_{h, \min}}{2}
\end{align*}
\]

In these equations, \( \sigma_\gamma \) is the vertical gravity stress, in MPa; \( \gamma \) is the average density of the overlying strata, usually equal to 0.025 t/m³; \( H \) is the depth of the sample location, in m; \( \sigma_{T, \max} \) is the maximum horizontal tectonic stress, in MPa; \( \lambda \) is the lateral pressure coefficient, \( \lambda = \frac{\mu}{1-\mu} \); \( \mu \) is Poisson’s ratio, which is \( \mu = 0.25 \), according to experimental strata data in the Huaiabei coalfield; \( \sigma_{h, \max} \) is the maximum horizontal principal stress, in MPa; \( \sigma_{h, \min} \) is the minimum horizontal principal stress, in MPa; and \( \sigma_{h, \text{avg}} \) is the average horizontal stress, in MPa.

The data in Table 4 demonstrate that all principal stresses at each measured point are compressive and that the maximum horizontal principal stress and maximum horizontal tectonic stress both vary proportionally with increasing thickness of the overlying sill. A linear relationship also exists between the ratio \( \sigma_{h, \text{avg}}/\sigma_T \) and the thickness of the sill \( H_{\text{sill}} \) (in which the anticlockwise rotation of \( \phi \) seems to be positive), in degrees; and \( \sigma_{h, \text{avg}} \) is the average horizontal stress, in MPa.

The results of these calculations indicate that at station R559, which features a 145 m thick sill, the maximum horizontal principal stress is 29.96 MPa; at R555, which is not covered by a sill, the calculated stress is only 8.09 MPa. Similarly, the calculated maximum horizontal tectonic stress at R559 is 25.62 MPa, while the maximum horizontal tectonic stress at R555 is 5.29 MPa. These results indicate that magma intrusion exerts a strong influence on the local stress field distribution. The direction of maximum principal stress in this region is nearly NNE, which is consistent with the results obtained from analysis of the tectonic stress field (Han et al., 1993; Yang, 1996).

![Fig. 6. The absolute and relative distance variations between the No. 3 and No. 7 coal seams. a. Variations in absolute distance (H_3to7). b. Variations in relative distance (H_3to7).](image-url)
4.2. Results of the drilling cuttings quantity

Drilling cuttings quantity \( (S) \) is one of the indices used to predict coal and gas outburst risk (Yu, 1992). It is measured by drilling a 42 mm diameter borehole along a coal seam, with the quantity of drilling cuttings per meter defined as the drilling cuttings quantity \( (S) \). Because this \( S \) value is mainly influenced by the diameter of the borehole, whose deformation is mainly controlled by its stress concentration, this index is always used to reflect stress distribution and is recognized as the outburst prediction index by the national regulation of coal mine gas control (State Administration of Work Safety of China, 2009). Generally, as ground stress increases, values of drilling cutting quantities will increase significantly along with the possibility of an outburst. In this paper, values of \( (S) \) were continuously measured during underground coal mining in regions featuring different average sill thicknesses, such as the conveyor roadway of the II 1026 working face (150 m thick sill), the conveyor roadway of the 10,410 working face (50 m thick sill) and the II 1015 working face (0 m thick sill). Statistical results of these analyses are shown in Fig. 10. Measured values vary widely between sills of different thicknesses, however, in general, \( S \) values increase with increasing sill thickness. A value of \( S \) four times greater than the critical value (6 kg/m) was found in the conveyor roadway of the II 1026 working face, near a region in which an actual outburst accident occurred (Wang et al., 2013). These measured values of drilling cuttings quantity \( (S) \) therefore allow us to adequately verify the relationship between sills and localized stress distribution.

5. Discussion

5.1. Relationships between magmatic sills and outburst hazards

Magma is a high-temperature and high-pressure fluid. Magmatic intrusions can alter the properties of coal, including its rank, mechanical properties, cleat and pore structures, and adsorption-desorption refrigeration. The ratio of the horizontal maximum principal stress \( \sigma_{h,av} \) and the vertical stress \( \sigma_v \) is shown in Fig. 8. The relationship between \( \sigma_{h,av}/\sigma_v \) and sill thickness.

### Table 3

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<th>Sample number</th>
<th>Sample location</th>
<th>Depth/m</th>
<th>Direction/°</th>
<th>Thickness of overlying sill/m</th>
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### Table 4

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<th>( \sigma_{h,ave}/\text{MPa} )</th>
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behaviors. The metamorphic grade of coal increases with increasing proximity to the sill; additionally, thermal metamorphism of the sill produces cracks and pores in the underlying coal seam and generates hydrocarbon (Yao et al., 2011). Moreover, this low-permeability sill can serve as a top seal for underlying coal seams, leading to high gas contents and abnormal gas pressures in coal reservoirs (Wang et al., 2014a).

Magma intrusion is one of the main factors influencing the evolution and distribution of in situ stress. Before an intrusion occurs, the surrounding rock mass is always in a force balance state. When magma intrusion occurs, equilibrium is disturbed and localized stress is redistributed. It is well established that gas-coal outbursts are the combined result of multiple factors, such as in situ stress, gas pressure, and the physical and mechanical properties of coal. Because ground stress can control the migration of gas through effective stress, it is considered to be one of the dominant factors controlling outburst mine disasters (Cheng et al., 2013; Wang et al., 2014C). Coal with high in situ stress consistently features a high gas storage capacity and low mechanical strength; these highly stressed coals tend to have a high risk of gas-coal outburst accidents (Cheng et al., 2013). This trend was confirmed in the Haizi coalmine, where all eleven gas outburst accidents from 1984 to 2009 occurred beneath the thick sill (Table 5). The outburst frequencies of the No. 7 and No. 8 coal seams are higher than those of the No. 10 coal seam (Table 5). These data demonstrate the fact that outburst frequencies and gas emission amounts tend to decrease with increasing distance between the sill and coal seam. Additionally, within the same coal seams, gas emission amounts recorded in different accidents display a positive correlation with sill thicknesses, as shown in Fig. 11. In general, as sill thickness increases, so does the risk of a larger outburst; these data suggest that this is the effect of ground stress redistribution that is induced by the intrusion of magma.

5.2. Implications of prevention of coal mine outburst hazards

The occurrence, distribution, and size of intrusive igneous sills play important roles in coal mining safety. When a thick-hard igneous sill overlies a coal seam, the risk of gas outburst in the mine is amplified by the combined effects of magma squeezing, thermal metamorphism and sill entrapment (Wang et al., 2014a). Regional gas control plans for eliminating outburst risks must therefore first be implemented prior to beginning mine extraction in outburst coal seams (State Administration of Work Safety of China, 2009). With effective gas drainage, these gassy and outburst-prone coal seams could be altered to become non-gassy seams without the risk of outbursts, thus facilitating the simultaneous extraction of coal and gas in a safe environment (Cheng, 2010). These data suggest that a gas drainage plan with an optimized borehole layout is the key to safe coal mining in outburst-prone coal seams. The effectiveness of gas drainage is determined by the permeability of the coal seam (Cheng et al., 2014), which is a stress-sensitive parameter that is inversely correlated with total stress (Connell et al., 2010). This study demonstrates that in situ stress increases with the increasing thickness of an overlying magmatic sill, which can change the permeability of underlying coal seams and thus reduce the effectiveness of the gas drainage plan. Because increasing sill thickness reduces permeability in underlying coal seams, the efficiency of a gas drainage plan is influenced by sill thickness. Based on these results, future workers should design gas drainage boreholes in

![Fig. 9. The relationship between the maximum horizontal tectonic stress and sill thickness.](image)

![Fig. 10. Actual measured values of drilling cuttings quantity (S) under different sill thicknesses.](image)

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Statistics of coal and gas outbursts in the Haizi coal mine.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal seam</td>
<td>Depth (m)</td>
</tr>
<tr>
<td>No. 7</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>410</td>
</tr>
<tr>
<td>No. 8</td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>423</td>
</tr>
<tr>
<td></td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>371</td>
</tr>
<tr>
<td>No. 10</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>500</td>
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<td></td>
<td>672</td>
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</table>
accordance with local sill thicknesses in order to establish an effective outburst mitigation plan. Smaller borehole spacing is also required for coal seams with thicker sills in order to achieve desirable gas drainage. These results could have important implications for coal gas outburst hazard prevention, allowing future workers to better ensure safe mining conditions.

6. Conclusions

1) The presence of complex geological structures suggests that magmatic intrusions have significant effects on preexisting rocks and are commonly distributed in the Huainai coalfield. Analysis of the cutting depths of the Tanlu Fracture Belt, the depth of the Moho interface and magma lithologies suggest that the sources of magma in this region comprise materials formed first by magmatic underplating at the crust-mantle boundary and then directly from the mantle in the Late Yanshanian. Analysis of existing fractures and faults further demonstrate that intrusive magma first traveled along the Tanlu Fracture Belt, then along the Subei fault and Dalijiau fault. It is also possible that magma upwelled along the Dalijiau fault before being stopped by a stress barrier, intruded along the soft No. 5 coal seam, and developed as a sill.

2) Comparing the conditions of the coal seam roof and floor reveals that the lithology and thickness of the roof and floor of the sill are nearly the same. Additionally, comparing the distances between the key coal seams (No. 3 and No. 7) reveals that the spacing between the No. 3 and No 7 coal seams increases with increasing sill thickness, whereas the relative distance remains essentially constant (approximately 250 m). These results indicate that magma squeezing is the main type of magma intrusion in this region.

3) According to the AE method, measured in situ stress distribution laws correlate well with the sill thickness (i.e., the thicker the sill, the larger the stress value). This conclusion is also indirectly supported by measurements determining the drilling cuttings quantity.

4) Stress redistribution induced by magma intrusions can directly influence the risk of gas-coal outbursts. This outburst risk increases proportionally with the thickness of the intrusive sill. It is therefore possible that stress redistribution induced by in situ magma intrusions could change the permeability of underlying coal seams, which can in turn provide guidance in drilling boreholes for mine gas drainage.

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