





Review Article

A Scientometric Review on Rockburst in Hard Rock: Two Decades of Review from 2000 to 2019

Weizhang Liang ¹, Bing Dai ^{2,3}, Guoyan Zhao ¹ and Hao Wu ¹

¹School of Resources and Safety Engineering, Central South University, Changsha 410083, China

²School of Resource Environment and Safety Engineering, University of South China, Hengyang 421001, China

³Deep Mining Laboratory of Shandong Gold Group Co., Ltd., Laizhou 261400, China

Correspondence should be addressed to Bing Dai; daibingusc@usc.edu.cn and Guoyan Zhao; gyzhao@csu.edu.cn

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Considerable advances have been made from diverse perspectives in rockburst research to guarantee the safety of deep underground activities. However, to date, few reviews have been made to systematically analyze the overall research status of rockburst. This study is aimed at providing a scientometric review on rockburst research in hard rock from 2000 to 2019. First, a total of 430 papers were collected from the Web of Science Core Collection database. Then, the CiteSpace software was adopted to conduct a scientometric analysis from five main aspects. Finally, the existing knowledge domains and future directions were discussed. Based on the results of this study, main countries, institutions, authors, and journals of rockburst research were revealed, and some important papers, hot topics, and evolutionary trends were found out. This review contributes to the integrated knowledge map of rockburst research in hard rock and provides researchers a valuable and in-depth understanding in this domain.

1. Introduction

Rockburst is one of the major engineering disasters caused by the violent release of accumulated strain energy in deep underground projects [1]. This phenomenon is often accompanied with the ejection of rock fragments, which would directly threaten the safety of workers [2]. The rockburst has become a universal problem, which has been recorded in many countries, such as South Africa, Canada, Australia, Chile, Sweden, China, India, Switzerland, and Pakistan [3–5]. Moreover, both the number and the intensity of rockburst show a growing trend with the increasing depth of underground activities [6, 7]. Hence, rockburst has become a key problem that needs to be urgently solved for the construction of deep underground projects.

The research of rockburst has increasingly attracted widespread attention of scholars. Given that considerable advances have been made in various aspects of rockburst researches, it is necessary to make a comprehensive overview. This is favorable for recognizing the existing knowledge domains and exploring some possible research directions.

Previous scholars have made some reviews on rockburst research from different perspectives. Zhou et al. [8] summarized the evaluation methods of rockburst. Afraei et al. [9] recapped the intelligent classification models for rockburst prediction. Keneti and Sainsbury [10] reviewed the published rockburst events and identified their contributing factors. Feng et al. [11] recapitulated the recent achievements of monitoring, warning, and control of rockburst in deep metal mines made by their team. However, these traditional literature reviews only focused on examining the contents of a small number of papers on a specific research domain. Few works have been undertaken to conduct synthetic and systematic reviews on rockburst research in recent decades from an overall perspective.

Given the above, scientometric methods (such as the cooperation, cooccurrence, and cocitation analyses) can be adopted to make an objective and comprehensive analysis on rockburst research. The scientometric analysis is powerful at providing quantitative analysis of academic literature based on mathematical and statistical methods [12]. The aim of conducting a scientometric analysis is to illustrate

the scientific development process and structure relationship based on the knowledge domain [13]. Currently, plenty of software has been developed to conduct scientometric analysis, such as the BibExcel, SciMAT, VOSviewer, and CiteSpace. Among them, CiteSpace developed by Chen [14] is a useful tool in analyzing and visualizing cocitation networks. This software focuses on identifying the intellectual bases, tracking the research fronts, and detecting the evolutionary trends. A distinct advantage of CiteSpace is that the literature data can be visualized to promote the understanding of previous researches and find out the implications hidden in abundant information. Because of its powerful functions, CiteSpace has been widely used in various areas [12, 15, 16].

Therefore, this study attempts to provide a scientometric review on rockburst research during 2000-2019 with the aid of CiteSpace, which can help to understand the existing knowledge body in this domain. Considering that the phenomena of rockburst in hard rock (such as granite) [17] and soft rock (such as coal) [18] are greatly different, this study only concentrates on the review of rockburst in hard rock. The main objectives of this study are (1) to summarize the rockburst research in hard rock according to the publications in the Web of Science Core Collection database from 2000 to 2019; (2) to understand the overall research status from the perspectives of cooperation, cooccurrence, and cocitation analyses; and (3) to identify the current hot topics, evolutionary trends, and future directions.

The remainder of this study is organized as follows. First, the review methodology, including the data retrieval strategy and scientometric analysis tool, is introduced. Then, the scientometric analysis results are presented from five main aspects, namely, the characteristic analysis of publication outputs, cooperation analysis, keyword cooccurrence and evolution analysis, cocitation analysis, and cluster analysis. Afterwards, the existing knowledge domains and future directions of rockburst research in hard rock are discussed. Finally, some main conclusions are summarized.

2. Research Methodology

The research methodology is introduced in this section, as shown in Figure 1. It can be seen that the methodology is mainly composed of two stages. The first one is to collect relevant literature data, and the second one is to conduct a scientometric analysis. The details of each step are described as follows.

2.1. Collect Relevant Literature Data. For a review work, collecting relevant literature data in a suitable way is the first step. The Web of Science Core Collection database is utilized to obtain objective literature data. This database is internationally recognized as the most comprehensive and authoritative scientific citation database, which includes the most influential papers in the world [12, 15]. Therefore, the quality and quantity of articles contained in this database are adequate for making a systemic review.

Then, the data retrieval strategy needs to be determined. Considering that the rockburst in soft rock mainly occurs in coal mines, the search terms are determined as TS (Topic

Search) = (rockburst* OR “rock burst” NOT coal), where “*” indicates a fuzzy search. The language, document type, and timespan are limited to “English”, “article AND review”, and “2000-2019” (approximately 20 years, retrieved date 15 April 2019), respectively. Based on this retrieval strategy, a total of 430 papers are identified.

After the relevant literature is retrieved, it is essential to export valid data for the purpose of scientometric analysis. The data includes the full records (title, abstract, keywords, etc.) and cited references of all papers, which should be saved in the text format to meet the requirement of the scientometric software.

2.2. Conduct Scientometric Analyses. In this study, CiteSpace with version 5.3.R4 is adopted to conduct the scientometric analysis. First, the literature data should be imported into this software. Then, the scientometric analysis is performed to achieve desired goals. This study conducts a scientometric analysis from five aspects: the characteristic analysis of publication outputs (namely, presenting the amount of publications and citations each year), cooperation analysis (namely, illustrating the cooperation network of authors, institutions, and countries), keyword cooccurrence analysis (namely, visualizing the cooccurrence and evolution networks of keywords), cocitation analysis (namely, identifying cocited references, cocited authors, and cocited journals), and cluster analysis (namely, dividing the articles into several knowledge domains based on the title, keyword, or abstract). Thereafter, a comprehensive knowledge map can be created.

Notably, when some graphs are produced by CiteSpace in the analysis process, the betweenness centrality is a common and valuable metric to quantitatively determine the importance of nodes in these graphs. A node with a large betweenness centrality value (higher than 0.1) means it plays a core role in the visualized network, which is called the turning point and identified with purple trims. The betweenness centrality proposed by Freeman [19] can be calculated with

$$BC_i = \sum_{i \neq j \neq k} \frac{n_{jk}^i}{g_{jk}}, \quad (1)$$

where g_{jk} means the number of the shortest paths from node j to node k and n_{jk}^i indicates the number of those paths passing through node i .

In addition, for the following network generated by CiteSpace, the colors of nodes and links from a cool tone to a warm tone correspond to different years from past to present. The detailed color expression is shown in Figure 2.

3. Scientometric Analysis Results

In this section, the review of rockburst in hard rock is visualized according to the research methodology of scientometric analysis. The analysis results are as follows.

3.1. Characteristic Analysis of Publication Outputs. According to the retrieval results of rockburst in hard rock, the number of publications and citations for each year is

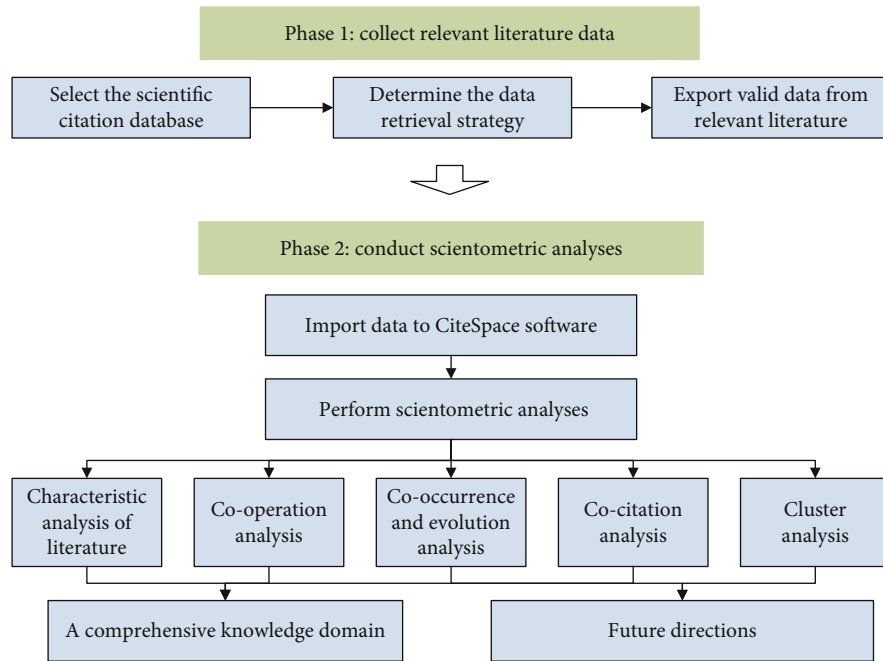


FIGURE 1: Frame of research methodology.



FIGURE 2: Color interpretation.

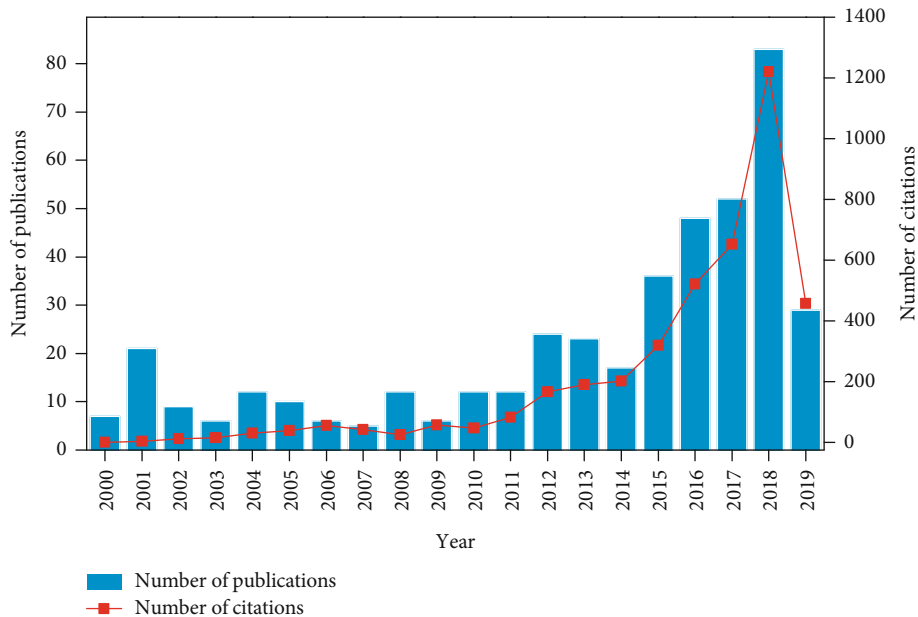


FIGURE 3: Number of publications and citations from 2000 to 2019.

indicated in Figure 3. It can be seen that the number of publications is rarely changed from 2000 to 2009, whereas markedly grows from 2009 to 2018. In recent ten years, the publications have increased from 6 in 2009 to 83 in 2018, and the average annual growth rate is up to 33.9%.

The citations have increased from 58 in 2009 to 1221 in 2018, with an average annual growth rate of 40.3%. It can be concluded that a great number of researchers have paid more attention to the field of rockburst in hard rock since 2009.

3.2. Cooperation Analysis. With the development of globalization, the academic exchanges and collaboration have become more and more popular. Identifying the collaboration relations is beneficial to understand the current research status. The country cooperation network, institution cooperation network, and author cooperation network are generated to illustrate the collaboration relationship from the macroscopic, mesoscopic, and microscopic levels, respectively.

Generally, the node size represents the total number of articles published by the countries, institutions, or authors, and the thickness of links demonstrates the intensity of cooperative relationships in the cooperation analysis graphs.

3.2.1. Country Cooperation Analysis. Figure 4 presents the country cooperation network of rockburst research in hard rock. Based on this network, the leading countries in this domain are identified. The top 5 countries with the largest number of publications are China (238 papers), Canada (47 papers), Russia (35 papers), Australia (33 papers), and South Africa (29 papers), respectively. It demonstrates that these countries have made outstanding contributions to the rockburst research in hard rock. The large number of published papers indicates that associated studies of this field are advanced to some extent in these countries. Comparing with other countries, China has made the most prominent contribution to the development of rockburst in hard rock in recent twenty years. The number of publications of China from 2000 to 2019 is shown in Figure 5. With regard to the international collaborations, researchers from China, Canada, and Australia collaborate with each other and those from other countries closely.

In addition, the pivotal nodes are identified by calculating the betweenness centrality with Equation (1). A country with a high centrality is labeled with purple trims in Figure 4, which demonstrates that this country plays a significant role in the development of rockburst research. It can be seen that China (centrality = 0.24), Australia (centrality = 0.11), and Canada (centrality = 0.03) are three key nodes in this network. Notably, China plays an important role in international cooperation and exchanges for the rockburst research in hard rock.

3.2.2. Institution Cooperation Analysis. The institution cooperation network of rockburst research in hard rock is indicated in Figure 6. It can be seen that most of the research institutions are from China, Canada, and Australia. Among them, major institutions in China are the Chinese Academic Sciences (57 papers), China University of Mining and Technology (32 papers), Northeastern University (32 papers), Central South University (31 papers), and Dalian University of Technology (12 papers). The institutions in Canada primarily include the Laurentian University (14 papers), McGill University (9 papers), Queen's University (8 papers), and University of Toronto (5 papers). The institutions in Australia mainly contain the University of Adelaide (7 papers), University of Western Australia (7 papers), and Monash University (6 papers). Additionally, some other productive research institutions include the Russian Academy of Sciences in Russia (23 papers), University of the Witwaters-

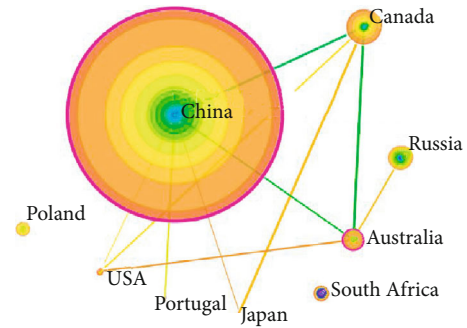


FIGURE 4: Country cooperation network.

rand in South Africa (12 papers), and Colorado School of Mines in the USA (7 papers). It is clear that the number of papers published in Chinese Academic Sciences ranks first all over the world.

In the aspect of betweenness centrality, institutions such as Chinese Academic Sciences (centrality = 0.39), Central South University (centrality = 0.20), China University of Mining and Technology (centrality = 0.16), and Northeastern University (centrality = 0.15) are crucial nodes in the network. In recent twenty years, these institutions have made great contributions to the rockburst research in hard rock.

3.2.3. Author Cooperation Analysis. The major author cooperation network of rockburst research in hard rock is shown in Figure 7. This network is powerful at finding the collaboration relations of authors and distinguishing the influential authors. According to the size of nodes in this network, it is clear that the top three authors with the largest number of publications are Xiating Feng (31 papers), Manchao He (17 papers), and Xibing Li (15 papers), respectively. Furthermore, they are the central authors of three large collaborative networks. The central authors of a network have more collaborative actions than others. For example, Xiating Feng is the central author of the largest network which contains Bingrui Chen, Guangliang Feng, and Guoshao Su. Manchao He is the central author of the second largest network which contains Ming Cai, Luis Ribeiro E. Sousa, and Weili Gong. Xibing Li is the central author of the third largest network which contains Hani S. Mitri, Jian Zhou, and Longjun Dong.

The influence of researchers depends on how they connect to others in the author cooperation network, which can be indicated by the betweenness centrality in CiteSpace. According to the value of betweenness centrality, researchers such as Xiating Feng (centrality = 0.15) and Manchao He (centrality = 0.10) have a large influence in the field of rockburst in hard rock.

3.3. Keyword Cooccurrence and Evolution Analysis. Keywords are the core and essence of an article, which can describe the research content representatively and concisely. Accordingly, keywords with high frequency are often used to identify hot topics in a certain research domain [20]. The keyword cooccurrence network generated by CiteSpace can indicate the cooccurrence degree of a keyword in selected papers. Through this network, the research hotspots and

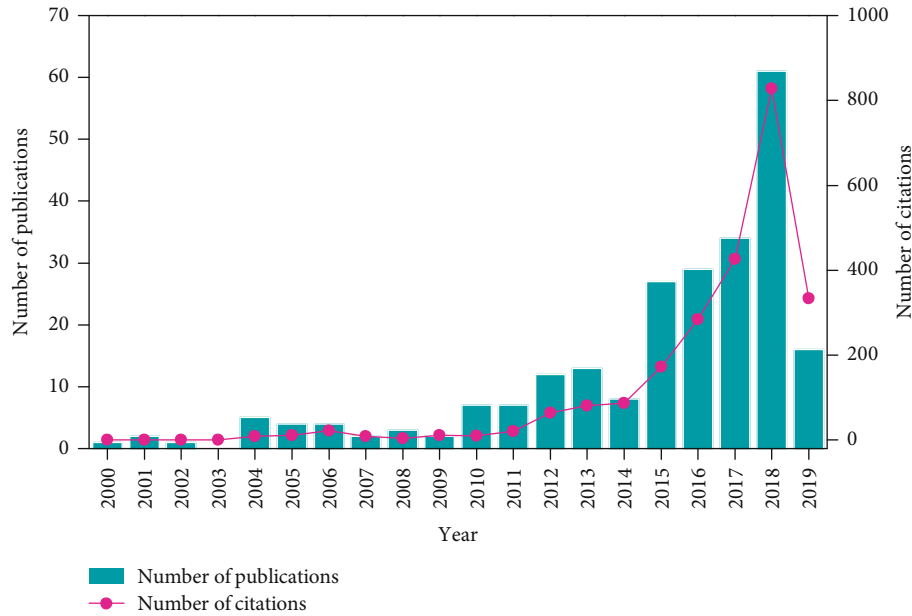


FIGURE 5: Number of publications and citations of China from 2000 to 2019.



FIGURE 6: Institution cooperation network.

frontiers can be detected. In addition, the transitions of a research field can be monitored by analyzing the evolution of keywords over time. The keyword cooccurrence and evolution analysis are as follows.

3.3.1. *Keyword Cooccurrence Analysis.* The keyword cooccurrence network of rockburst research in hard rock is shown in Figure 8. In this network, the size of keywords is proportional to the occurrence frequency. Keywords with a frequency exceeding 20 include “prediction” (frequency = 49), “failure” (frequency = 47), “rock” (frequency = 45), “tunnel” (frequency = 43), “stress” (frequency = 39), “fracture”

(frequency = 34), “mine” (frequency = 32), “behavior” (frequency = 31), “damage” (frequency = 28), “mechanism” (frequency = 28), “strength” (frequency = 27), “Jinping II hydropower station” (frequency = 27), “model” (frequency = 26), “acoustic emission” (frequency = 25), “rock mechanics” (frequency = 25), “earthquake” (frequency = 21), “energy” (frequency = 21), “compression” (frequency = 20), and “numerical simulation” (frequency = 20). Note that the keywords “rockburst” and “rock burst” are removed as they do not depict the current research trend. Moreover, the keywords “prediction” and “rockburst prediction” are merged as they denote the same entity. Although there are also some

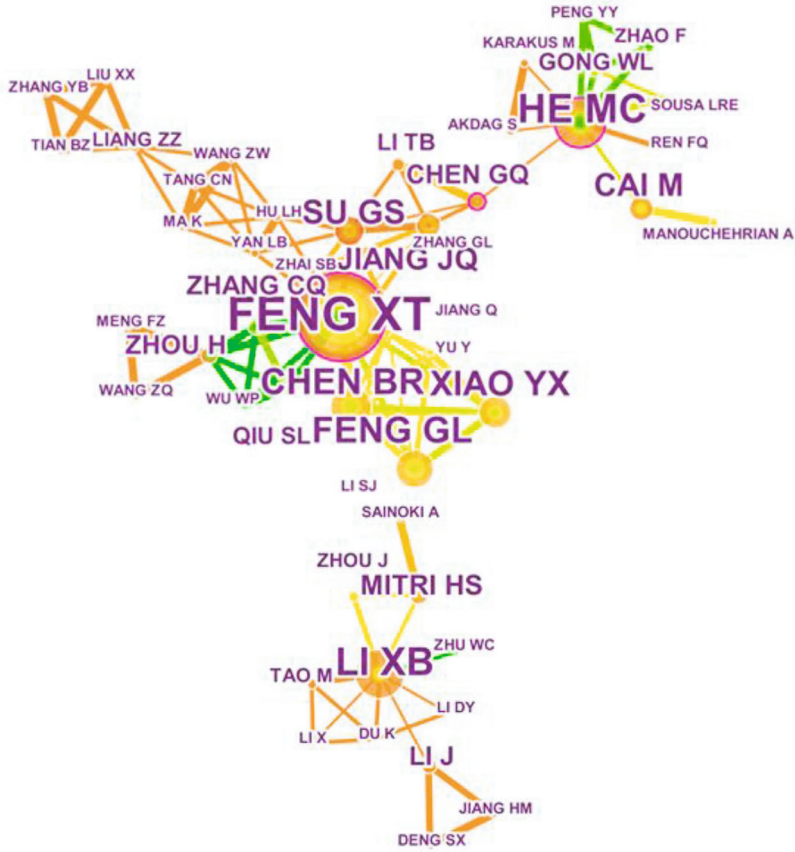


FIGURE 7: Author cooperation network.



FIGURE 8: Keyword cooccurrence network.

keywords with the same meanings, they are not merged because their numbers are very few in this dataset and the overall trend is not affected.

Obviously, the keyword “prediction” occurs most frequently in recent twenty years. Reasonable prediction of rockburst is a necessary prerequisite for ensuring project safety and is helpful to take effective measures in advance [21]. Various rockburst prediction methods have been proposed by researchers. They can be divided into four classifications, including empirical methods [22–24], simulation techniques [25–27], mathematical algorithms [28–30], and monitoring technologies [11, 31, 32]. The specific approaches of different categories are indicated in Figure 9 [8]. Furthermore, the keyword “mechanism” occurs frequently, which indicates that the mechanism research of rockburst is a hot-spot. The mechanism of rockburst is the foundation for developing prediction and prevention approaches [33]. Numerous researchers have analyzed the mechanisms of rockburst through laboratory experiments and case records. For instance, He et al. [34] simulated the evolution process of rockburst under true-triaxial unloading conditions in a laboratory to understand the bursting mechanism of rock. Gong et al. [35] introduced the process of rockburst induced by spalling failure through experimental simulation to investigate its mechanisms. Xiao et al. [36] studied the evolution mechanisms of rockburst by identifying the types of rock mass failure (tensile, shear, or mixed) based on microseismic monitoring technology. Currently, other scholars have also proposed many theories, such as the energy theory [37], strength theory [38], and two-body interaction theory [39], to illustrate mechanisms of rockburst from different aspects.

In addition, “tunnel” and “mine” are frequent keywords, which demonstrates that the rockburst in hard rock mainly occurs in the tunnel and mine. Specifically, the keyword “Jinping II hydropower station” has a high frequency. The tunnel system in this hydropower station contains seven parallel tunnels (four headrace tunnels, two assistant tunnels, and one drainage tunnel). The buried depth of most tunnels is between 1900 m and 2400 m, and the main rock is marble with high brittleness and strength [40]. In this kind of geological condition, the risk of rockburst is very high. According to the records, hundreds of rockbursts have been encountered during the excavation process [41, 42]. This makes the Jinping II hydropower station become an important site for studying rockburst, and plenty of related scientific outputs have been published.

3.3.2. Keyword Evolution Analysis. The time factor is not considered in the keyword cooccurrence network, which cannot indicate the changes in trends with time. To conduct the keyword evolution analysis, a time-zone view of the keyword cooccurrence network is shown in Figure 10. The number at the bottom of Figure 10 indicates the year that the corresponding keyword first appeared. Based on the frequency of keywords with time, it is clear that the year of 2009 is an important time turning point. From 2000 to 2009, the number of keywords with high frequency is relatively very small. After 2009, many new keywords are beginning to emerge frequently and constantly, which indicates that the rockburst

research in hard rock enters a rapid development stage. For clarity, the top 15 keywords related to rockburst in hard rock during 2000–2009 and 2010–2019 are listed in Table 1.

According to the keyword cooccurrence and evolution with time indicated in Figure 10 and Table 1, the overall trend of rockburst research in hard rock can be obtained. In the period of 2000 to 2009, the rockburst research in hard rock develops steadily. Scholars mainly pay close attention to the mechanism of rockburst and the rock failure or fracture during rockburst evolution. Additionally, as the centrality of keyword “mining” is up to 0.43, it can be inferred that the rockburst encountered during mining plays an important role in understanding the mechanism. The researches in this period have laid a solid foundation for the prosperity of the later rockburst research. In the period of 2010 to 2019, the rockburst research in hard rock achieves rapid development and becomes hot topics. More and more scholars have focused on this field, and researches in this area are more comprehensive. On the one hand, the basic researches of rock mechanics and mechanisms related to rockburst have been further developed. Many scholars have successfully reproduced the occurrence of rockburst through laboratory tests and numerical simulation, which deepened the understanding of the rockburst mechanism [34, 43]. On the other hand, many efforts have been made to solve field rockburst issues. For instance, the microseismic monitoring has gradually become an important means for monitoring and warning of rockburst all over the world [36]. The philosophy of support in burst-prone ground has been fundamentally changed. For example, Cai [44] proposed seven important principles of rockburst support, namely, the avoid rockburst principle, flexible/yielding support principle, address the weakest link principle, integrated system support principle, simplicity principle, cost-effectiveness principle, and observational construction principle. Malan and Napier [45] advanced a new design approach of rockburst support in shallow-dipping tabular stopes at great depths.

Furthermore, some keywords have relatively high centrality values during 2010–2019, such as “failure” (centrality = 0.13), “behavior” (centrality = 0.13), “acoustic emission” (centrality = 0.11), “fracture” (centrality = 0.10), and “strength” (centrality = 0.10). Generally, these keywords connect different topics in rockburst research. Based on these results, studying the rock failure or fracture behavior plays a vital role in better understanding the rockburst mechanism, predicting the rockburst risk and conducting support strategy.

3.4. Cocitation Analysis. If two papers are simultaneously cited by a certain paper, then a reference cocitation relationship between them is formed. Meanwhile, the author cocitation and journal cocitation can be similarly defined. Then, the reference cocitation analysis, author cocitation analysis, and journal cocitation analysis are conducted as follows.

3.4.1. Reference Cocitation Analysis. The influential papers of the rockburst research in hard rock can be identified through a reference cocitation analysis. Figure 11 demonstrates the reference cocitation network. Each node represents a paper

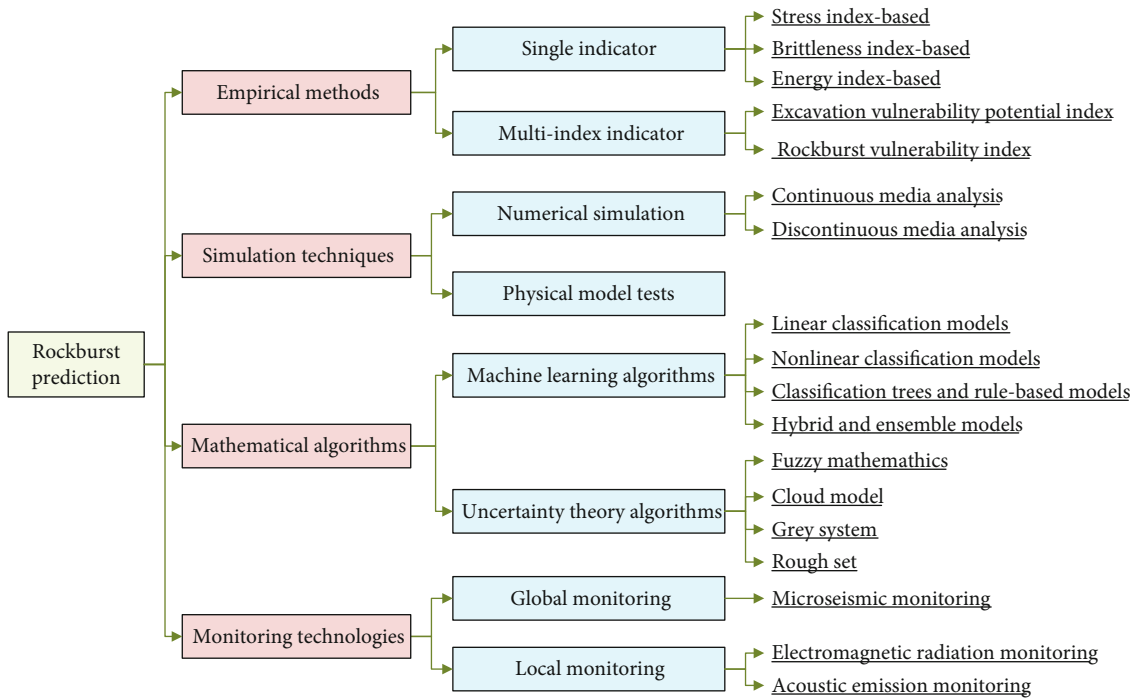


FIGURE 9: Approaches of different categories for rockburst prediction, modified from Reference [8].

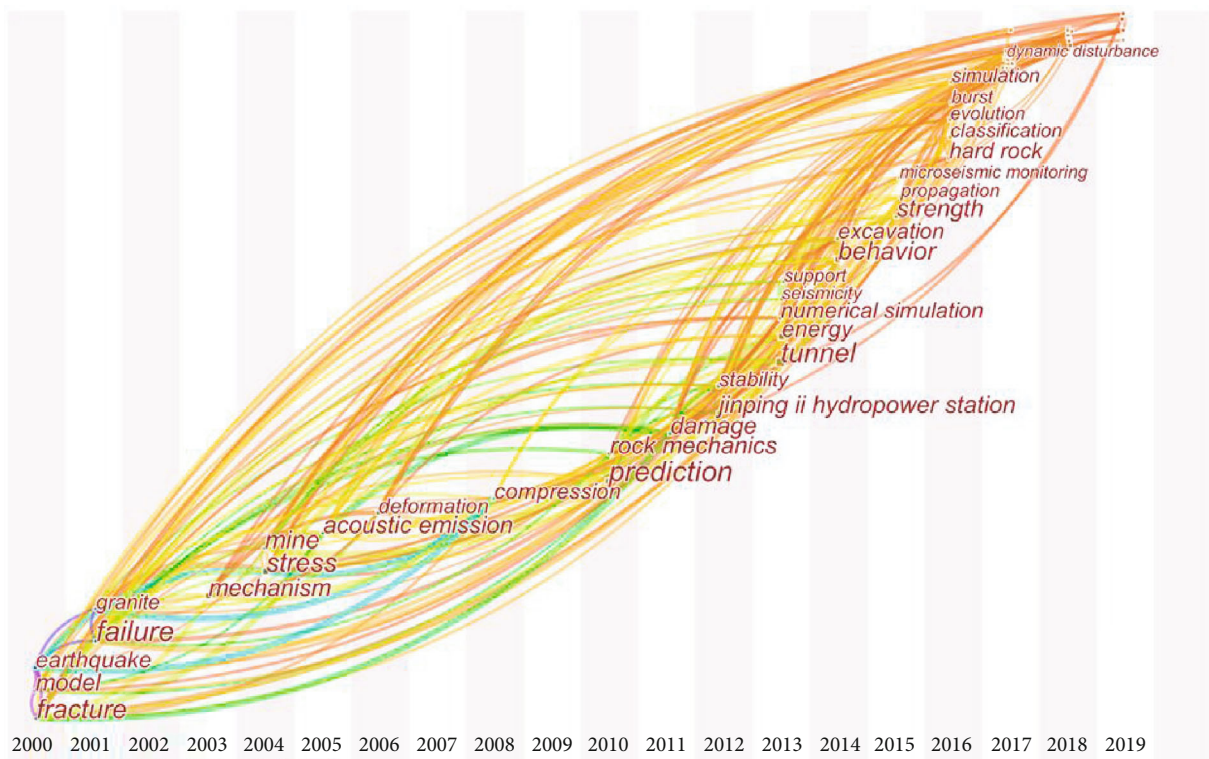


FIGURE 10: Time-zone view of the keyword cooccurrence network.

that is recognized by the first author's name and the publication year, and its size means the total number of times being cited. The large nodes indicate that these papers are cited

many times and widely recognized by scholars. Thus, they can be considered very important in this field. The top 10 cited articles are listed in Table 2. It should be noted that

TABLE 1: Top 15 keywords related to rockburst in hard rock during 2000-2009 and 2010-2019.

Keyword	Frequency	Centrality
2000-2009		
Earthquake	6	0.08
Rock	5	0.06
Model	4	0.03
Stress	4	0.05
Fracture	4	0
Granite	4	0.01
Mining	2	0.43
Deformation	2	0
Failure	2	0
Compression	2	0
Optimization	2	0
Mechanism	2	0
Acoustic emission	2	0
Mine	2	0
Microseismicity	2	0
2010-2019		
Prediction	49	0.06
Failure	45	0.13
Tunnel	43	0.04
Rock	40	0.06
Stress	35	0.07
Behavior	31	0.13
Fracture	30	0.10
Mine	30	0.16
Damage	28	0.18
Jinping II hydropower station	27	0.09
Strength	27	0.10
Mechanism	26	0.04
Rock mechanics	25	0.07
Acoustic emission	23	0.11
Model	22	0.06

the cited frequency is obtained by CiteSpace from the selected 430 papers, which may be different from that by Google Scholar.

According to Table 2, the top 10 cited articles mainly focus on the experimental research of rockburst, field rockburst case analysis in Jinping II hydropower station, rock support in burst-prone ground, and numerical simulation of rockburst. For example, He et al. [34, 52] proposed innovative test devices and methods for rockburst experiments and conducted numerous experimental investigations on the rockburst behavior. The team of Feng [46–48, 50, 51] did many studies on analyzing field rockburst cases in Jinping II hydropower station and made outstanding contributions in the rockburst mechanism, prediction, and prevention. Kaiser and Cai [3] made great achievements in designing the rock support system under rockburst conditions and developed a systematic rockburst support manual.

In the aspect of numerical simulation of rockburst, Zhu et al. [49] simulated the evolution process of rockburst triggered by dynamic disturbance, which is helpful for recognizing the mechanism of rockburst under both static and dynamic stress conditions. Jiang et al. [50] proposed a new simulation index (the Local Energy Release Rate (LERR)) from the perspective of energy release to predict the rockburst intensity. All these researches have received extensive attention.

To indicate the latest hot papers, the top 10 cited articles of rockburst research in hard rock from 2015 to 2019 are also summarized. These articles are the same with top 10 cited articles from 2000 to 2019, although the ranks of some of them are different. This may be related to the fact that there have been a large number of articles published in the past five years (see Figure 3). The cited frequency of these articles from 2015 to 2019 is also shown in Table 2. These articles also play an important role in the study of rockburst in the past five years. In addition, the cited frequency of these articles in 2018 is summarized (see Table 2). Among them, the article (He et al. [34]) still occupies the top position in all papers. This means that their research results still have an important impact on the present. It can be inferred that the simulation research of the rockburst process in the laboratory is a hot topic at present.

3.4.2. Author Cocitation Analysis. The author cocitation analysis can be used to determine the connections among authors whose publications are cited simultaneously in the same papers. The author cocitation network is indicated in Figure 12. Each node represents an author, and its size means the total number of times this author has been quoted. The top 10 authors with regard to citation are Peter K. Kaiser (frequency = 107, Canada), W.D. Ortlepp (frequency = 104, South Africa), Manchao He (frequency = 91, China), Ming Cai (frequency = 87, Canada), N.G.W. Cook (frequency = 80, South Africa), Evert Hoek (frequency = 75, Canada), Xiating Feng (frequency = 73, China), Chuanqing Zhang (frequency = 57, China), C.D. Martin (frequency = 51, Canada), Jinan Wang (frequency = 48, China), and Chunan Tang (frequency = 43, China). Most of these scholars are internationally renowned in the field of rockburst research and have gained wide recognition. In addition, according to the countries with the most highly quoted authors, the rockburst research in hard rock has been performed well in Canada, South Africa, and China. In particular, the rockburst research in Canada and South Africa has a long history and develops well.

A scholar with a high citation frequency does not necessarily have a high betweenness centrality, whereas authors with both high citation frequency and high betweenness centrality are very likely to have a strong impact on this research domain. Among the above ten authors with high citations, the authors with high betweenness centrality are Evert Hoek (centrality = 0.25) and W.D. Ortlepp (centrality = 0.17). Evert Hoek has made great achievements in rock mechanics, which lays a solid foundation for understanding the rockburst mechanism [53, 54]. Ortlepp summarized several different mechanisms of rockburst through case studies and made a vital contribution to the understanding of rockburst

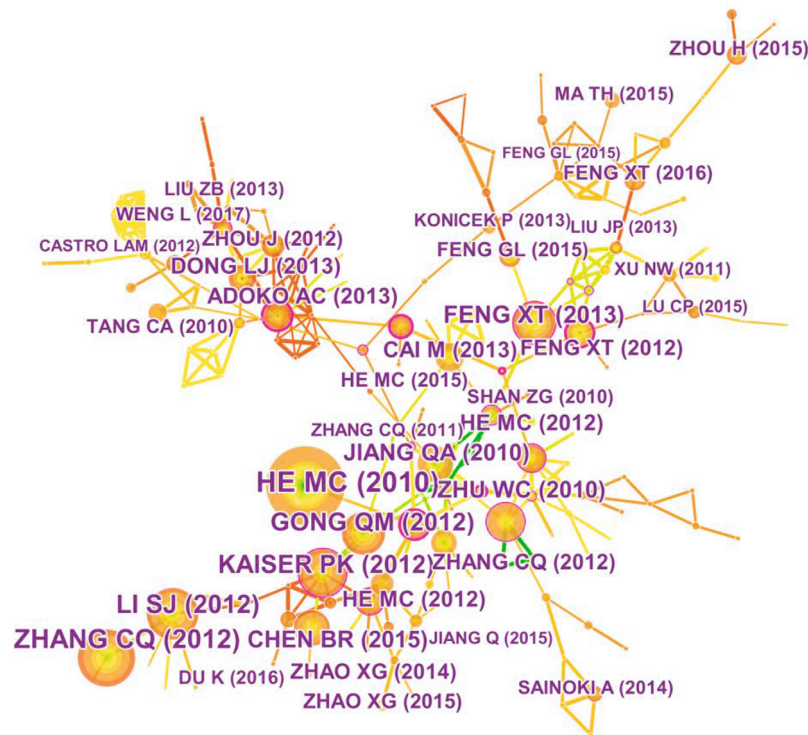


FIGURE 11: Reference cocitation network.

TABLE 2: Top 10 cited articles of rockburst research in hard rock.

Author & year	Title	Cited frequency	Cited frequency (per year)	Cited frequency from 2015 to 2019	Cited frequency in 2018	Google Scholar
He et al. (2010) [34]	Rock burst process of limestone and its acoustic emission characteristics under true-triaxial unloading conditions	54	2.7	42	19	321
Zhang et al. (2012) [46]	Case histories of four extremely intense rockbursts in deep tunnels	40	2	37	11	96
Li et al. (2012) [47]	In situ monitoring of rockburst nucleation and evolution in the deeply buried tunnels of Jinping II hydropower station	36	1.8	33	13	102
Kaiser and Cai (2012) [3]	Design of rock support system under rockburst condition	33	1.65	31	15	160
Gong et al. (2012) [48]	Rock burst and slabbing failure and its influence on TBM excavation at headrace tunnels in Jinping II hydropower station	30	1.5	27	7	106
Zhu et al. (2010) [49]	Numerical simulation on rockburst of underground opening triggered by dynamic disturbance	26	1.3	24	13	90
Jiang et al. (2010) [50]	Rockburst characteristics and numerical simulation based on a new energy index: a case study of a tunnel at 2500 m depth	25	1.25	22	11	92
Chen et al. (2015) [51]	Rock burst intensity classification based on the radiated energy with damage intensity at Jinping II hydropower station, China	25	1.25	25	8	60
Cai (2013) [44]	Principles of rock support in burst-prone ground	20	1	19	9	83
He et al. (2012) [52]	Experimental investigation of bedding plane orientation on the rockburst behavior of sandstone	19	0.95	17	5	51

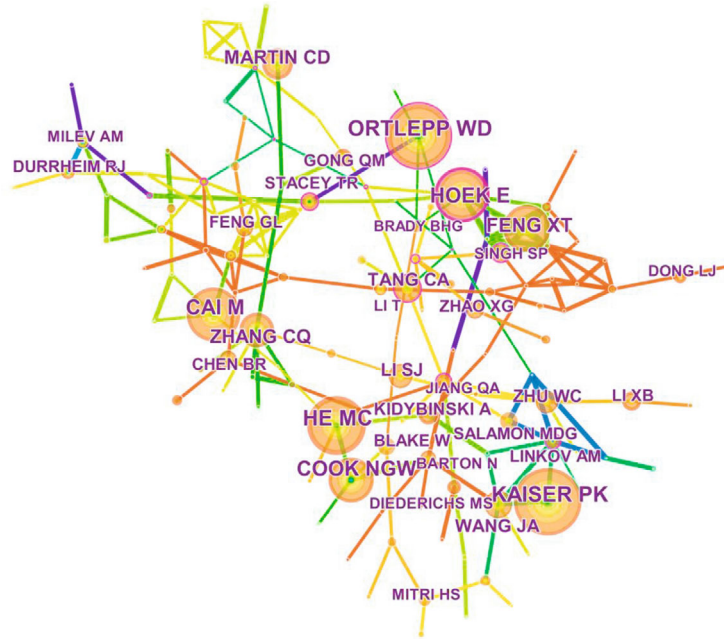


FIGURE 12: Author cocitation network.

[2, 7]. These two scholars are all very renowned and have made an outstanding contribution in this field.

Moreover, the author cocitation analysis from 2015 to 2019 is conducted to detect the latest most cited authors. The top 10 authors are Peter K. Kaiser (frequency = 84, Canada), W.D. Ortlepp (frequency = 79, South Africa), Manchao He (frequency = 79, China), Ming Cai (frequency = 73, Canada), Xiating Feng (frequency = 71, China), Evert Hoek (frequency = 63, Canada), N.G.W. Cook (frequency = 61, South Africa), Chuanqing Zhang (frequency = 49, China), C.D. Martin (frequency = 42, Canada), Jinan Wang (frequency = 39, China), and Wancheng Zhu (frequency = 37, China). Although the ranks are somewhat different, most of the authors are the same with the top 10 authors from 2000 to 2019. Their outcomes still have a large impact on the present researches.

3.4.3. Journal Cocitation Analysis. The top 10 journals in terms of publication number for rockburst research in hard rock are listed in Table 3. *Tunnelling and Underground Space Technology* published 42 articles (9.767%) and ranked the first place. Both *International Journal of Rock Mechanics and Mining Sciences* and *Rock Mechanics and Rock Engineering* published 40 articles (9.302%) and equally occupied the second position. The number of articles published in the first three journals is all no less than 40, which means that these journals are better recognized by scholars in this field.

The journal cocitation network produced by CiteSpace is adopted to identify the most significantly cited journals, as shown in Figure 13. Each node size represents the citation frequency of a journal. In general, the journals with higher citation frequency have more authority and influence in this domain. For clarity, the top 10 journals in terms of citation for rockburst research in hard rock are listed in Table 4. It

is worth noting that the three journals with the highest citation frequency also belong to the top three journals in terms of publication number. Accordingly, it can be concluded that these three journals have made great contributions in the field of rockburst research.

3.5. Cluster Analysis. The cluster analysis is an important data mining technology for detecting the semantic themes hidden in the textual data. CiteSpace provides a function to conduct cluster analysis using the noun phrases from titles, keywords, or abstracts of citing papers. The cluster labels can be created based on the latent semantic indexing (LSI) algorithm, log-likelihood ratio (LLR) algorithm, or mutual information (MI) algorithm [55]. Then, the research data can be classified into different units, and the underlying research topics and their interrelationships can be identified.

In this study, the LSI algorithm is employed to generate cluster labels using keywords of citing papers, which can obtain desirable results. The main clusters in the rockburst research of hard rock are shown in Figure 14. It can be seen that the network is classified into six main clusters, namely, the rockburst prediction (cluster #0), rock mechanics (cluster #1), acoustic emission (cluster #2), microseismic monitoring (cluster #3), strainburst (cluster #4), and numerical simulation (cluster #5). These six clusters, which contained majority of the papers, can be regarded as the main research topics. Some links exist between clusters, and some parts overlap. It can be inferred that there are some associations between these clusters.

The detailed characteristics of each cluster are listed in Table 5. The size (see the second column) indicates the number of papers included in each cluster. Cluster #0 occupies the first position, which is composed of 36 papers. The silhouette score (see the third column) is a significant

TABLE 3: Top 10 journals in terms of publication number.

Journal	Host country	Count	Percentage
<i>Tunnelling and Underground Space Technology</i>	United Kingdom	42	9.767%
<i>International Journal of Rock Mechanics and Mining Sciences</i>	United Kingdom	40	9.302%
<i>Rock Mechanics and Rock Engineering</i>	Germany	40	9.302%
<i>Journal of the Southern African Institute of Mining and Metallurgy</i>	South Africa	31	7.210%
<i>Journal of Mining Science</i>	USA	30	6.977%
<i>Engineering Geology</i>	Netherlands	13	3.023%
<i>Shock and Vibration</i>	Egypt	13	3.023%
<i>Advances in Civil Engineering</i>	Egypt	10	2.326%
<i>Archives of Mining Sciences</i>	Poland	9	2.093%
<i>Bulletin of Engineering Geology and the Environment</i>	Germany	9	2.093%

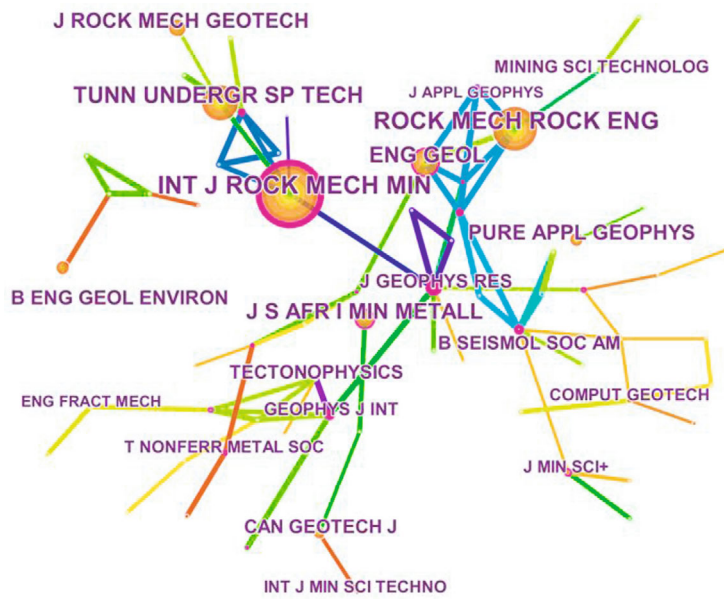


FIGURE 13: Journal cocitation network.

TABLE 4: Top 10 journals in terms of citation.

Journal	Host country	Citation
<i>International Journal of Rock Mechanics and Mining Sciences</i>	United Kingdom	299
<i>Rock Mechanics and Rock Engineering</i>	Germany	205
<i>Tunnelling and Underground Space Technology</i>	United Kingdom	186
<i>Engineering Geology</i>	Netherlands	143
<i>Journal of the Southern African Institute of Mining and Metallurgy</i>	South Africa	123
<i>Pure and Applied Geophysics</i>	Switzerland	105
<i>Journal of Rock Mechanics and Geotechnical Engineering</i>	China	102
<i>Bulletin of Engineering Geology and the Environment</i>	Germany	79
<i>Bulletin of the Seismological Society of America</i>	USA	67
<i>Canadian Geotechnical Journal</i>	Canada	66

indicator to measure the quality of clusters [55]. The larger the silhouette scores (the maximum is 1.00), the more homogeneous the cluster. The silhouette scores of all clusters in this

study exceed 0.82, and most of them are above 0.90. These high scores demonstrate that the cluster performance is great, and the content of each paper matches well with its cluster

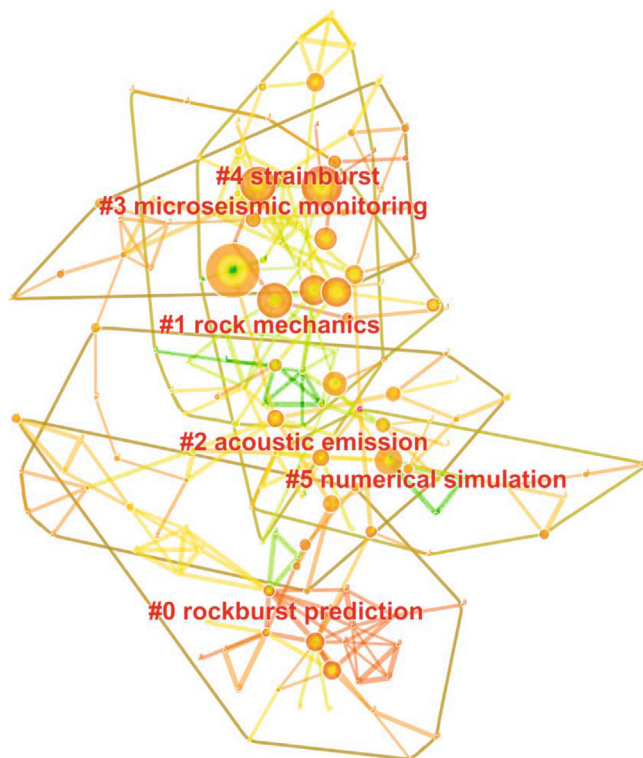


FIGURE 14: Main clusters in rockburst research of hard rock.

TABLE 5: Six main clusters in rockburst research of hard rock.

Cluster ID	Size	Silhouette score	Cluster label	Mean (cite year)
#0	36	0.994	Rockburst prediction	2012
#1	28	0.935	Rock mechanics	2011
#2	25	0.903	Acoustic emission	2013
#3	25	0.911	Microseismic monitoring	2013
#4	21	0.823	Strainburst	2011
#5	17	0.942	Numerical simulation	2011

[12]. The mean (cite year) (see the fifth column) represents the average year of publication in each cluster, which can determine whether a cluster includes old or latest papers. These clusters all comprise the papers with an average publication year of 2011 or later, and their average publication years are close. This situation indicates that the rockburst research of hard rock has been comprehensively developed in these six aspects.

According to the clustering results in Figure 14 and Table 5, the main research topics are identified. Generally, the rockburst researches can be divided into three classifications from the perspective of research contents, namely,

the rockburst mechanism, prediction, and prevention. Obviously, rockburst prediction (cluster #0) is a hot topic. Additionally, although the label of the rockburst mechanism has not been created, the rock mechanics (cluster #1) and acoustic emission (cluster #2) are often used to research the rockburst mechanism. Accordingly, it can be also deemed as a hot topic. Considering that rock mechanics (cluster #1) is the foundation of rockburst researches, it is also an important research direction. The research methods of rockburst can be classified into four aspects, namely, the theoretical analysis, laboratory experiment, numerical simulation, and field monitoring. Intuitively, microseismic monitoring (cluster #3) and numerical simulation (cluster #5) are the main research methods. Because acoustic emission (cluster #2) is frequently used to identify the fracture of rock when conducting the rockburst simulation experiment, laboratory experiment is also an important research method. The type of rockburst can be separated into three types, namely, the strainburst, pillar burst, and fault-slip burst. Apparently, strainburst (cluster #4) is currently the most popular research type of rockburst.

4. Discussion

In this section, the existing knowledge domains and future directions of rockburst researches in hard rock are discussed.

4.1. Existing Knowledge Domains. According to the scientometric analysis results, an integrated knowledge map of rockburst research in hard rock is shown in Figure 15. It can be seen that the main research topics of rockburst in hard rock from 2000 to 2019 have been summarized, which is favorable for advancing the understanding of the existing knowledge body in this domain. Compared with the prior review of Zhou et al. [8], Afraei et al. [9], Keneti and Sainsbury [10], and Feng et al. [11], knowledge domains discussed in this study are more systematic.

First, the current hot research topics are identified based on the keyword cooccurrence analysis and cluster analysis. From the aspect of research contents, the mechanism and prediction of rockburst are hot topics. From the aspect of research approaches, the methods of laboratory experiment, numerical simulation, and microseismic monitoring are adopted more frequently. From the aspect of rockburst types, the researches of strainburst are more mature. In addition, the rock mechanics, as the foundation of rockburst researches, is heavily adopted by numerous scholars to reveal the mechanism of rockburst.

Second, the evolutionary trends are obtained according to the keyword evolution analysis. In summary, the evolutionary trends of rockburst research in hard rock can be divided into two stages. The first stage (from 2000 to 2009) focuses on the rockburst mechanism and the rock failure or fracture characteristics. The latter stage (from 2010 to 2019) develops more rapidly and comprehensively based on the previous stage. In this stage, not only is the rockburst mechanism studied more profoundly but also are numerous rockburst prediction and prevention methods proposed to solve field rockburst issues. The research trends gradually move

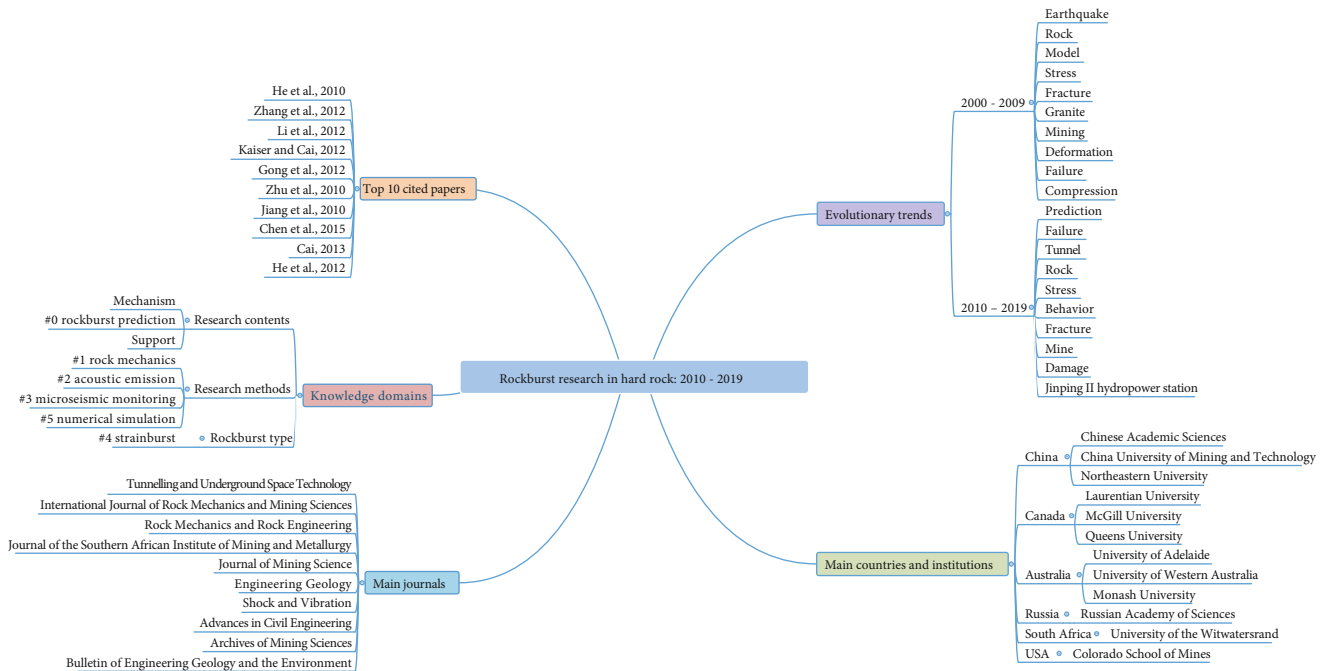


FIGURE 15: Comprehensive knowledge map of rockburst research in hard rock: 2000-2019.

from theory to practice, and the ultimate goal is to predict and prevent rockburst.

Third, the top 10 cited papers are acquired according to the reference cocitation analysis. These papers have been recognized by the majority of researchers and played an important role in the development of this field. All in all, the top 10 cited articles mainly focus on experimental research, field case analysis, rock support in burst-prone ground, and numerical simulation.

Last, the major countries, institutions, authors, and journals are recognized and analyzed through the cooperation analysis and cocitation analysis. It is notable that the institutions and authors in China have made significant contribution to the rockburst research in hard rock. As the depth of mines, tunnels, and other underground projects increases rapidly, more and more rockburst cases have occurred in China [11, 39, 46]. Therefore, the rockburst disaster has become a key challenge and attracted wide attention of the state and enterprises.

4.2. Future Directions. Based on the review of rockburst research in hard rock from 2000 to 2019, some possible directions that need further investigations are identified as follows.

- (1) The universal mechanics theory can be established to reveal the mechanism of rockburst. Although the evolution process of rockburst has been simulated through laboratory tests, the essence of rockburst is not illustrated from the theoretical level. Therefore, the brittle failure theory of hard rock should be further studied and improved, specifically from the microscopic perspective

- (2) The occurrence time of rockburst can be further explored. Plenty of approaches have been adopted to predict rockburst, and the intensity and location of rockburst can be well determined. However, there is not an efficient method to predict the occurrence time of rockburst. The microseismic monitoring method may be an effective method by analyzing the evolution regularities of rock rupture signals over time during the rockburst evolution process, which is valuable to study in depth
- (3) The development process and mechanism of fault-slip burst deserve more attention. Compared to the strainburst, the research of fault-slip burst is relatively rare. However, the intensity and severity of fault-slip burst are larger. Accordingly, it is meaningful to study the development process and mechanism of fault-slip burst and then to propose feasible prediction and prevention approaches
- (4) The high stress utilization technologies can be developed to control rockburst. High stress is one of the main factors causing rockburst. In general, effective stress relief technologies are developed to control rockburst. In contrast, the high stress can be conducive to fragmentation of hard rock with the strategy of “convert harm into benefit.” Therefore, it is possible to develop proper technologies for utilizing the high energy as opposed to weakening it, so that most of the energy is adopted to crush hard rock. Then, the purpose of controlling rockburst can be achieved simultaneously
- (5) The prediction and prevention methods in uncertain environments can be proposed. Although a large

number of prediction and prevention methods of rockburst are proposed, the prediction accuracy is not satisfactory, and numerous rockburst accidents still occur. One of the most important reasons is that the rock mass is anisotropic and inhomogeneous, and the external environment is usually uncertain and complicated. As a result, studying the prediction and prevention methods in uncertain environments is significant

5. Conclusions

This study reviewed the rockburst research in hard rock between 2000 and 2019 through a scientometric analysis of 430 papers. With the help of CiteSpace, the country, institution, and author cooperation analysis; keyword cooccurrence and evolution analysis; reference, author, and journal cocitation analysis; and cluster analysis were conducted in detail. Based on the above analyses, some major conclusions were summarized as follows.

- (1) The publications increased rapidly, specifically from 2009 to 2018, which indicated that a large number of scholars have paid more attention to the field of rockburst research in hard rock since 2009
- (2) With respect to the number of publications, China had a prominent leading position among all countries, Chinese Academic Sciences was most productive among all institutions, Xiating Feng ranked the top among all authors, and *Tunnelling and Underground Space Technology* occupied the first place among all journals
- (3) According to the keyword cooccurrence analysis, the mechanism and prediction of rockburst were hot topics. Based on the keyword evolution analysis, the evolutionary trends were divided into two stages. The stage from 2000 to 2009 focused on the rockburst mechanism and the rock failure or fracture characteristics, and the stage from 2010 to 2019 developed more rapidly and comprehensively from the aspects of mechanism, prediction, and prevention of rockburst
- (4) In terms of the number of citation, “Rock burst process of limestone and its acoustic emission characteristics under true-triaxial unloading conditions” was the most cocited reference, Peter K. Kaiser and W.D. Ortlepp were most highly quoted authors, and *International Journal of Rock Mechanics and Mining Sciences* received the most citations in this domain
- (5) With regard to the cluster analysis, “rockburst prediction,” “rock mechanics,” “acoustic emission,” “microseismic monitoring,” “strainburst,” and “numerical simulation” were six main clusters, which represented the popular research topics
- (6) Based on the scientometric analysis, a comprehensive knowledge map of rockburst research in hard rock

was presented, which helped to understand the overall research status in this field

Notably, the above analyses were conducted only based on the data retrieved from the Web of Science Core Collection database. In the future, some other types of databases can be used to produce a more comprehensive knowledge map for rockburst research in hard rock. In addition, some keywords with the same meanings should be considered when conducting keyword cooccurrence and evolution analysis.

Conflicts of Interest

The authors declare no conflict of interest.

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