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Research Article

Study on Characteristics of Mining Earthquake in Multicoal Seam Mining under Thick and Hard Strata in High Position

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Rock burst has become one of the most serious world's problems in coal resources mining, and fracture and movement of thick and hard strata in high position is the main reason to induce strong mining earthquake and rock burst. Multicoal seam mining of 10302 working face in Baodian coal mine is selected as an engineering background, which has thick and hard strata in high position. Using SOS microseismic monitoring system to collect microseismic events and date during multicoal seam mining, characteristic and difference of microseismic in multicoal seam mining under thick and hard rock in high position is analyzed systematically. The main research work is as follows: reveal temporal and spatial distribution and evolution law of microseismic and analyze difference and correlation of microseismic in multicoal mining under thick and hard strata in high position, especially the relationship between mining earthquake with high energy and fracture and movement of thick and hard strata in high position. With the characteristics of microseismic, rock burst mechanism and difference induced by thick and hard strata in high position are discussed. The research and achievement could make guidance to multicoal seam mining safety under thick and hard strata in high position.

1. Introduction

Rock burst has become a major threat to deep coal resources mining, due to its obvious characteristics of suddenness, instantaneity, and violence. The fracture and movement of thick and hard strata with characteristics of high strength, huge thickness, and high position overlying coal seam play a key role to rock burst. Thick and hard strata are widespread in coal measure strata around the world, such as huge sedimentary fine sandstone (Baodian coal mine, Jining, China), huge sedimentary conglomerate (Huafeng coal mine, Qufu, China), and huge intrusive igneous rock (Yangliu coal mine, Huaibei, China) [1–3].

In recent decades, many scholars and experts focused on mining dynamic disaster caused by fracture and movement of thick and hard strata and carried out a lot of research work. Based on various research methods, such as theoretical analysis, numerical simulation, and field monitoring, many scholars [4–9], which represented by Jiang, Dou, and Pan, made large research and exploratory work, especially in fracture and movement law of strata, characteristics of spatial structure evolution of thick and hard strata, microseismic activity, and mechanism of rock burst. All the above research work made an important guidance to prevent and control rock burst under thick and hard strata.

Jiang et al. studied the internal relationship between spatial structure failure characteristics of thick and hard strata in high position and mining earthquake activity and analyzed the dynamic mechanism preliminarily [10]. Wu et al. revealed temporal and spatial distribution and evolution of microseismic activity in a single coal seam mining under thick and hard strata in high position [11]. Zhang and Jiang et al., based on different mining sequence of working face in engineering, established elastic sheet mechanical model of overlying thick and hard strata under different boundary conditions, to calculate fracture step and reveal the mechanism of dynamic disasters, such as rock burst, gas deflagration, and water gushing [12–14]. Wang and Zhang et al. focused on thick fine sandstone in high position, studied the first fracture mechanical mechanism and secondary movement law, and also revealed dynamic disaster under repeated mining [15, 16]. According to the theory of medium and thick elastic plates, some scholars preliminarily established a solution model to solve fracture step of huge thick and hard strata and compared with fracture step in engineering to confirm each other [17–19]. In recent years, with improvement and development of microseismic monitoring system, researchers deduced and analyzed fracture and movement law of thick and hard strata according to collecting microseismic data in engineering practices and carried out lot of conclusions [20–22]. Numerous other scholars have conducted a lot of exploration and research work on the mechanism and law of mining earthquakes activity of thick and hard strata based on various points and view [23–25].

At present, with continuous coal resources mining and consumption, the single coal seam mining under thick and hard strata in high position is nearing completion in worldwide, and multicoal seam of lower part mining is imperative. However, the current research results on fracture and movement mechanism, dynamic mechanism, and microseismic activity of thick and hard strata in high position are mainly concentrated on the single coal seam mining. Therefore, it is urgent to research on the dynamic mechanism of multicoal seam mining under thick and hard strata in high position to guide coal resources mining safety.

This paper takes multicoal seam mining in 10302 working face in Baodian coal mine under huge fine sandstone (commonly known as "red beds") as an engineering practice. Based on SOS microseismic monitoring system to collect microseismic events during mining, temporal and spatial distribution and evolution law of mining earthquake activities in multicoal seam mining is analyzed, and its inherent differences are researched, and the dynamic mechanism is discussed.

2. Layout of SOS Microseismic Monitoring System

2.1. Engineering Geological Conditions. Baodian coal mine is located in Jining City, Shandong Province, China, and is a modern large-scale production mine. The tenth mining area in the mine field is located in the middle of Yanzhou syncline, and geological structure is relatively simple without large fault structures. The main mining coal seams are upper and lower of #3 coal seams (hereinafter, 3^{up} and 3^{low}), and both of them show strong bursting tendency. The thickness of #3 upper coal seam is 5.86 m, and #3 lower coal seam is 3.18 m. The tenth mining area is divided into six working faces, whose length of working faces 01 and 02 is 170 m, and 03 to 06 is 200–240 m. Pillar-free roadway technology is adopted in adjacent working faces. The composition of the overlying strata in the tenth mining area is relatively complex, with multiple layers of strata with different lithology, and contains multiple thick and hard strata. The uppermost layer of overlying strata is near 200 m fine siltstone, commonly known as "red beds," with a compressive strength of 70 MPa and tensile strength of 9 MPa, which has a vertical distance is 130 m to #3 coal seam. The layout of working face and overlying strata in the tenth mining area are shown in Figure 1. During working face 10302 mining, working face 10301 was mined over and upper coal seam of 10303 was only mined.

2.2. SOS Microseismic Monitoring System. SOS monitoring system (seismological observation system), researched and development by the Polish Institute of Mining Research, is mainly used to monitor mining earthquake, determine vibration parameters near working face, and predict dynamic disaster of mining. The SOS is composed of recording analysis system and microseismic probe, which can locate and record microseismic activities real-time during coal seam mining. SOS is shown in Figure 2.

A total of 19 microseismic probes are arranged in Baodian coal mine field. In order to accurately record microseismic activities during mining of working face, 10 probes (#1, #2, #3, #4, #5, #6, #7, #9, #10, and #18) were arranged in the tenth mining area and near working face. The layout of microseismic probes is shown in Figure 3.

The existing research results show that microseismic events with energy higher than 10^4 J make important reference value to analyze and predict dynamic disasters. So, the following will focus on analyzing temporal and spatial distribution and evolution law of mining earthquake activities with energy higher than 10^4 J, during 10302 working face mining.

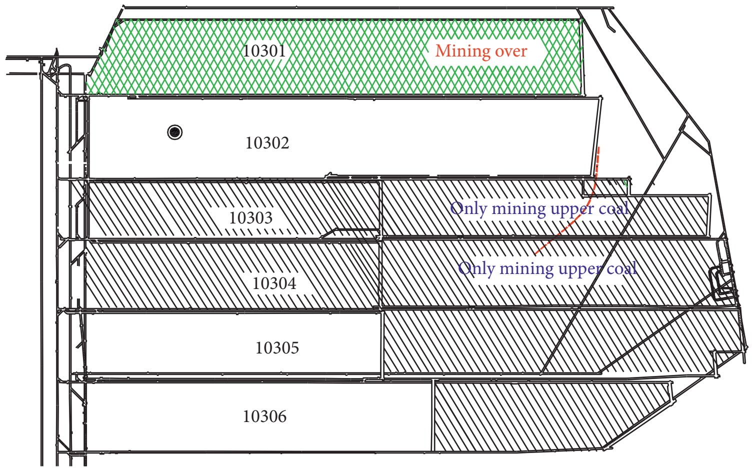
3. Temporal Distribution and Evolution Law

3.1. Temporal Distribution and Evolution Law of Mining Earthquake. According to energy level of microseismic activities, which was collected during 10302 working face mining, frequency of microseismic activities is analyzed by energy level in multicoal seam mining under red beds. Upper coal seam mining is shown in Figure 4, and lower coal seam mining is shown in Figure 5.

According to frequency of microseismic activities every day, temporal distribution and evolution law during multicoal seam mining show the following common characteristics:

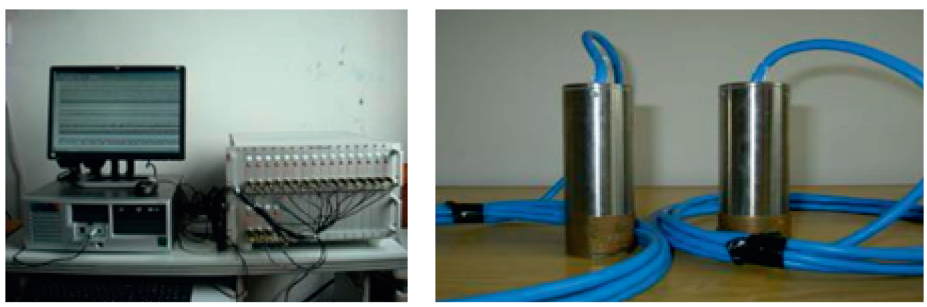
(1) Lower energy microseismic events (10^2 J < E < 10^4 J) exist throughout working face mining, which is induced by fracture and movement of overlying strata causing energy release. According to the key strata theory, lower energy microseismic events are mainly caused by fracture and movement of strata below the key strata (red beds). There is no obvious temporal law of microseismic events with lower energy, which randomly occurred, because fracture and movement step of immediate roof and weak strength strata are less and they are without obvious periodic law.

(2) Mining earthquake event (E > 10^4 J) does not always run through working face mining but occur at intervals because occurrence of mining earthquake



Lithology	Thickness (m)
Overlying strata	120
Fine sandstone	200
Mudstone	9.65
Medium sandstone	13.15
Sandstone	11.53
Fine sandstone	19.45
Siltstone	17.9
Mudstone	9.85
Medium sandstone	6.5
Mudstone	9.88
Siltstone	8.73
Sandstone	18.02
Siltstone	3.56
3 upper coal seam	5.86
Sandstone	13.27
3 lower coal seam	3.18

Figure 1: The layout of working face and overlying strata in the tenth mining area.



(a) (b)

Figure 2: (a) Microseismic probe. (b) Recording analysis system of SOS.

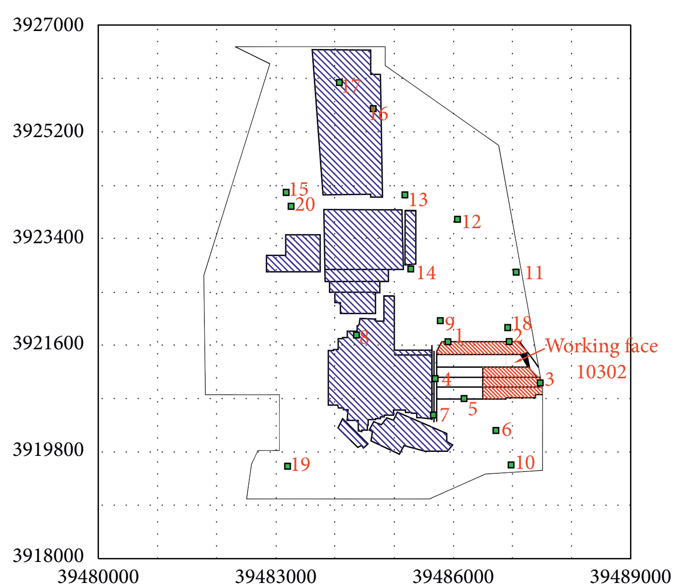
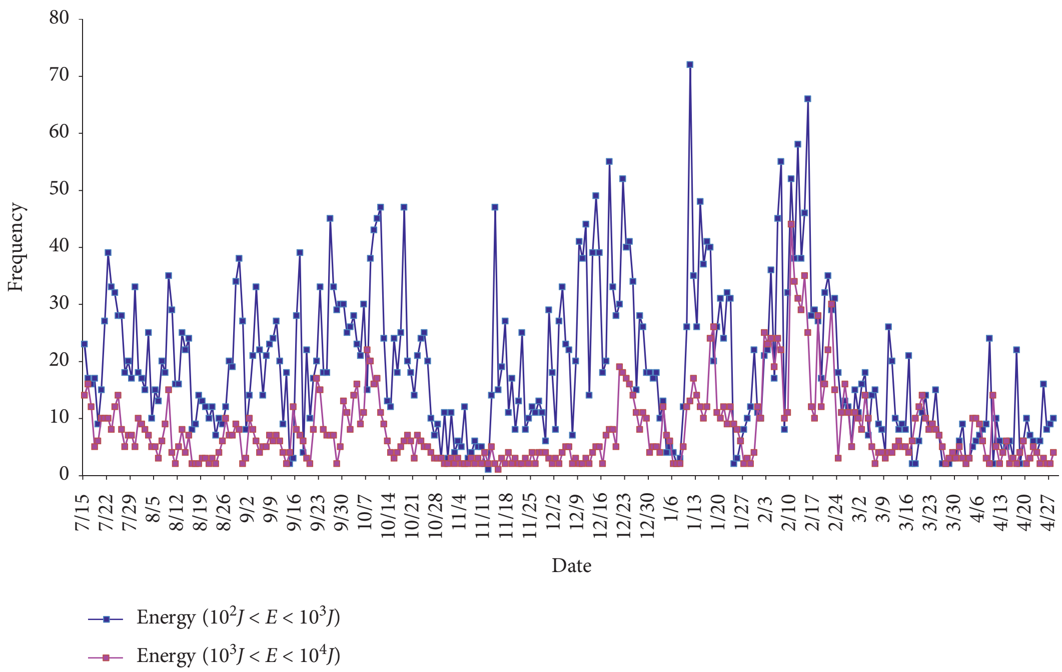


Figure 3: The layout of SOS microseismic monitoring system in Baodian coal mine.



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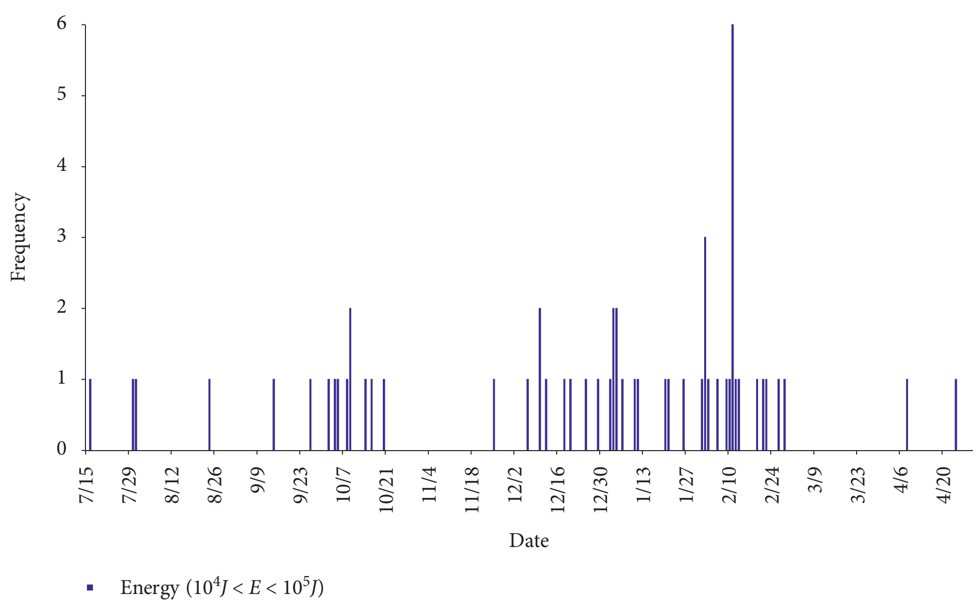

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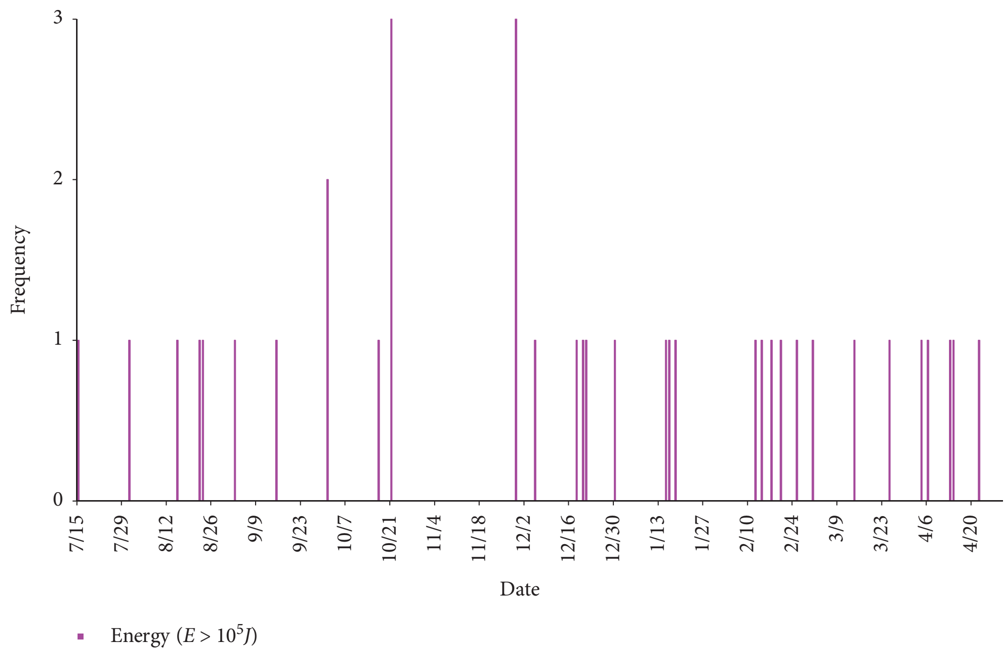
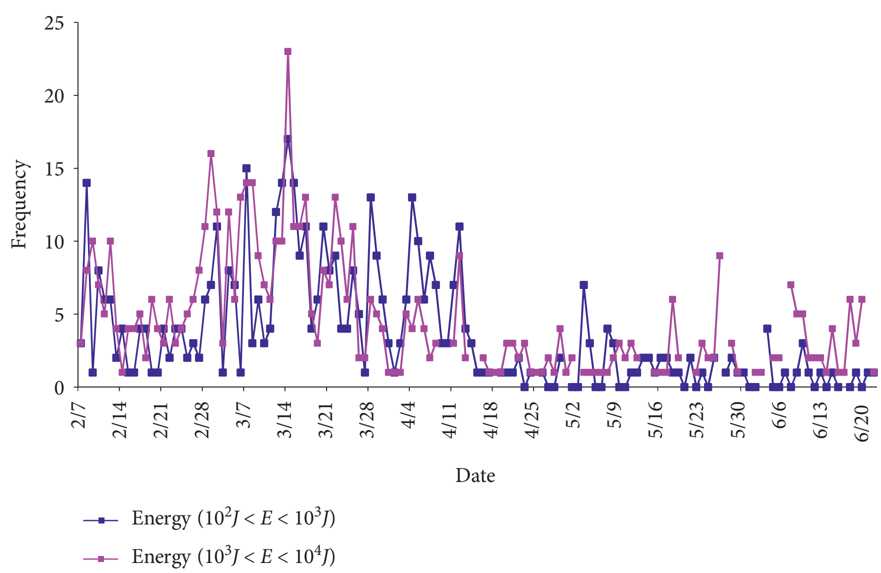


(c)

Figure 4: Temporal distribution and evolution law of microseismic events and mining earthquake during upper coal seam mining. (a) Energy level 10^2 J < E < 10^4 J. (b) Energy level 10^4 J < E < 10^5 J. (c) Energy level $E > 10^5$ J.



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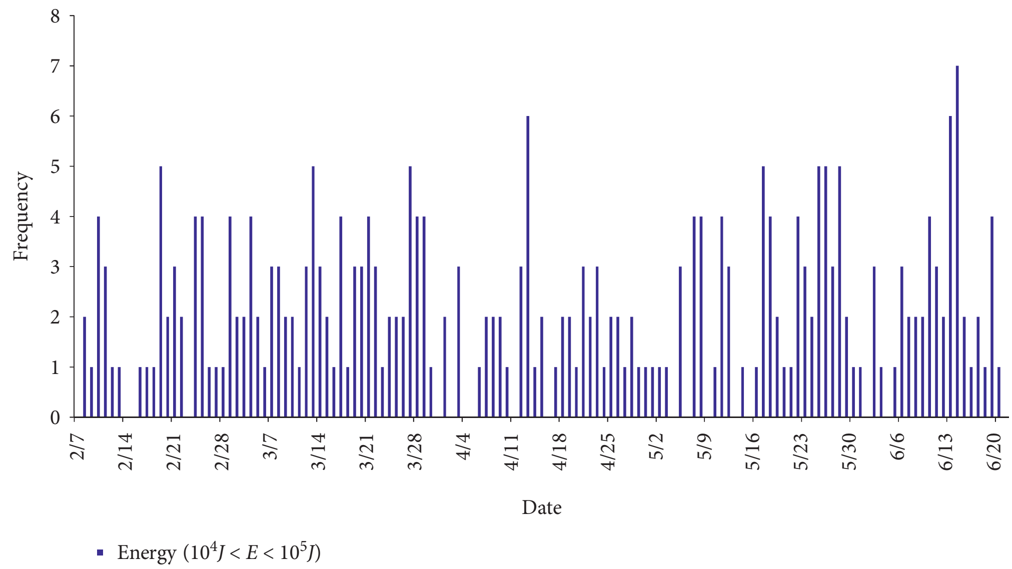

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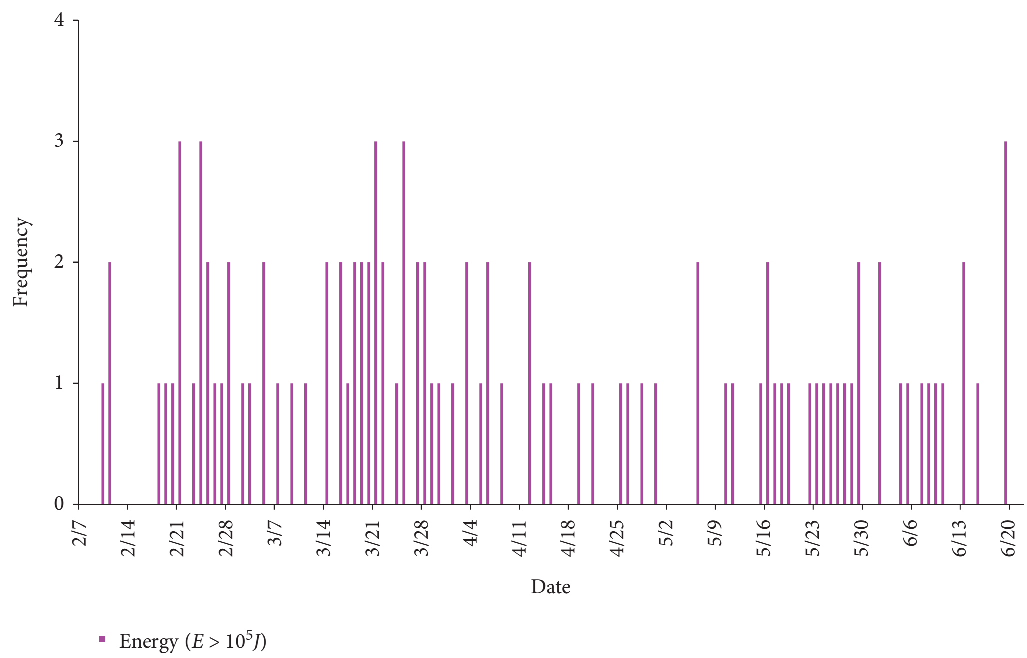


(c)

Figure 5: Temporal distribution and evolution law of microseismic events and mining earthquake during lower coal seam mining. (a) Energy level 10^2 J $< E < 10^4$ J. (b) Energy level 10^4 J $< E < 10^5$ J. (c) Energy level $E > 10^5$ J.

events is mainly caused by fracture and movement of the key strata (red beds). Especially strong mining earthquake events with high energy ($E > 10^5$ J) occur more obviously, with obvious periodicity in time, and the law is more obvious during upper coal seam mining.

(3) The occurrence frequency of microseismic events with lower energy is higher than that of mining earthquake with high energy. With increase of energy levels, occurrence frequency of microseismic shows a sharp decreasing trend.

3.2. Differences of Temporal Distribution and Evolution Law of Mining Earthquake. According to energy level of microseismic events, all microseismic activities collected during 10302 working face mining are analyzed statistically, just as shown in Table 1.

According to Table 1, Figures 4 and 5, there are obvious differences of temporal distribution and evolution law of mining earthquake in multicoal seam mining under red beds as follows:

(1) The total number of microseismic activities in the upper coal seam mining is more than that in the

Table 1: Statistical table of mining earthquake by energy level.

Coal seam	Energy (J)				
	10^2~10^3	10^3~10^4	10^4~10^5	$>10^5$	Total
Upper frequency	5061	1736	62	32	6891
Lower frequency	436	565	276	105	1382

lower coal seam mining, which indicates that damage and fracture of strata is the main reason to conduct microseismic events. The law is consistent with the existing theory that fracture and damage of strata in the first mining is stronger than that in repeated mining.

(2) The number of microseismic activities with low energy level (less than 10^4 J) in upper coal seam mining is much more than that in the lower coal seam mining. The main reason is that microseismic activity with low energy level is mainly caused by fracture of strata under the red beds, and during the upper coal seam mining, fracture and movement of strata is much strong than that in the lower coal seam mining.

(3) The total number of mining earthquake events with energy higher than 10^4 J in upper coal seam mining, which make a serious influence to excavating and mining activities, is less than that in lower coal seam mining. This indicates that the red beds are not fully moved during the upper coal seam mining, which shows "fracture-hanging" state, and fracture degree is not violent. With lower coal seam mining, red bed fracture and movement secondary occurs with much violent, inducing mining earthquake frequency. It is determined that fracture and movement of red beds is the reason for mine earthquake events.

(4) The frequency of strong mine earthquake ($E > 10^5$ J) in the upper coal seam mining is significantly less than that in the lower coal seam mining. The strong mining earthquake in upper coal seam mining shows certain regularity, especially the time interval between two strong mining earthquakes is not too long, which can be considered as advancing distance in actual mining. However, strong mine earthquake activities in the lower coal seam mining is intensive, disorder, and poor regularity. This indicates that the length of rock blocks, which formed by the fracture of the red beds in the upper coal seam, is almost the same size, but it is uncertain and ambiguous in the secondary movement during the lower coal seam mining.

4. Spatial Distribution and Evolution Law

Based on microseismic events, spatial distribution of microseismic and mining earthquake activities in plane and profile in tenth mining area was established, by using Surfer and AutoCAD software comprehensively, especially in working face 10302, just as shown in Figures 6 and 7.

4.1. Spatial Distribution and Evolution Law of Upper Coal Seam Mining. On the plane, microseismic events with low energy ($E < 10^4$ J) are mainly distributed in working face 10302 and near haulage gate of working face 10301. The main reason is that working face 10301 has been mined over, and working face 10302 mining causes further movement of overlying strata on working face 10301. On the profile, low-energy microseismic events are mainly concentrated on lower strata under red beds.

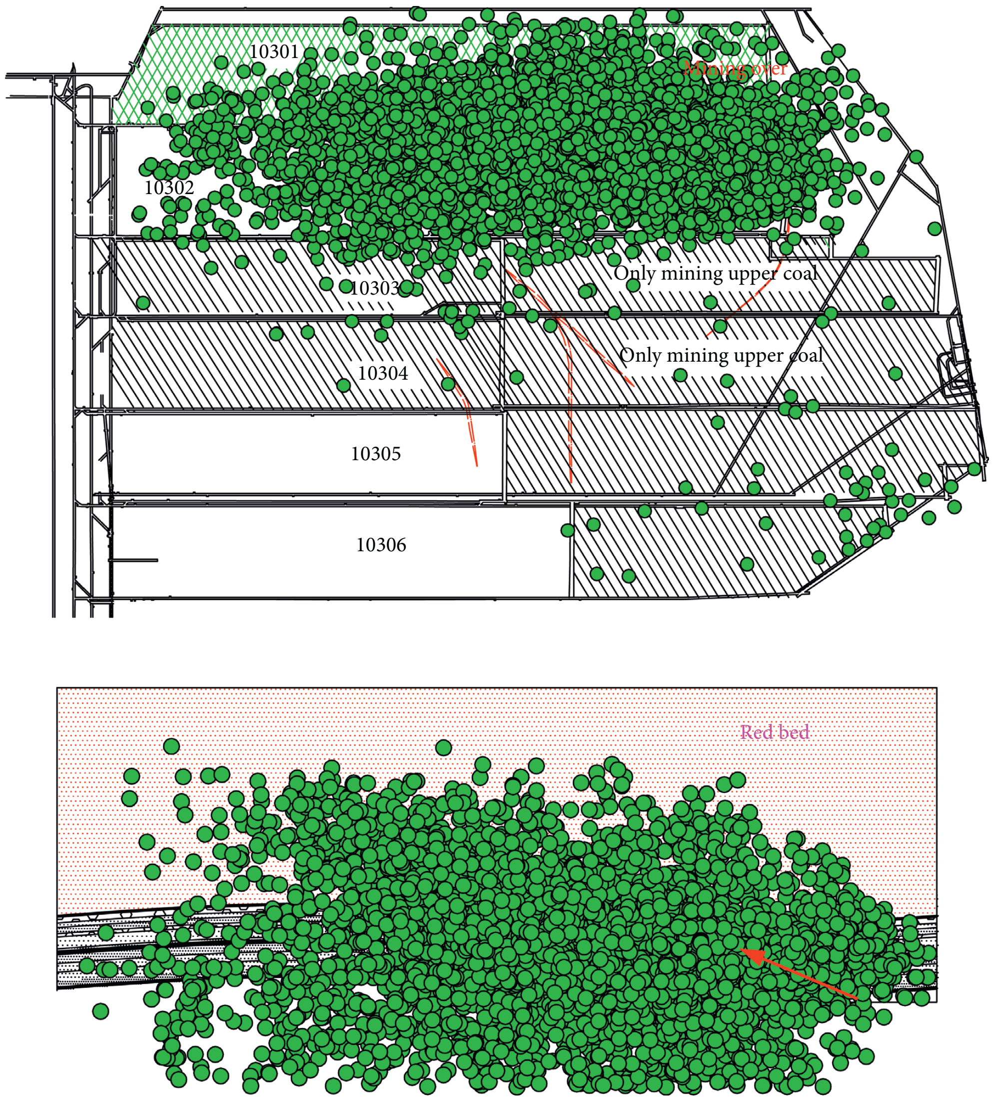
Mining earthquake events ($E > 10^4$ J) are mainly distributed in the middle area of the working face 10302 on the plane, and almost all concentrated on red beds on the profile. It indicates that the damage and fracture of red beds is the main reason to induce mine earthquake during upper coal seam mining. Due to characteristics of huge thickness, high strength, and high position of red beds, the fracture step is large, when working face 10302 advances to middle area, red beds fractured and strong mining earthquake are induced. On the profile, microseismic and mining earthquake activities show a trend "from bottom strata to up strata," which proved that the damage and fracture of strata is gradually developing upward.

4.2. Spatial Distribution and Evolution Law of Lower Coal Seam Mining. The spatial distribution of low-energy microseismic events ($E < 10^4$ J) is scattered, and there is no obvious law and trend. On the plane, mining earthquake events ($E > 10^4$ J) are densely concentrated on both sides of working face 10302, and on the profile, mostly concentrated on the lower strata under red beds, especially strong mining earthquake events with energy higher than 10^5 J is shown more obvious. This is the biggest difference of spatial distribution and evolution of mining earthquake between upper coal seam mining and lower coal seam mining in mining earthquake. With lower coal seam mining, induced fractured, and secondary movement of red beds, gob compaction and mining earthquake was caused.

5. Difference of Dynamic Mechanism in Multicoal Seam Mining

There are obvious differences of temporal and spatial distribution and evolution of microseismic and mining earthquake, between upper coal seam mining and lower coal seam mining under thick and hard strata in high position, especially the strong mining earthquake with high energy. Therefore, analyzing the dynamic mechanism of multicoal seam mining under thick and hard strata in high position is important to guide preventing rock burst and designing reasonable control measures.

5.1. Dynamic Mechanism of Upper Coal Seam Mining. With coal seam mining, area of exposure of thick and hard strata in high position is increasing, high abutment pressure occurs on coal seam in front of working face, and mining earthquake is induced. The thick and hard strata fractured and released a large amount of energy to shock mining space,



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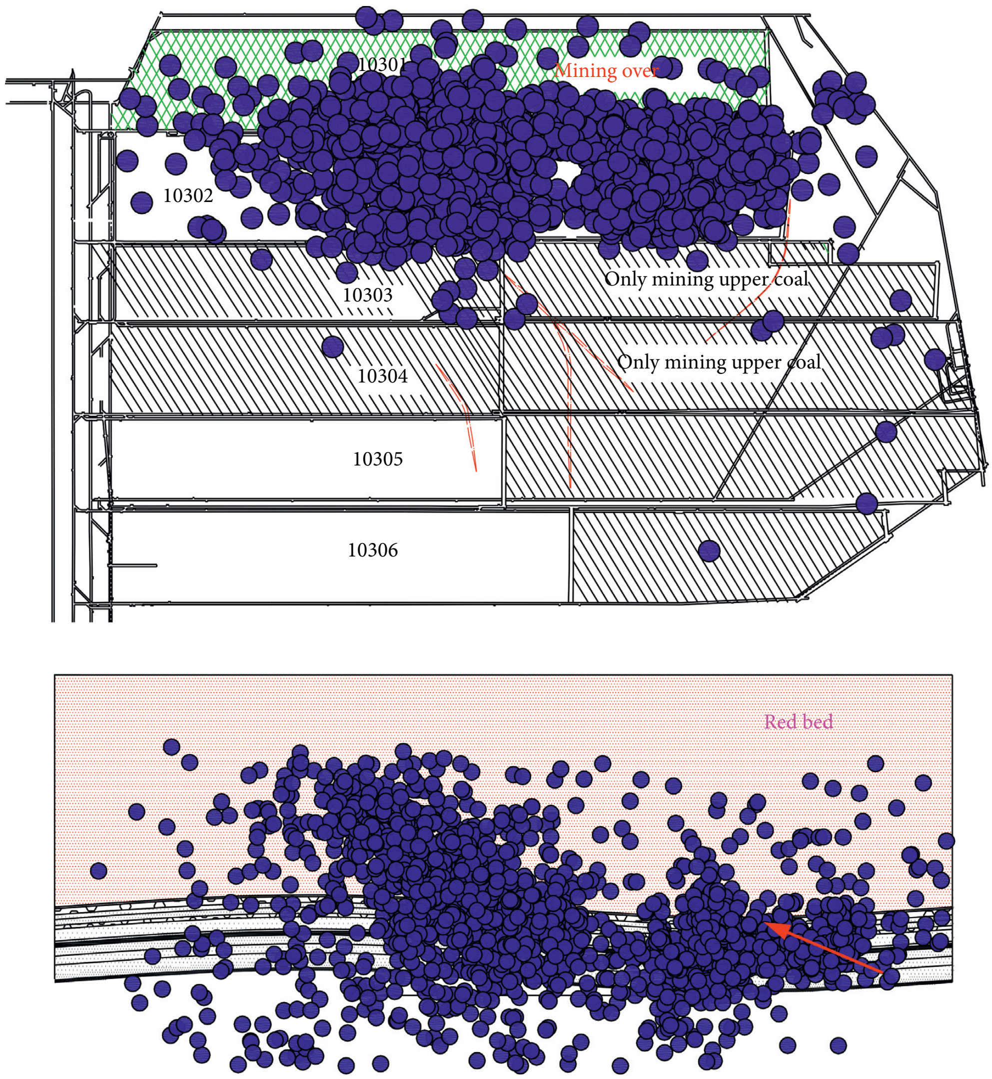

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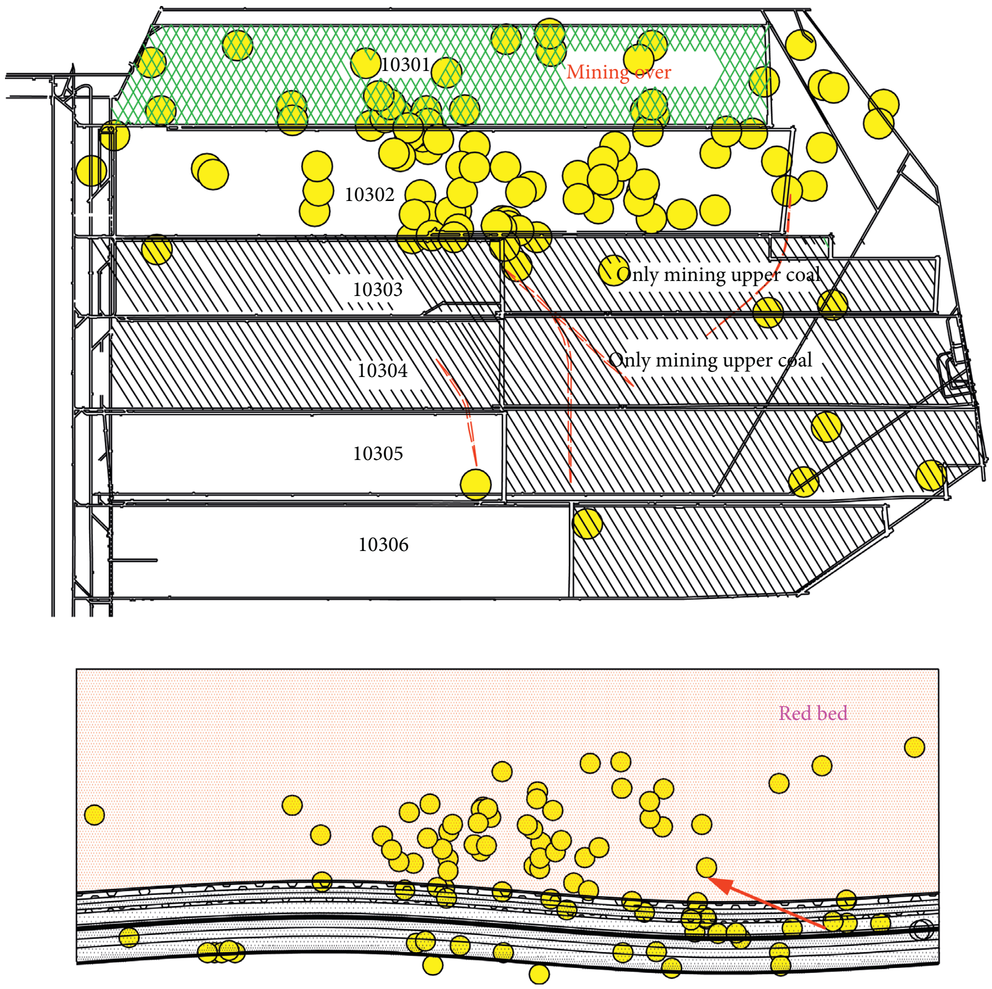

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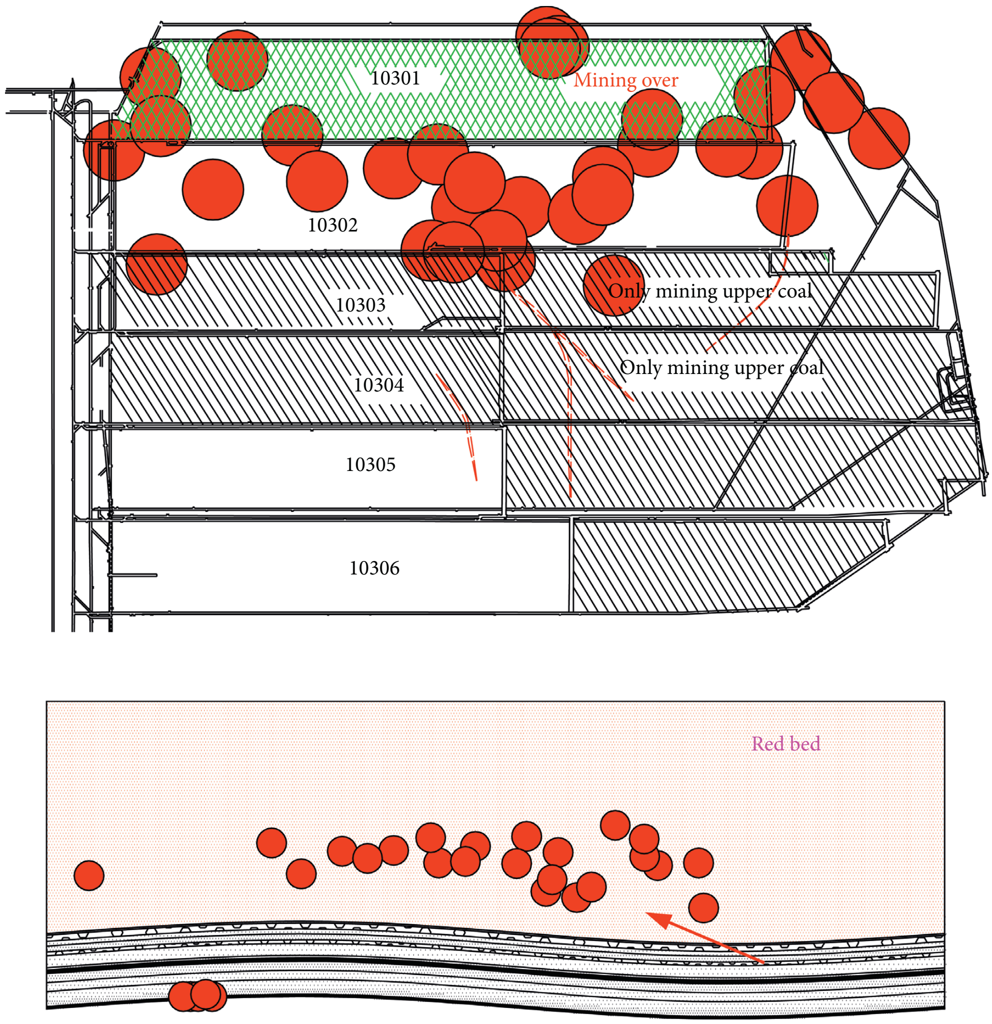


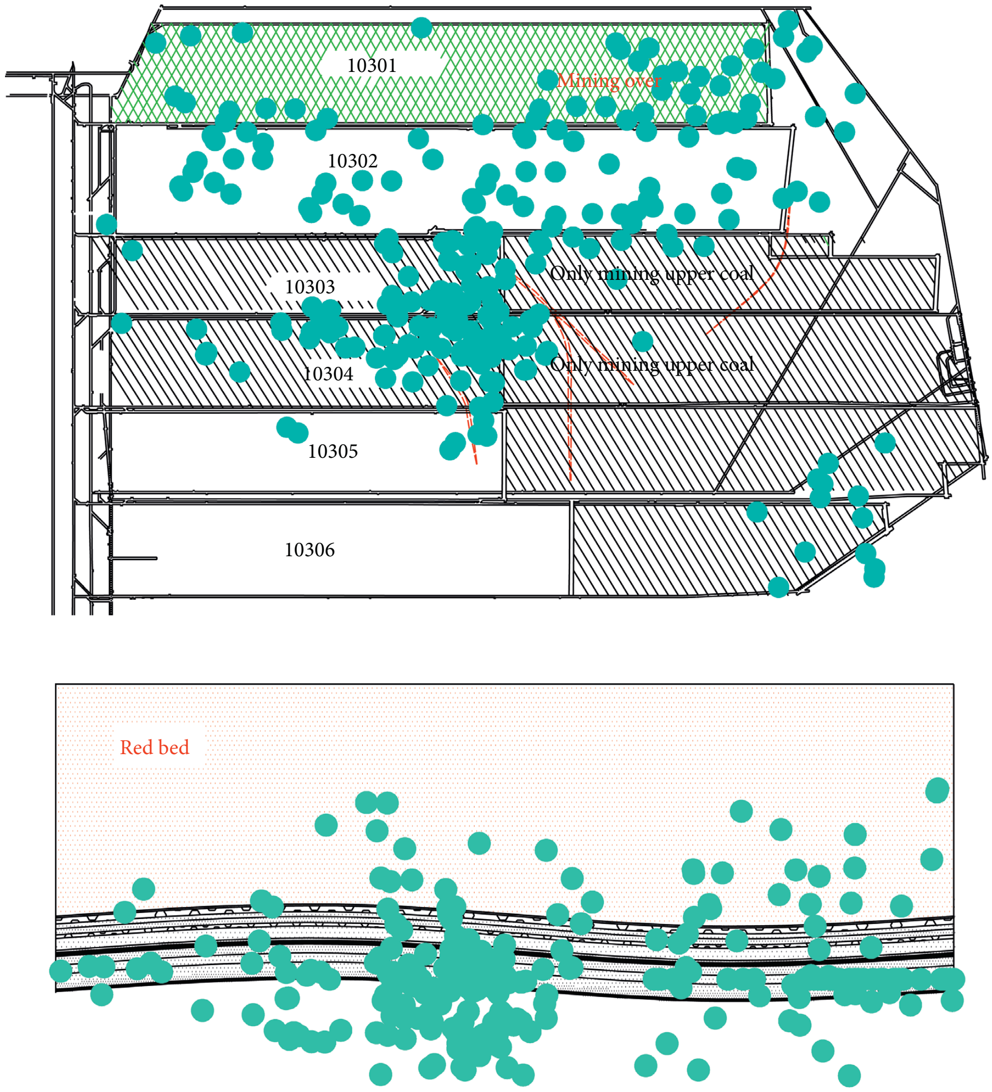
(d)

FIGURE 6: Microseismic and mining earthquake events spatial distribution of plane and profile during upper coal seam mining in 10302 working face. (a) Energy level 10^2 J < E < 10^3 J. (b) Energy level 10^3 J < E < 10^4 J. (c) Energy level 10^4 J < E < 10^5 J. (d) Energy level E > 10^5 J.

when exposed area reached the limit of fractured step. Because of characteristics of thick and hard strata, fractured strata are not moved fully and squeezed with each other to form a continuous hinged rock block stable structure. In summary, the dynamic mechanism of the upper coal seam mining is induced by the damage and fracture of overall structure of thick and hard strata in high position as shown in Figure 8.

5.2. Dynamic Mechanism of Lower Coal Seam Mining. With the lower coal seam mining, line of rock movement expands outwards, movement and settlement space increase to overlying strata, breaking stable and balanced of continuous hinged rock block structure, and making fractured rock block movement and settlement secondary. The dynamic mechanism is divided into two forms according to location of fractured rock block in high position. As settlement space increases to central rock block, vertical stress is changed suddenly, and shear stress exceeds the limit, making "shear slip type" dynamic. Because of line of rock movement expands outwards, high concentrated stress is generated on both boundary rock blocks to compact lower collapsed rock strata, causing "slip settlement type."

The two dynamic forms cross each other and promote each other: settlement of central rock block increases caused by "shear slip type," which leads to an increase in vertical displacement distance between the boundary rock blocks, increasing possibility of boundary rock block slip and settlement along the slope. Stress concentration of boundary rock block near central rock block increases caused by "slip settlement type," which squeezes central rock block and causes further settlement, and in turn, promotes slip and settlement of boundary rock block as shown in Figure 8.



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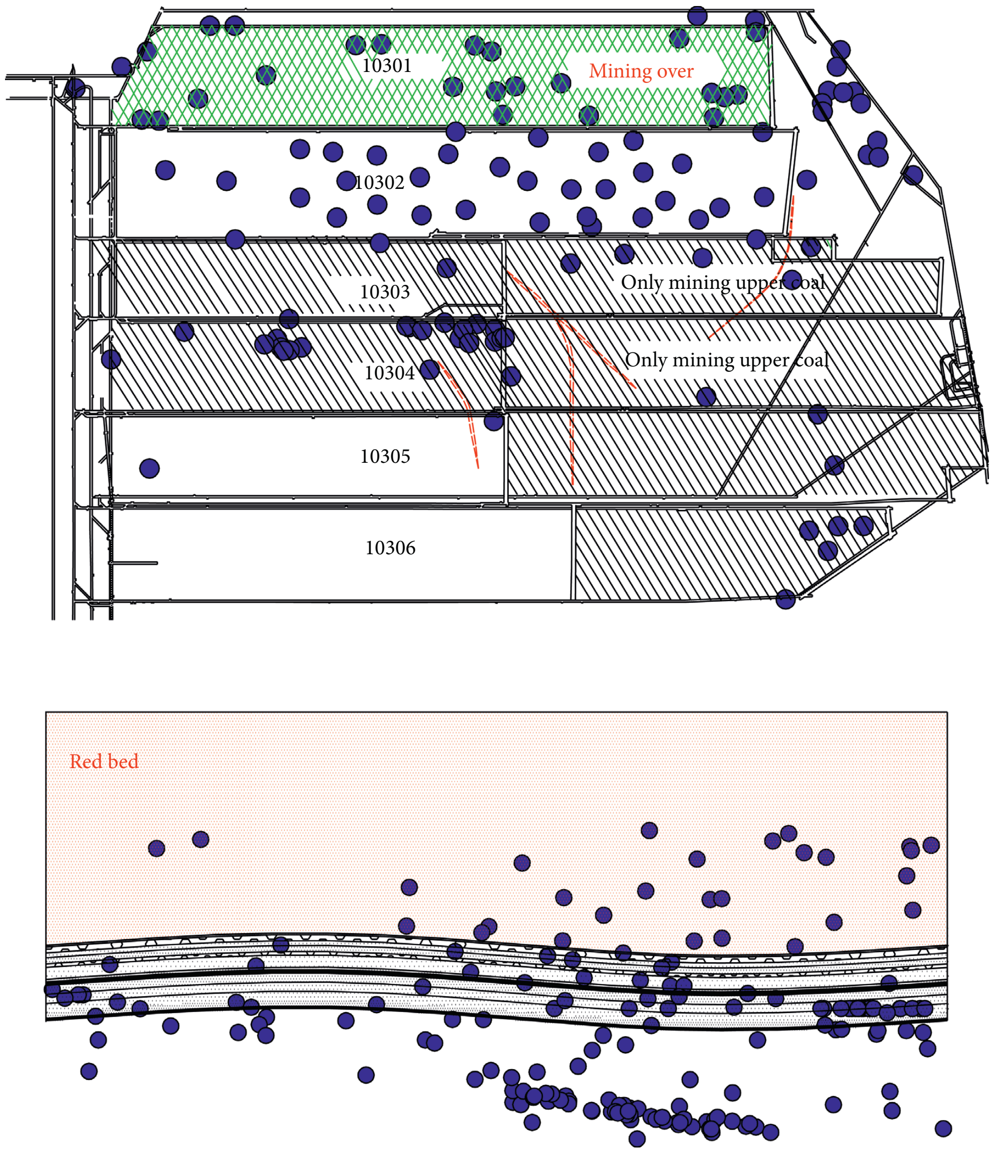

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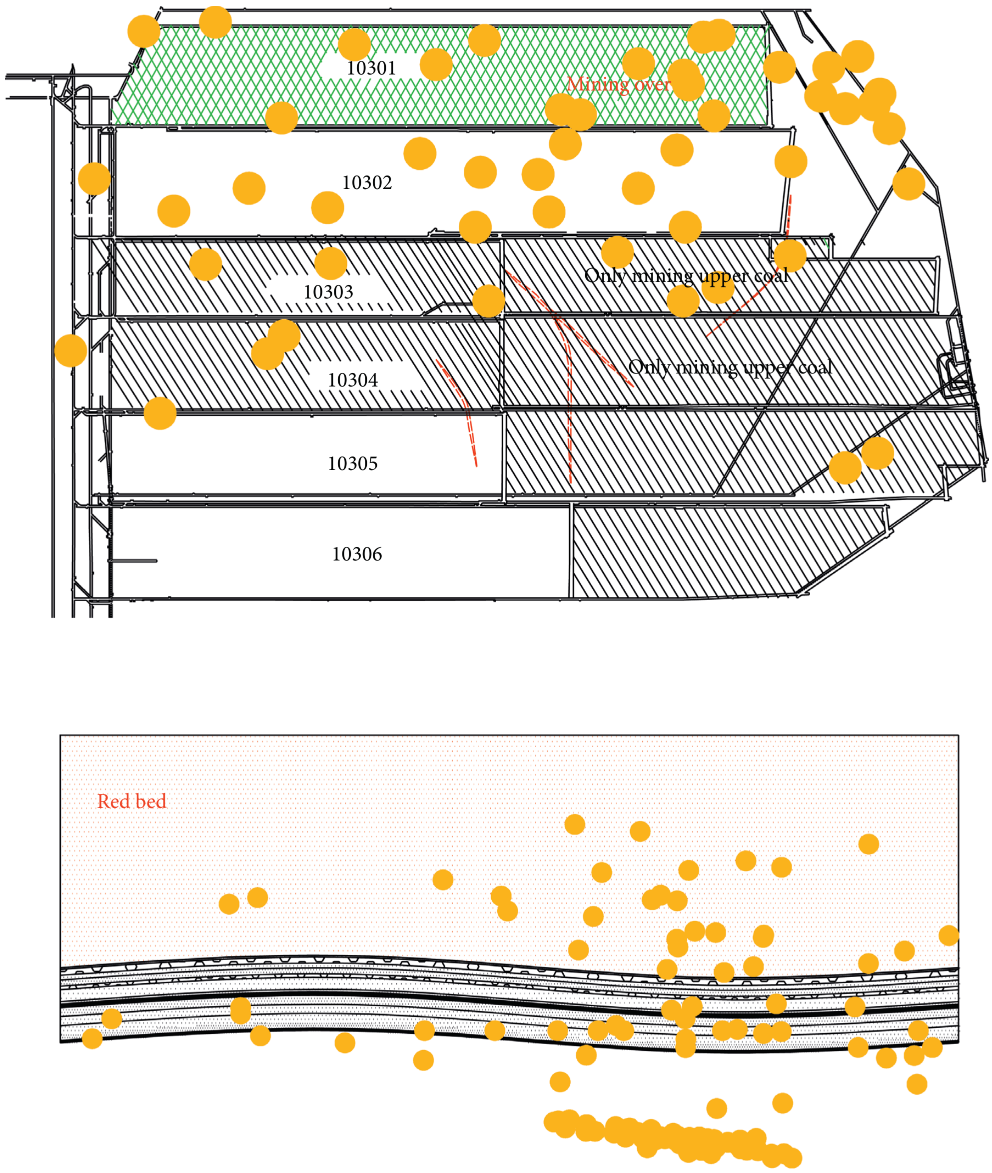

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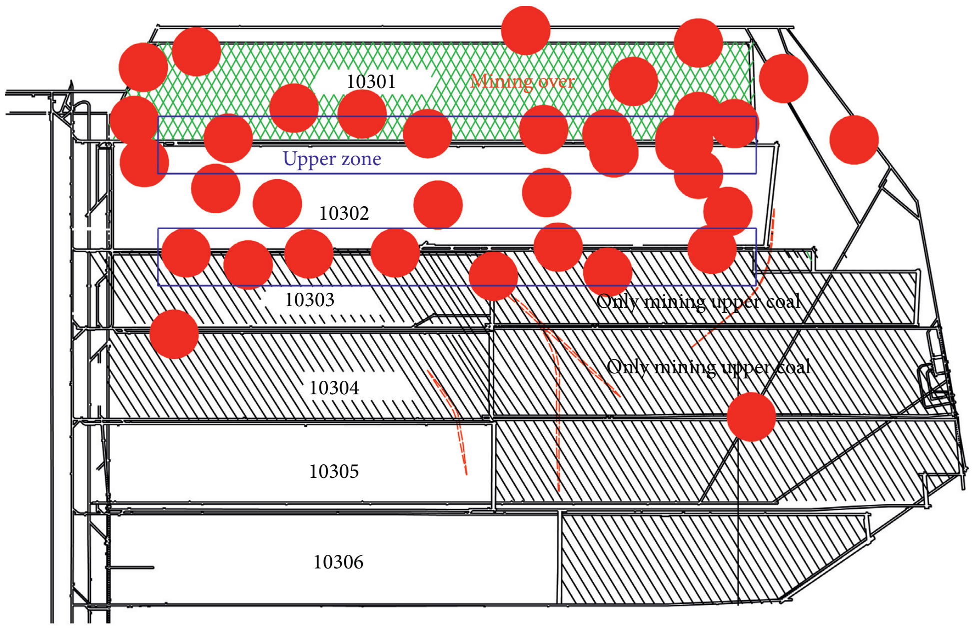

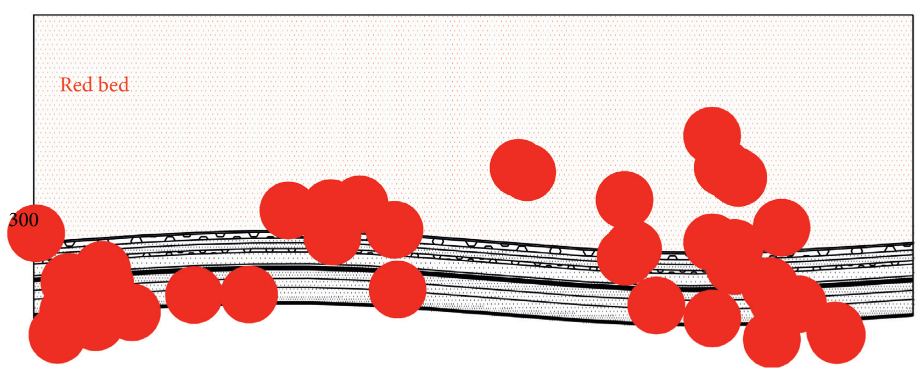

(d)

Figure 7: Microseismic and mining earthquake events spatial distribution of plane and profile during lower coal seam mining in 10302 working face. (a) Energy level 10^2 J < E < 10^3 J. (b) Energy level 10^3 J < E < 10^4 J. (c) Energy level 10^4 J < E < 10^5 J. (d) Energy level E > 10^5 J.

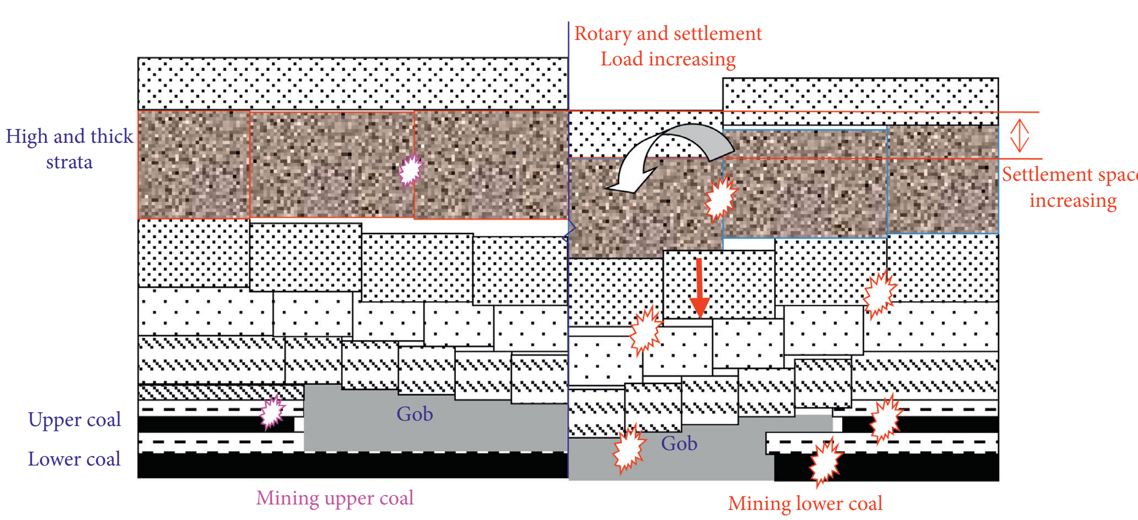

Figure 8: Dynamic mechanism of multicoal seam mining under thick and hard strata in high position.

6. Conclusions

Based on SOS, microseismic activities are collected, to reveal temporal and spatial distribution and evolution law of mining earthquake, difference between upper coal seam mining and lower coal seam mining under thick and hard strata in high position is analyzed, and the dynamic mechanism of multicoal seam mining is discussed. The main research conclusions are as follows:

(1) Microseismic events with low energy occur more than mining earthquakes in multicoal seam mining under thick and hard strata in high position, and microseismic events occur without obvious regularity. During the upper coal seam mining, there are obvious time intervals between strong mining earthquake events, which are caused by periodic fracture of thick and hard strata. During the lower coal seam mining, mining earthquake events occur more than that in the upper coal seam mining, but without obvious temporal regularity.

(2) The spatial distribution of microseismic events in multicoal seam mining under thick and hard strata in high position is without obvious regularity. During the upper coal seam mining, strong mining earthquakes are mainly concentrated on the thick and hard strata, and also in the middle of working face. During the lower coal seam mining, strong mining earthquakes are mainly distributed on both sides of the working face, and also in the lower strata below thick and hard strata, which indicate that the lower coal seam mining caused the secondary movement of fractured thick and hard strata in high position, inducing strong mining earthquake.

(3) Under thick and hard strata in high position, the dynamic mechanism in upper coal mining is caused by damage, fracture, and movement of the overall strata structure, and strata are not fully fractured, which formed a continuous and stable hinged rock block structure. The lower coal seam mining causes movement line of the strata expanding outward, and space for settlement and movement increases, causing secondary movement of fractured rock block, which induce rock burst. The dynamic type can be divided into "shear and slip type" and "slip settlement type".

Data Availability

All data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All the authors contributed extensively to the work. Shuli Wang contributed to theoretical analysis and wrote the paper. Guangli Zhu and Kaizhi Zhang analyzed microseismic data. Lei Yang modified the manuscript.

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