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Stress-induced trend: the clustering feature of coal mine disasters and earthquakes in China

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Abstract Nearly half of coal mine disasters in China have been found to occur in clusters or to be accompanied by earthquakes nearby, in which all the disaster types are involved. Stress disturbances seem to exist among mining areas and to be responsible for the observed clustering. The earthquakes accompanied by coal mine disasters may be the vital geophysical evidence for tectonic stress disturbances around mining areas. This paper analyzes all the possible causative factors to demonstrate the authenticity and reliability of the observed phenomena. A quantitative study was performed on the degree of clustering, and space–time distribution curves are obtained. Under the threshold of 100 km, 47% of disasters are involved in cluster series and 372 coal mine disasters accompanied by earthquakes. The majority cluster series lasting for 1–2 days correspond well earthquakes nearby, which are speculated to be related to local stress disturbance. While the minority lasting longer than 4 days correspond well with fatal earthquakes, which are speculated to be related to regional stress disturbance. The cluster series possess multiple properties, such as the area, the distance, the related disasters, etc., and compared with the energy and the magnitude of earthquakes, good correspondences are acquired. It indicates that the cluster series of coal mine disasters and earthquakes are linked with fatal earthquakes and may serve as footprints of regional stress disturbance. Speculations relating to the geological model are made, and five disaster-causing models are examined. To earthquake research and disaster prevention, widely scientific significance is suggested.

Keywords Earthquake · Coal mine disaster · Cluster feature · Stress disturbance

1 Introduction

It is clear that tectonic stress contributes to most fatal coal mine roof disasters (He 2000; Zhang and Song 2006). Areas with intensive tectonic stress are strictly prohibited to mine directly. The protective measure is to mine in the vicinities where tectonic stress is less intensive. By this measure, the intensive stress is relieved to safe level (Zhang and Yang 2013; Zhang and Zhang 2010; Zhou 2012). Now, a question is put forward: with the coal dug out, the intensive tectonic stress is released, but where has it gone? Theoretically, the stress does not disappear, but shifts to load onto the neighboring structures. In another word, stress disturbance should widely exist among different mining areas over larger scopes, and potentially may cause stress-induced disasters in neighboring coal mines. The question can be divided into the following sub-questions: the existence of stress disturbance among coal mines; the distance that stress disturbance may impact on; the possibilities for the stress disturbance around mining area to interact with tectonic stress disturbance.

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Previously, coalmine disasters have more often been considered in isolation. For example, rock bursts have seldom been thought to be related to mining in neighboring coal mines, to the effects of tectonic movement, or to a combination of the two. Similar to earthquake research, it is difficult to conduct scientific research on such a question; it is not feasible to use a research strategy starting from causations, but rather from results, i.e. to observe the space–time distribution of coalmine disasters directly. If the above analysis is correct, coalmine disasters should present clustering features over large areas.

Historically, fully macroscopic observations of coalmine disasters have not been made, but stress disturbance around mining areas has been widely reported all over the world, and in particular around coalmines in China. For example, on 29 January 1986, three fatal coal bursts occurred in coalmines of Sunagawa City in Japan that were ascribed to earthquakes occurred nearby (Chen 1995a, b). On 14 February 2004, a fatal gas explosion (causing 214 deaths) occurred in Sunjiawan Coalmine in Fushun City, Liaoning Province, in which mine quakes caused gas to be released and the gas was ignited by workers wrongly switching a wire. On 3 November 2012, an earthquake occurred near Qianqiu Coalmine of Yima City, Henan Province, and 28 min later, a fatal rock burst trapped 59 workers underground (they were rescued 48 h later). During the past two decades, hundreds of similar disasters have occurred, but because of a lack of macroscopic observation, they were not linked together. In the present study, such disasters were examined as a group rather than individually.

As early as 1980s, mine quakes in some coalmines in China were first found to tend to response to fatal earthquakes, which was the earliest, but slender evidence of local stress disturbance interacting with tectonic movement (Zhang and Sun 1985; Xu 1987; Xiao 1999). Regarded as stress window, the mine quakes were expected to predict some fatal earthquakes or to discover the deeper geological mechanism of the coalmine disasters. The cluster feature of coalmine disasters and earthquakes discovered in the paper may be the new evidence that human mining interacts with stress field.

Recently, in China, nearly half of coal mine disasters are found not to occur randomly, but either not to occur, or to occur successively on adjacent areas, presenting cluster feature. Some are found to be accompanied by earthquakes (with M_S magnitudes lower than 5.0) nearby, in which all the disaster types are involved. Of all the causative factors, stress disturbance, the only one that can cause all kinds of disasters at one time, seems to exist among mining areas and brings about the cluster feature.

China possesses as many as 26,395 coal mines, exceeding the total coal mines of other countries in the world (Chinese State Administration of Coal Mine Safety 2004). These coal mines' mining may become an experiment conducted over continental China, in which an important mechanical property of superficial crust was verified: Dug in tens of thousands of mines over continental scope for tens of years (with tens of thousands mine goafs left), the superficial crust around mining areas may become less stable and more likely to fluctuate. The cluster feature and its coinciding with earthquakes may be the reaction of superficial crust to excessive mining. No source or publications have reported the cluster feature of coal mine disasters.

2 Data processing

Coalmine disaster records were obtained from the Chinese State Administration of Coal Mine Safety (CSACMS). From 1 January 2000 to 26 October 2006, CSACMS recorded 7425 disasters. The data were incompletely collected before 1 July 2001 and only partly published after 1 March 2006. During the period from 1 July 2001 to 28 February 2006, information about the disasters was well collected and fully published. This paper considers these disaster records using rigorous criteria, and those events that are largely the result of human error, e.g. electrocutions, drownings, fires, gas disasters caused by bad ventilation, and rock falls without sustaining measures, have been excluded (1529 in total). The remaining 5825 were geological disasters in which no obvious human errors were described.

As a space–time analysis, an issue cannot be ignored, i.e. the reliability of these geological disasters seems to be disputed. All the 5825 disasters were inadequately descripted on the causation, and they previously had been ascribed to human errors by most experts, even though no enough evidence had supported such explanation. Historically, coal mine disasters in China had been collected by two organizations: CCMSA and individual state-owned mining companies. Disasters occurred in those huge state-owned mines were collected by the related mining companies (at the same time reported to CCMSA) which were well described on the causation. In fact, there still exist some serious problems. Some disasters, such as rock falls, rock bursts, generally have occurred overwhelmingly. The so-called "causation" were just the descriptions on the course of disasters, not the real causation. Those occurring in small mines were collected only by CCMSA. Their causation were not well descripted, but the disaster type, the location and the date had been accurately recorded. Comparatively, the former are fit for concrete analyses, but they accounted for only 10.2% of the total and limited to several individual regions. However, the latter (89.8%)

covering the whole continental scopes, may be more suitable for space–time analysis.

Of all the 5825 geological disasters, 89.8% disasters had occurred in small mines. According to their connections with stress, the disasters are reclassified into four types, i.e. roadway disasters, gas disasters, water disasters and transport disasters. Roadway disasters (3472 in total) include all those related to stress disturbance, such as floor lift, side falling, rock fall, rock collapse and rock burst. Gas disasters (1259 in total) include gas explosion, gas asphyxiation, gas-coal burst and coal dust explosion (could not be identified easily, but be descripted as gas explosion). Water disasters (316 in total) mean water running into mining space from mine goafs, aquifers, and cause deaths. Transport disasters (778 in total) mean derailment or conveyor belt disasters. Surfacely, transport disasters are not related to geological factors, but the processes, segments and sites of transport cannot be separated from mining space. As many as 378 transport disasters alone or with other disasters involved in cluster series have attracted enough attention to define all the transport disasters as an independent disaster type.

All the 5825 geological disasters are located to the nearest town. There is a 3 km deviation between coal mine and nearest town averagely, which brings about just 1 mm error on China map by a scale of 1 : 3,000,000 and has become acceptable for space–time analysis.

3 Samples

On almost all days in the period examined, there were clustered samples, as can be seen in detail in Figs. 1–6.

3.1 Cluster-series samples

All the disaster types may occur in cluster series. They are doubted to be caused by stress disturbance.

3.1.1 Case 1: Roadway disasters

During the 2 days from 9 to 10 November 2003, there were nine coal mine disasters in China. On 9 November, two roadway disasters occurred in the coal mines of Huangshi Town and Nanyang Town, Leiyang City, Hunan Province, causing three deaths. On 10 November, another roadway disaster occurred in Dashi Town, Leiyang City, causing two deaths. The distances between these three coal mines are 9–19 ± 3 km (Series ID: 385 in Fig. 1).

3.1.2 Case 2: Roadway disasters

On 24 November 2003, a roadway disaster occurred at Dajinggou Coal Mine in Gaoshiya Town, Fugu County, Shanxi Province, causing one death. On 25 November, 34.8 ± 3 km away, another roadway disaster occurred in Yujianliang Coal Mine at Tadian Town, Shenmu County, causing one fatality (Series ID: 391 in Fig. 2).

3.1.3 Case 3: Gas disasters

At 19:55 on 12 June 2001, a gas explosion occurred at Liuziqing Coal Mine of Qinglong Town, Fengjie County, Chongqing City, causing three deaths. At 10:15 on 13 June, another gas explosion occurred in Fenshuiling Coal Mine, Shataping Town, Sangzhi County, Hunan Province,

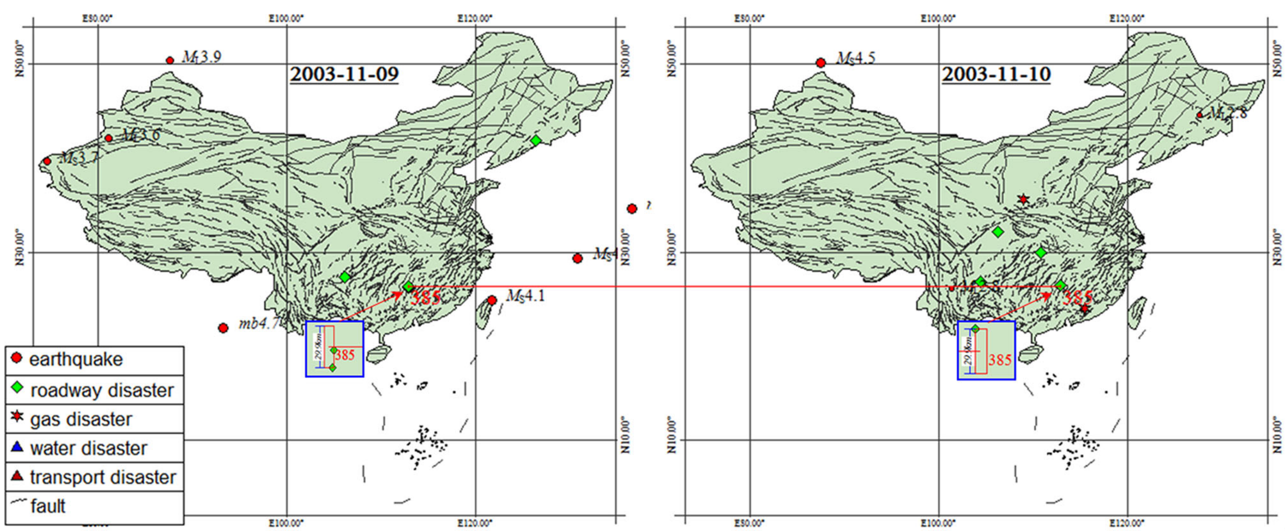

Fig. 1 Earthquakes and coal mine disasters occurring during the period from 9 to 10 November 2003 (faults are modified from a 1 : 2,500,000 Chinese Geological Map published by the Chinese Geological Survey, similarly hereinafter)

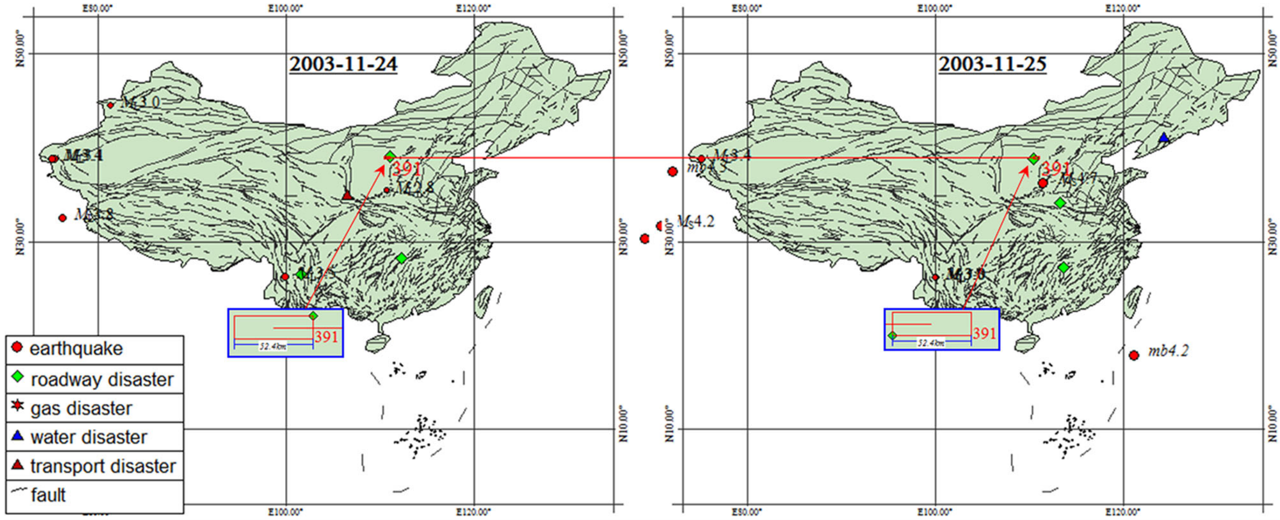

Fig. 2 Earthquakes and coal mine disasters occurring during the period from 24 to 25 November 2003

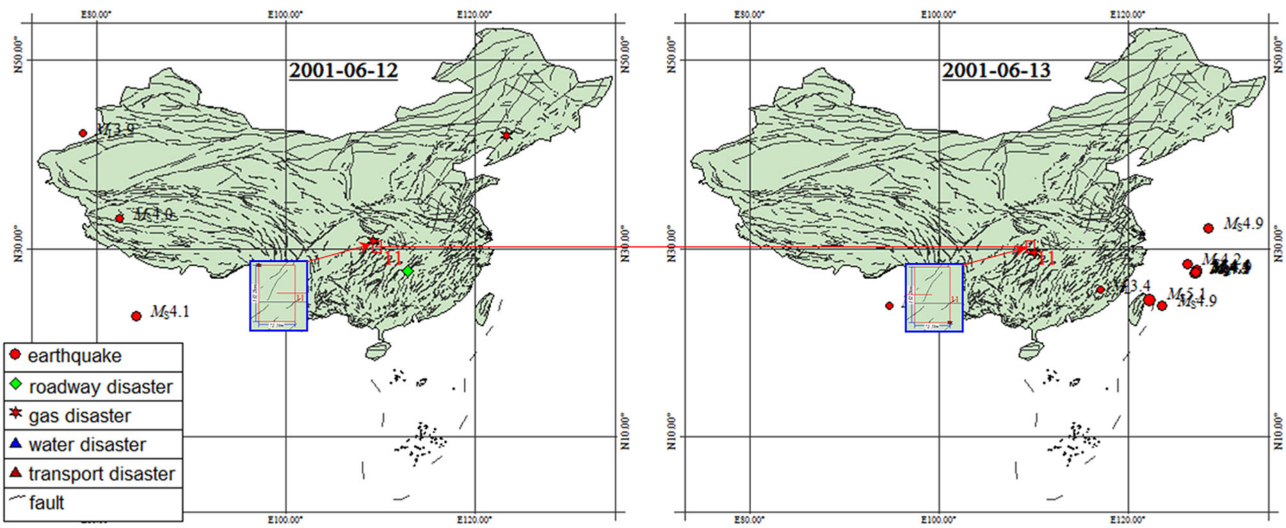

Fig. 3 Earthquakes and coal mine disasters occurring during the period from 12 to 13 June 2001

causing six deaths. They are 93.7 ± 3 km away from each other (Series ID: 11 in Fig. 3).

3.2 Disasters accompanied by earthquakes

There were many disasters accompanied by earthquakes nearby and all the disaster types were involved (more samples, see Supplementary I[1]).

3.2.1 Case 1

A M_L 3.0 earthquake occurred at 01:09 on 9 June 2004 14 km to northwest of Wanshou Town Xingwen County Sichuan Province. At 20:10, a roadway disaster with 1 death occurred in Qinggangpo Coal Mine. The distance between them is 15 ± 3 km. (Series ID: 463, in Fig. 4).

3.2.2 Case 2

A M_L 3.4 earthquake occurred at 19:11 on 9 June 2004 to the southeast of Pingchuan District, Baiyin City. On 10 June 2004, a transport disaster occurred in Gongrong Coal Mine, Pingchuan District, Baiyin City, causing one death. The distance between them is 33 ± 3 km (Series ID: 464 in Fig. 4).

1 http://pan.baidu.com/s/1sjnCEh3.

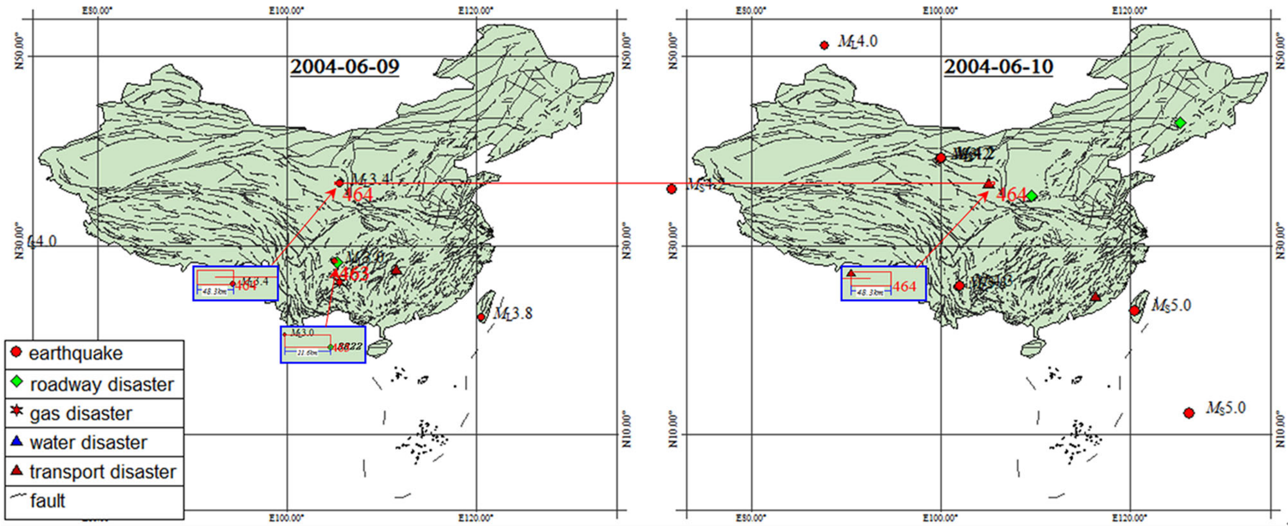

Fig. 4 Earthquakes and coal mine disasters occurring during the period from 9 to 10 June 2004

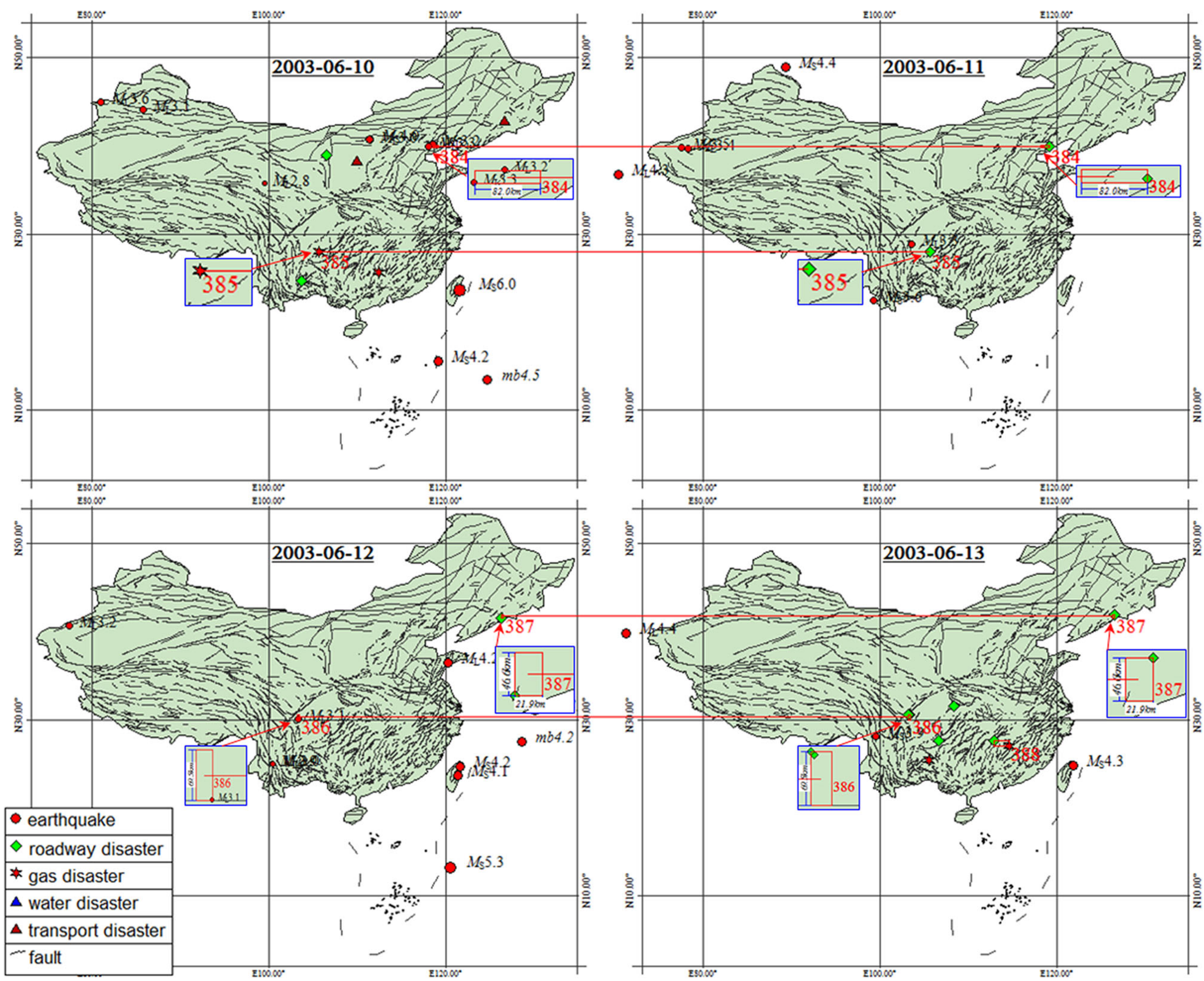

Fig. 5 Earthquakes and coal mine disasters occurring during the period from 10 to 13 June 2003

3.2.3 Case 3

A M_L 3.2 earthquake occurred in Funing County at 21:43:23.1 on 10 June 2003 at the location shown in Fig. 5. On 11 June, two roadway disasters occurred in Yiyuankou Coal Mine and CaoShan Coal Mine of Funing County, Qinhuangdao City, Hebei Province. (Series ID: 384, 2 days, Fig. 5).

3.2.4 Case 4

At 09:30 on 10 June 2003, a gas explosion occurred in Fumin Coal Mine, Jianzhu Town, Gulin County, Luzhou City, Sichuan Province. At 00:20 on 11 June 2003, a roadway disaster occurred in Tianba Coal Mine, Jianzhu Town, Gulin County, Luzhou City, Sichuan Province (Series ID: 385, 2 days, Fig. 5).

3.2.5 Case 5

At 00:00 on 12 June 2003, a roadway disaster occurred in Gangyao Coal Mine, Badaojiang District, Baishan City, Jilin Province. At 08:40 on 13 June, a roadway disaster occurred in Dacheng Coal Mine, Badaojiang District, Baishan City, Jilin Province (Series ID: 387, 2 days, Fig. 5).

3.2.6 Case 6

At 02:02:55.9 on 12 June 2003, a M_L 3.1 earthquake occurred at 30.01° N 103.47° E. At 18:00, a roadway disaster occurred in Renwan Coal Mine, Xiling Town, Dayi County, Chengdu City, Sichuan Province. At 21:05 on 13 June 2003, a roadway disaster occurred in Yanggou Coal Mine, Tiangongmiao Town, Dayi County, Chengdu City, Sichuan Province (Series ID: 386, 2 days, Fig. 5).

3.3 Disasters accompanied by microearthquakes

The paper lists the cluster series during the period from 5 to 8 June 2004. Seismic data are quoted from the Chinese Earthquake Catalogue (Chinese Seismic Data Management and Service System of Seismic Network Center 2020).

3.3.1 Case 1

On 4 June 2004, two earthquakes with magnitudes of M_L 0.9 and M_L 1.3 occurred in Hongling Coal Mine, Shenyang City, Liaoning Province. At 07:20 on 5 June, an asphyxia disaster occurred in Hongling Coal Mine, Shenyang City, Liaoning Province (Series ID: 1006, 3 days, Fig. 6).

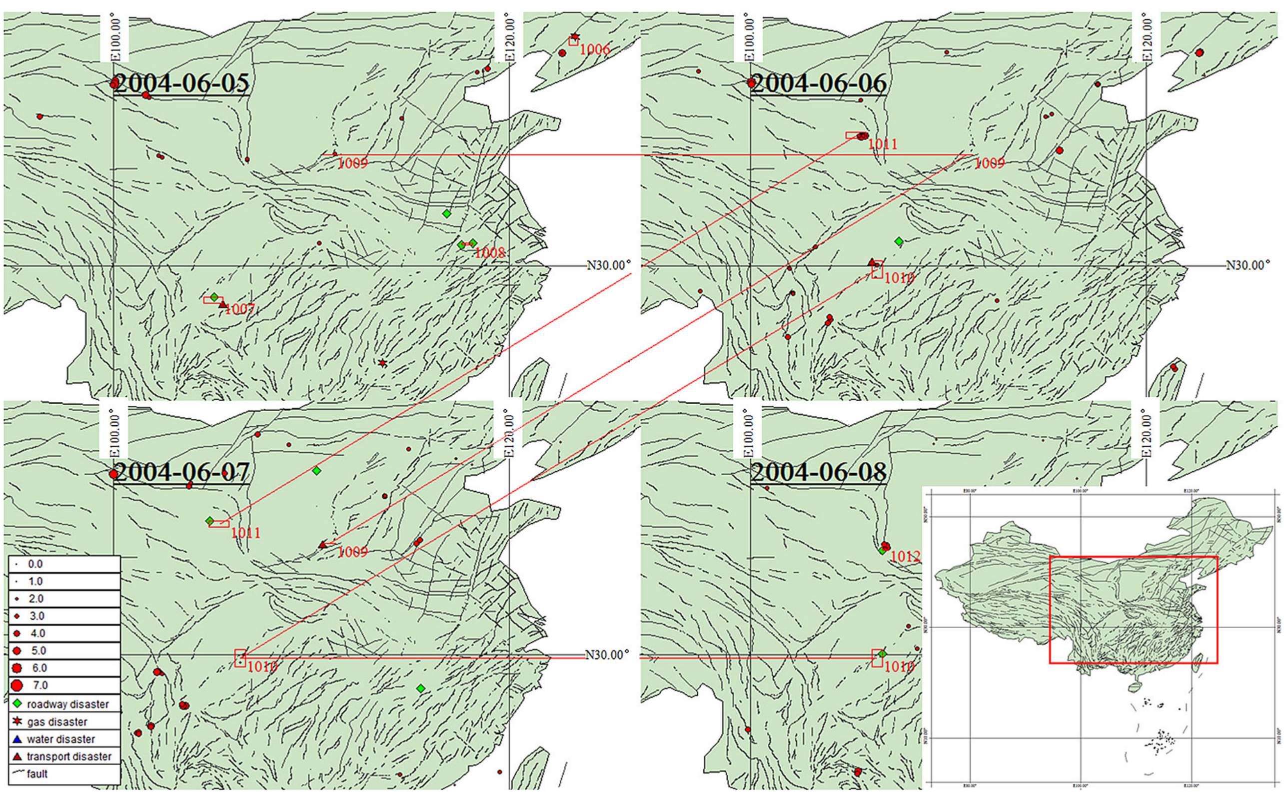

Fig. 6 Coal mine disasters and microearthquakes occurring over continental China during the period from 5 to 8 June 2004

3.3.2 Case 2

At 15:30 on 4 June 2004, a transport disaster occurred in Jiaocun Coal Mine, Gao County, Yibin City, Sichuan Province. At 16:00 on 5 June 2004, a roadway disaster occurred in Jinxing Coal Mine, Wukuang Town, Jiangan County, Yibin City, Sichuan Province. At 18:30, a transport disaster occurred in Xiaojiahe Coal Mine, Zhendong County, Xuyong County, Yibin City, Sichuan Province. (Series ID: 1007, 2 days, Fig. 6).

3.3.3 Case 3

At 11:00 on 5 June 2004, a roadway disaster occurred in Yangcun Coal Mine, Fanchang County, Wuhu City, Anhui Province. At 12:00 on 5 June 2004, a roadway disaster occurred in Xinxing Coal Mine, Wuwei County, Chaohu City, Anhui Province. The distance between the coal mines is 56 ± 3 km (Series ID: 1008, 1 days, Fig. 6).

3.3.4 Case 4

On 5 June 2004, A M_L 2.2 earthquake occurred to the east of Xiayukou Coal Mine, Hancheng City, Shanxi Province. On 6 June 2004, no earthquake or coal mine disaster occurred. At 07:00 on 7 June 2004, a transport disaster occurred in Xiayukou Coal Mine, Hancheng City Shanxi Province (Series ID: 1009, 3 days, Fig. 6).

3.3.5 Case 5

At 17:30 on 6 June 2004, a transport disaster occurred at Caojiagou Coal Mine, Hechuan County, Chongqing City, which was accompanied by a series of earthquakes with magnitudes ranging from M_L 1.5 to M_L 1.9. The epicenters are 14 ± 3 km and 52 ± 3 km to east of Caojiagou Coal Mine, respectively. On 7 June, another two earthquakes occurred in this area. At 11:00 on 8 June, a roadway disaster occurred in Hongyanwan Coal Mine, Beibei District, Chongqing City (Series ID: 1010, 3 days, Fig. 6).

3.3.6 Case 6

At 17:30 on 6 June 2004, a series of earthquakes with magnitudes ranging from M_L 2.0 to M_L 3.6 occurred 93 ± 3 km to the east of Dangjiashui Coal Mine, Baiyin City, Gansu Province. At 20:20 on 7 June, a roadway disaster occurred in Dangjiashui Coal Mine (Series ID: 1011, 2 days, Fig. 6).

3.3.7 Case 7

At 03:43.29 on 8 June 2004, a M_L 2.5 earthquake occurred in Chongxin County, 22 ± 3 km to the east of Huating Coal Mine, Gansu Province. At 09:10 on the same day, a roadway disaster occurred in Huating Coal Mine. Between 11:23 and 14:36, another four earthquakes occurred in Chongxin County, Gansu Province (Series ID: 1012, 1 days, Fig. 6).

3.3.8 Summary of characteristics

(1) The disasters involved in these cluster series include roadway disasters, gas disasters, water disasters, and transport disasters. Quite a few were accompanied by earthquakes.

(2) The distance between events in these cluster series is much greater than the mining depth, even as far as 100 km, and this is unlikely to be noticed without examining a broader perspective. There were 158 disasters occurring in different towns of the same county within 1 or 2 days, accounting for 2.71% of the total.

(3) With microearthquakes introduced, more than 60% of coal mine disasters are found to be accompanied by microearthquakes, in which microearthquakes tended to occur two days before coal mine disasters did.

In the past, microearthquakes were taken as “background” earthquakes. They occurred quite often but could not reflect the activities of the faults. Now, microearthquakes accompanying with coal mine disasters indicates they are more likely caused by mining activities.

(4) The cluster characteristics vary slightly from region to region. The number of cluster series in South China is much higher than that in North China. Coal mine disasters in Southeast China tended to coincide with the Taiwan seismic belts. Once earthquakes occurred in the Taiwan seismic belts, more disasters would occur in coal mines of Guangdong and Fujian Province. Coal mine disasters in Sichuan, Yunnan and Guizhou Province coincide with local earthquake belts.

(5) It is not merely the fatal earthquakes that accompanied by disaster directly, but more often those with magnitude lower than M_S 5.0.

(6) Regions, such as Xinjiang Autonomous Region and Heilongjiang Province, possess fewer earthquakes and fewer coal mines, but their coal mine disasters still present cluster feature or accompany by earthquakes. Their thresholds may be as long as 100 km and may work as the threshold reference for the

regions with higher density of coal mines, such as Sichuan, Guizhou and Yunnan Province (Geoscience Data Sharing Service Platform 2020).

(7) In some special geological structures, such as Liupan Mountain (Liupan Mountain locates at the boundary of the Qinghai–Tibet Plate and the North China Plate. Earlier, Tapponnier (Tapponnier et al. 1981, 1986) argued that extrusion collision of India Plate brought about the uplift of the Qinghai–Tibet Plateau and at LiuPan Mountain, the extrusion stress was transmitted to the North China Plate.), more coal mine disasters are found to be accompanied by earthquakes, indicating that high geostress may interact with mining activity.

4 Quantitative research

Once the cluster feature was accepted by the readers, the following questions may be put forward: how many disasters are involved in a cluster series? How many disasters are accompanied by earthquakes nearby? How long do the series generally last?

Cluster analysis is a complex topic in mathematics. There are several analysis methods, including systematic clustering, hierarchical clustering, dynamic clustering, and ordered sample clustering. Systematic clustering has been widely used in many research fields, for example geology, meteorology, and demographics (Yang 2010; Xi and Tan 2009). The variables used to describe the degree of proximity of the objects may be the real distance in geographical space or the differences among certain properties of the objects. The degree of spatial clustering of coalmine disasters is acquired based on systematic clustering (by Euclidean distance).

The concept of space clustering degree cannot be separated from space threshold. If there are n objects in a 2D space, each possesses $n - 1$ distances between it and the rest $n - 1$ objects. For a given object, all the $n - 1$ distances are compared with a fixed space threshold. If some are shorter than the space threshold, the related objects will be included into the cluster series. The object newly included into series will be selected as the new central object, through which new neighboring objects within the scope of threshold will be picked out in Fig. 7. A fixed space threshold will get a fixed number of cluster series and further get fixed objects involved in cluster series. A series of continuously increased space thresholds will get a series of cluster series and the objects involved in cluster series.

Similarly, the concept of time clustering degree cannot be separated from time threshold. Two day is selected as time threshold in this paper. For example, on the first day, an earthquake occurred around a coal mine (within space threshold). If a coal mine disaster or an earthquake occurred on the second day, a cluster series by 2-day duration formed. If a coal mine disaster occurred not on the second day, but on the third day. It is taken as a cluster series by 3-day duration, but not by 2-day duration.

The space and time thresholds are the two basic restrictions imposed on series, under which there are $S \times T$ (*S: Space; T: Time*) restrictions imposed on calculations, see Table 1.

The time threshold determines the duration of the series and the space threshold determines the geographical scope of the series, and they both have a positive effect on the size of the series. With increasing time and space thresholds, the number of events included in the series will increase sharply. A time threshold of three or more days may result in very large series. All statistical results and event mapping are based on 2-day threshold.

The time threshold is a way to measure the duration of cluster series. For example, consider a mining area around which earthquakes or disasters occurred every day from Monday to Friday. Measured by a 2-day time threshold, a 5-day series would be obtained. If no events occurred on the Tuesday, only a single 3-day series would be obtained (Wednesday, Thursday, and Friday). If no events occurred on the Wednesday, then two 2-day series would be obtained: one from Monday to Tuesday and the other from Thursday to Friday. This 2-day duration restriction provides a conservative result. However, for a 3-day time threshold, if no events had occurred on any single day from Tuesday to Thursday, a 5-day series would still be obtained. The series in Figs. 1, 2, 3, 4, 5, and 6 were tracked under the restrictions of a 60-km space threshold and 2-day time threshold.

Once the thresholds are fixed, the number of cluster series and the number of related coalmine disasters will also be fixed. Each cluster series possesses multiple properties, such as duration, area, and circumference. Each event in a series also possesses multiple properties, such as distance and event count. If the events are sorted by distance, a spatial clustering curve can be acquired, as shown in Figs. 8 and 9. If the events are sorted by duration, a temporal clustering curve can be acquired, as shown in Fig. 10.

4.1 The proportion of disasters associated in series and the number of earthquakes accompanied by disasters

Using the above method, the proportion of disasters that are associated in series and the number of earthquakes accompanied by disasters were obtained. As many as 158 disasters occurred in coalmines in different towns of the

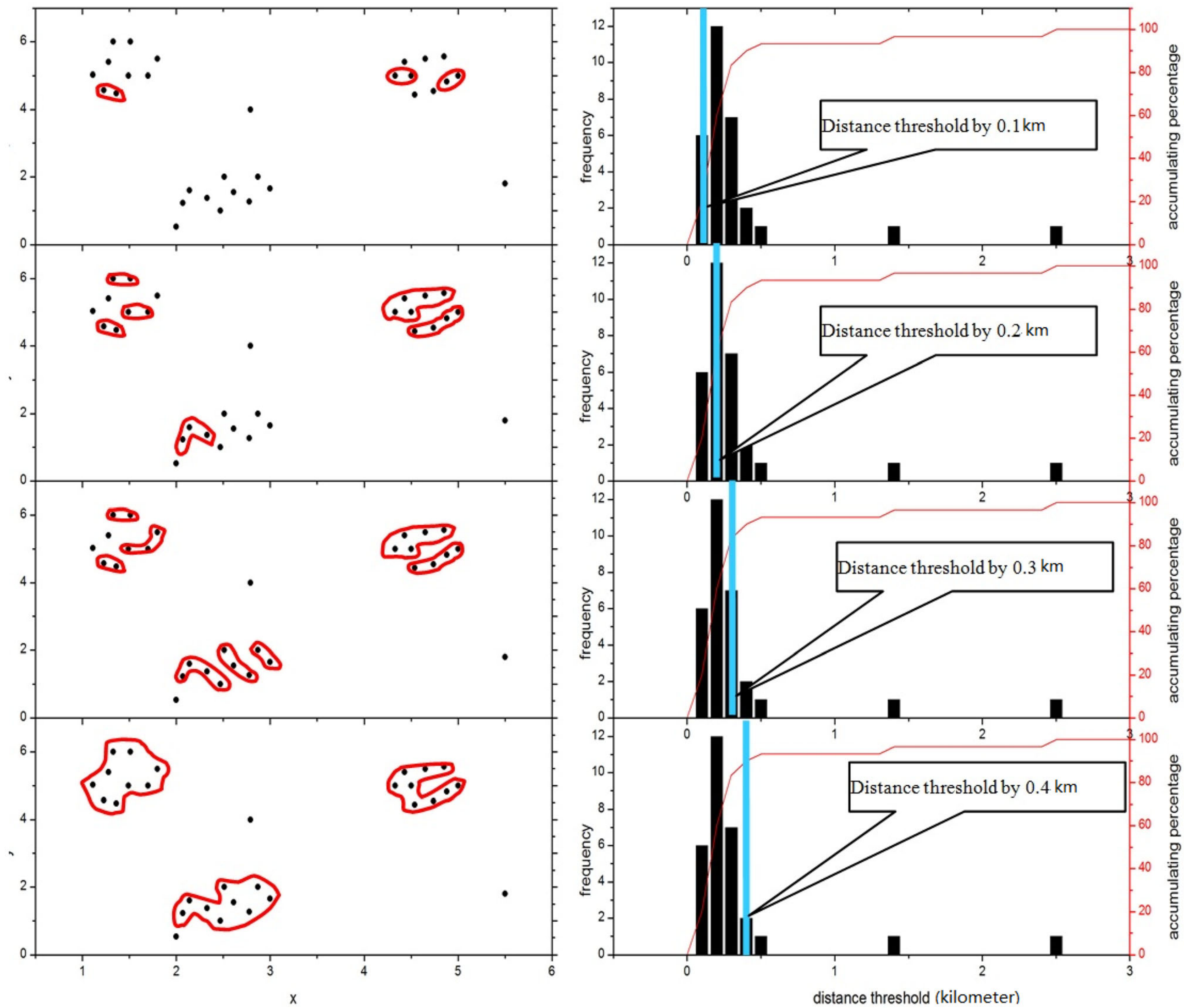

Fig. 7 Establishing the degree of spatial clustering of disasters. Restricted by 0.1 km, the proportion in series is 20%; restricted by 0.2 km, the proportion is 60%; restricted by 0.3 km, the proportion is 83.33%; restricted by 0.4 km, the proportion is 90%

Table 1 Time and space threshold restrictions imposed on cluster series

Distance (km)	1 day	2 days	3 days
10	Series	Series	Series
20	Series	Series	Series
30	Series	Series	Series
40	Series	Series	Series
…	…	…	…
100	Series	Series	Series

same county within 1 or 2 days and these can be presumed to be directly caused by the neighboring coalmine disasters. As shown in Fig. 8, within 50 ± 2 km, 25.98% are involved in the series; within 100 ± 2 km, 47.45% are involved; and within 170 ± 2 km, 65.2% are involved. Similarly, the number of earthquakes accompanying disasters can also be acquired. As shown in Fig. 9, within 50 ± 2 km, 82 disasters are accompanied by earthquakes; within 100 ± 2 km, 372 disasters are accompanied by earthquakes; and within 170 ± 2 km, 696 disasters are accompanied by earthquakes.

4.2 The duration of series

The duration of series potentially reflects the time taken for stress to be transmitted. All the cluster series have been tracked out under restrictions of 30, 40, 50, …, 100 km space threshold and a 2-day time threshold. If sorted by the day number of series, a collection of frequency distribution curves along *x* axis is achieved. As it is shown in Fig. 10,

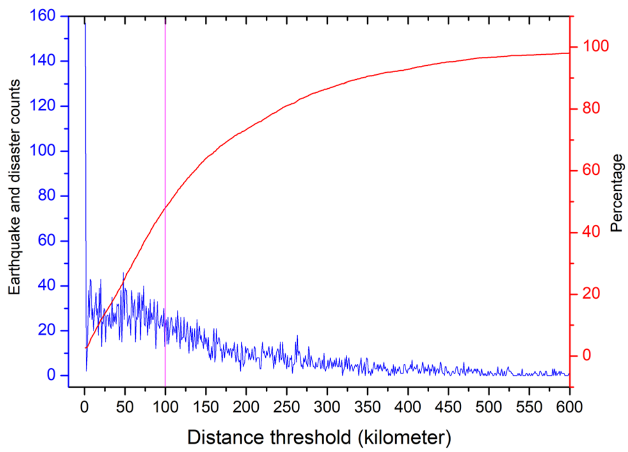

Fig. 8 Space clustering degree. Left *y* axis: earthquake and disaster counts in cluster series; right *y* axis: cumulative percentage; *x* axis: space threshold among disaster mines (100-km threshold and 2-day time threshold)

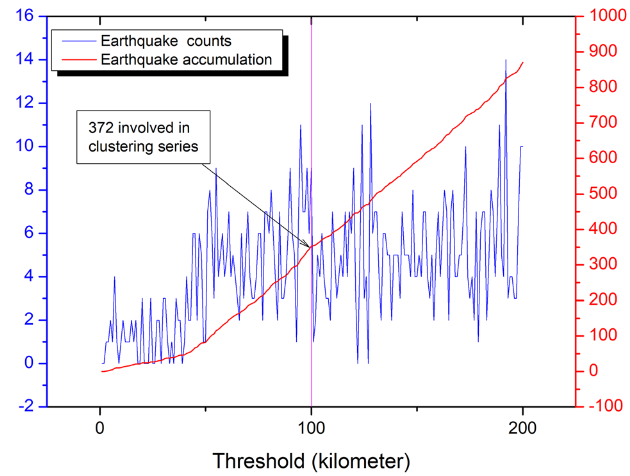

Fig. 9 Earthquake counts. Left *y* axis: earthquake counts in cluster series; right *y* axis: earthquake accumulation; *x* axis: space threshold among disaster mines (100-km threshold and 2-day time threshold)

most series last for 2 days, followed in order by 1 day and 3 days. The number of those longer than 4 days decreased sharply, but they coincided with fatal earthquakes very well.

4.3 The relationship between space threshold and cluster series

Greater space thresholds result in a larger number of series and more associated disasters. At a 170-km threshold, the summit of the cluster series increases to 1134 and includes 3848 disasters (accounting for 65.2%) and 840 earthquakes. As shown in Fig. 11, for space thresholds greater than 170 km, small series merge to form larger ones, and the total number of series begins to decrease. The paper fails to acquire an optimal threshold, and the frequencies of cluster series under thresholds ranging from 0 to 600 km were obtained. Space thresholds ranging from 10 to 90 km resulted in more series. Those greater than 170 km obtained ambiguous series. A conservative threshold of 100 km is therefore recommended in this paper.

4.4 Coincidence with earthquakes

The cluster series possess multiple properties, such as the area, the number of disasters, the number of earthquakes, the distance between events and their duration. If the regional stress field interacts with the local stress field, once fatal earthquakes occurred, the local stress field will be affected and the cluster series may change correspondingly. For example, more disasters or longer durations or larger scopes will present, which is also the physical basis of all the frequency comparisons. Good correlations have been found in Figs. 12 and 13. For more comparing items see Supplementary II (see footnote 1) (restricted by 90-km threshold and 2-day threshold).

The overall coincidences are the sum of individual sub-coincidences. For example, on 27 September 2003, a M_S 7.7 earthquake occurred to the north of the Altai Mountains. During the period from 26 to 27 September, 2003, four cluster series had been found, of which one lasted for 2 days and three lasted for 3 days. Good coincidences have been acquired between series counts, disaster counts, durations and earthquake counts, but no coincidence is acquired between series area, accumulation of area, distance between events and earthquake count. That is primarily because more series occurred in former comparisons, but they possess smaller area. This decreases or hides the coincidence in later comparisons. The similar cases exist in other fatal earthquakes. So the overall coincidences should be the sum of sub coincidences in every comparing item. The area, the distance, the duration, the series count and the disaster count (involved in series) may reflect the relativity between cluster series and earthquakes from different perspectives.

The earthquakes coinciding with disasters can be divided into three types. The first are fatal earthquakes (magnitude higher than M_S 7.0). Once fatal earthquakes occurred, more cluster series will present in certain mining areas, coinciding with earthquakes. Some cluster series may be 0–7 days earlier or later than the fatal earthquakes. The second are the earthquakes with magnitude from M_S 2.0 to M_S 6.0. They may occur over larger scope, but they are accompanied with more disasters. The third are the microearthquakes occurring near the disaster mine with magnitude from M_S 0.0 to M_S 2.0, and they are speculated to be caused by mining directly.

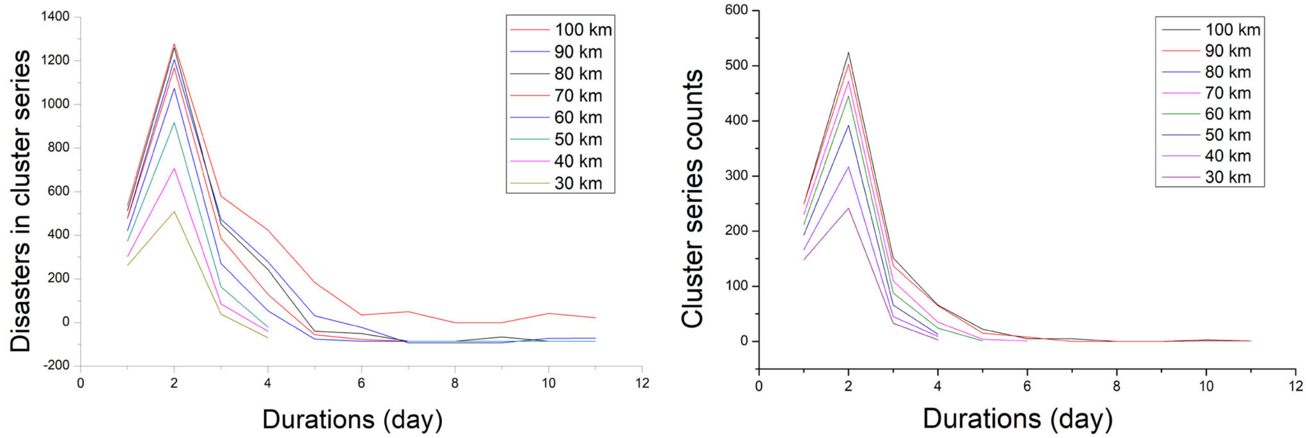

Fig. 10 The series durations (left) and the related disasters along the *x* axis (right) (restricted by 30, 40, 50, …, 100-km thresholds and a 2-day time threshold)

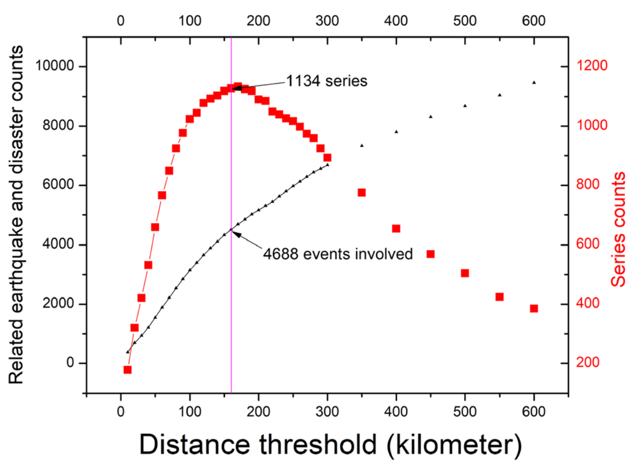

Fig. 11 The counts of series and related events. Left *y* axis: disaster and earthquake count in series; right *y* axis: series counts; *x* axis: distance in space (2-day time threshold)

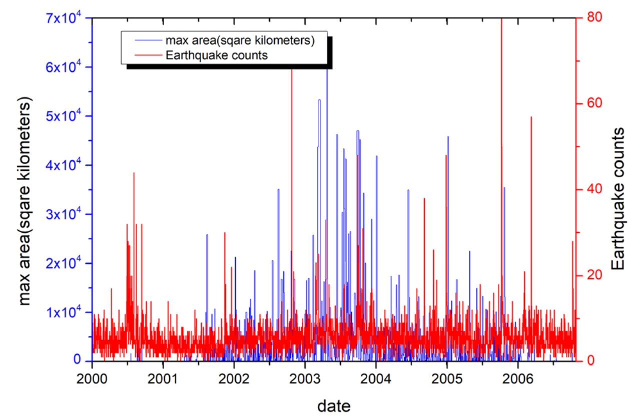

Fig. 12 The maximum area of series compared with the earthquake counts

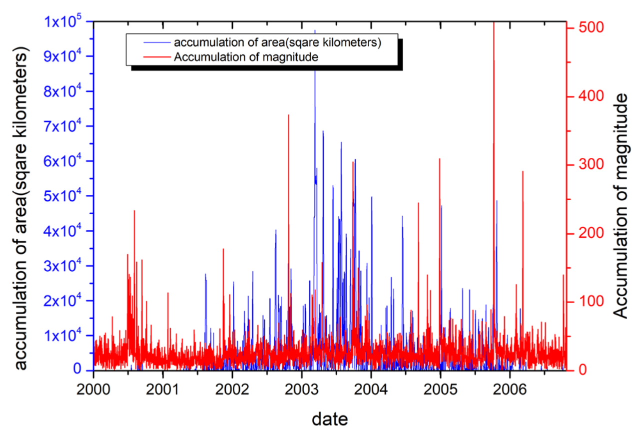

Fig. 13 The accumulation of series area compared with the accumulation of earthquake magnitude

5 Authenticity and reliability

Nearly half of coal mine disasters are involved in cluster series. Is it merely a coincidence or is there something deeper? All the possible causative factors should be taken into consideration.

5.1 Integrity

The authenticity of the data depends on its integrity. If CCMSA just published parts of the disaster records, the clustering features may not be the truth. According to CCMSA, the disasters were partly collected before 1 July 2001 and partly published after 1 March 2006. Comparatively, during the period from 1 July 2001 to 28 February 2006, the disasters had been well collected and fully published. In addition to the clustering feature, more than 60% disasters were accompanied by microearthquakes (with magnitudes lower than M_S 2.0). It indicates that stress disturbance surely occurred around coal mine disaster.

5.2 Human error

In traditional researches, coal mine disasters were mainly ascribed to human errors, such as safety violations, operator error or disrespect of the rules. If this explanation were right, human errors would present clustering feature. Are they contagious? Maybe there exist some factors that can affect spirits or behaviors of people over certain regions, controlled by which, people are more likely to make mistake or disrespect regulations (What's more, quite a few accompanied by earthquakes nearby). Obviously, this is a false proposition. The paper is inclined to ascribe the clustering feature as well as its coincidence with natural earthquakes to geological factors. Of all the causative factors, stress disturbance is the only one that can cause all kinds of disasters at the same time.

5.3 Inherent feature

When two unrelated types of events were mapped into one 2D space, there always will be some events that are near to each other. If this is taken as the evidence of cluster feature, then the judgment will be wrong. Obviously, the assumption is not consistent with the actual situation. First, neither the earthquakes nor the coal mine disasters are random events. Second, the two kinds of events not only occurred in close physical proximity, but also in close temporal proximity.

5.4 Coincidence

It could be assumed that the coal mine disasters involved in cluster series were independent from each other, whose clustering samples were just of a coincidence. This hypothesis, to some extent, is reasonable. As noted, there are 26,395 coal mines in China, and 89.8% of coal mines are the small ones running by the small companies, and possess a higher disaster probability. In this situation, though the neighboring coal mines are (assumed) not related to each other, there still exists a probability for several disasters to occur together. The high mine density and the high disaster probability may play a role. However, more than 26,000 coal mines distributing over continental scopes, the probability for several disasters to occur in the same mining area is therefore extremely low. Literally, coincidence is a synonym of low probability. More than 50% of disasters involved in cluster series make the assumption of coincidence false.

5.5 Geological factors

For a given coalfield, the properties of the surrounding rock, such as fractures, the faults, the stress sustaining ability, are roughly in the same level. In the same environment, the probability of several disasters occurring together exists and keeps a certain level. As is shown in this paper, spatial cluster series can occur at distances many times the mining depth, even as far as 100 km, exceeding the general range of coal fields. Therefore, the speculation that geological factors being the cause of the observed clustering is not correct. In addition, outwardly, it seemed that the cluster feature is ascribed to one disaster causing another. Generally, there are only tens of metric tons of rock fallen in a roof disaster. This raises a question: how can such a volume of rock cause another roadway disaster more than 80 km away? Perhaps the analysis between individual events is not feasible. The disasters should be put back to tectonic stress field and should be considered in terms of the tectonic stress field.

6 Recognition of clustering features

In further research, with microearthquakes introduced, the probability of coal mine disasters occurred occasionally together with microearthquakes increases sharply. If the events were judged as "clustering", more evidence is needed. The followings are the criterions of scientificity and the rationality that are employed in this paper.

6.1 Space restriction

To make judgement that the coal mine disasters are "accompanied" with earthquakes, the first step is to observe the map of coal mine disaster and earthquake repeatedly under a shorter space threshold (scanning radii). Then increase the space threshold gradually and examine on the map of coal mine disasters.

6.2 Time restriction

The definition of cluster feature demands that coal mine disaster and earthquake not only occur in physically proximate locations, but also occur successively. If earthquakes occurred quite often around a mining area, the judgment of "accompanied by earthquakes" may be not accurate. In this case, "accompanying" would be better described by "coincidence." Conversely, if very few or no earthquakes occur in a mining area, this judgment may be of high reliability. In this way, an objective judgment standard for "disasters accompanied by earthquakes" formed.

6.3 Enhance the magnitude, ignoring microearthquakes

The number of earthquakes with magnitude higher than M_S 2.0 decreases sharply. Accordingly, the probability for coal mine disaster and earthquake (with M_S magnitude higher than 2.0) occasionally to occur together also decreases sharply. If there still were disasters accompanied by earthquakes, the cognition of "accompanied by earthquakes" is more convincing. It is a more rigorous criterion.

6.4 Refer to the regions with fewer earthquakes and fewer coal mines

To acquire the max and the optimal space threshold of the cluster series is one of the most important task of the research, which is the scope of stress disturbance may impact on. Within optimal space threshold, the number of events involved in cluster series has more practical meanings. The regions, such as Xinjiang Uygur Autonomous Region, Liaoning, Heilongjiang Province, compared with Yunnan, Guizhou, Sichuan Province, are broader in territory, but they possess fewer earthquakes and fewer coal mines. The probability for earthquakes and coal mines to occur occasionally together is lower. If there still are some disasters accompanied by earthquakes, the threshold in these regions can be taken as a reference for other regions. For example, on 22 August 2001, a roadway disaster occurred in Coal Mine of Hainuke town, Qapqal County, Xinjiang Uygur Autonomous Region. On 23 August, two earthquakes with M_S magnitude of 3.3 and 4.1 occurred 112 ± 3 km to Northwest of coal mines. "Replayed" all the historical earthquakes and all the coal mine disasters in this region, the similar events was not found around this area. The threshold of 112 ± 3 km can be inferred to regions, such as Yunnan, Guizhou, Sichuan Province. For another sample, on 9 January 2002, a gas explosion disaster occurred in Wanlong Coal Mine, Tuquan County Inner Mongolia. On the same day, two earthquakes with M_S -magnitude of 2.6 and 3.0 occurred at the place 150 ± 3 km to the Northwest of disaster coal mine, in which the distance of 150 ± 3 km may work as a reference for other regions.

7 Mechanism

Of all the causative factors of coal mine disasters, stress disturbance is the only one that can bring about cluster feature. The paper tries to analyze on the possible mechanisms.

7.1 Meta-process and meta-mechanism

Once fatal earthquakes occurred, regional stress disturbance will accelerate. If the geological structure around mining area can sustain the stress disturbance, stress field may gradually reach to a new balance. Otherwise, the structure may collapse (mine quakes), which subsequently may cause stress-related disasters, such as roadway disaster, rock fall, rock burst as well as secondary disasters, such as gas disasters, water disasters, transport disasters. Because sustaining measures fails, the stress disturbance will be passed on among the adjacent structures until the stress disturbance is sustained or shared by neighboring geological structures. The whole transferring process presents "adaptive" characteristic, which may be the basis of cluster feature of disasters and earthquakes. As a meta-process, all the geological structures around a mining area will undergo this meta-process and finally reach to a new balance. This is illustrated in the flow chart in Fig. 14.

Considering the meta-mechanism, under a static load, the limit of material fracture depends not only on how large the force is, but also on the force per unit area, i.e. the pressure. When a force is applied to an object, the smaller contact area gets higher pressure. In a 3D geological coalmine space, the size of the tectonic structure that supports stress fluctuations ultimately decides that of contact area. When this area is smaller, there is a higher pressure, and this may ultimately lead to fracture of the material. Different coal mine sites or different mining stages may get different geological models. But the meta-process and the meta-mechanism, as the inherent law, will not change on different coal mine sites or on different mining stages.

7.2 Disaster-causing model

It has been clear that tectonic stress contributes to most fatal roadway disasters (He 2000; Zhang and Song 2006). As noted earlier, direct mining in areas with intensive tectonic stress is strictly prohibited. The protective measure is to mine in the vicinities on vertical or horizontal directions first, where tectonic stress is less intensive. By this measure, the intensive stress is relieved to safety level. Generally, for the complex mechanical problem, if sunk in individual coal mines at the very start, the scopes may be too narrow to find the connections among things. The feasible strategy may start on the whole mining areas rather than individual coal mine.

For coal fields in mid or late stage of mining, with the coal mined, an equal volume of goaf is left. The coal fields subsequently become the tectonic stress-unloaded fields, but what are the impacts of tectonic stress-unloaded fields on coal mines? The paper tries to make speculations.

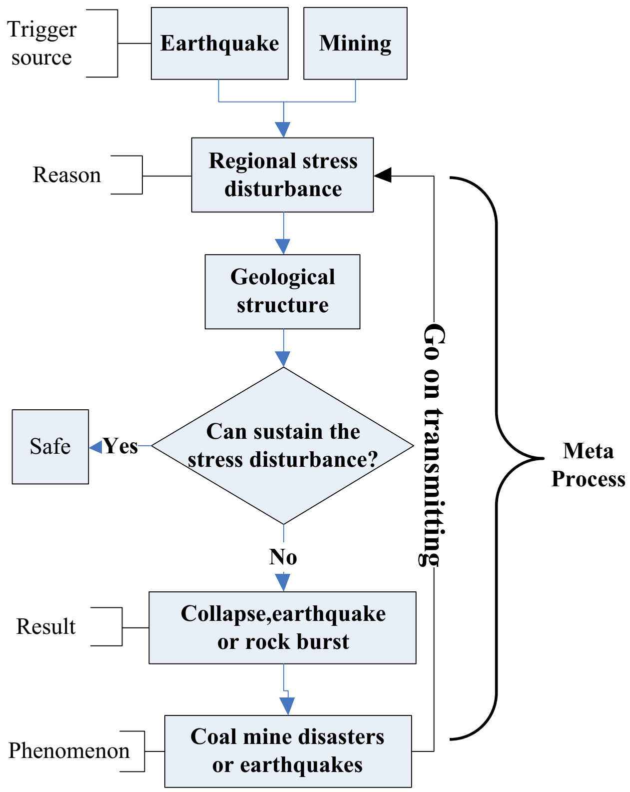

Fig. 14 Flow chart of the meta-process of stress disturbance bringing about coal mine disasters

7.2.1 *Fatal earthquakes cause disasters: regional stress disturbance impacts on local stress field*

Once fatal earthquakes occurred, the local deformation will be accelerated and the stress disturbance will load on the mining space. As is shown in Fig. 15, the sites, such as ①, ②, and ⑤ are loaded by compressive stress. If the structures of these sites are not intensive enough to carry the stress or the sustaining measure are invalid or absent, the structures may collapse and bring about stress-related disasters, such as rock burst, roadway disasters, gas disasters and transport disasters. During the process, the "meta-process" of stress disturbance play an important role. The stress disturbance is passed on among different geological structures until one is intensive enough to carry the stress or different structures share the whole stress disturbance.

7.2.2 *Disaster causes earthquake: mining over a large area unloads the regional tectonic stress*

If the coal mines in sites, such as ①, ②, and ⑤ in Fig. 15, dug along the NW–SE direction, the compress stress loaded on mining surface will increase gradually, and the compress stress will ultimately exceed the mechanics limit. The stress-related disasters, such as mine quake, rock burst, rock fall, roadway disaster will be inevitable. If mining along NW–SE direction does not cease, the regional tectonic stress will be unloaded and earthquakes will occur.

In mining spaces, intensive supporting measures over large areas are not always feasible. The stress disturbance that should have been supported will be transmitted to adjacent structures, and brings about coal mine disasters or even earthquakes.

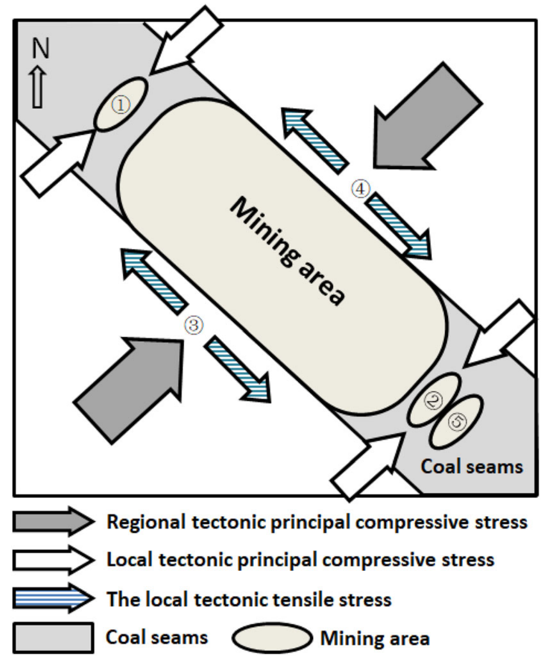

Fig. 15 Geological model of tectonic stress disturbances over a mining area leading to coal mine disasters (stress: with value changed solely, direction fixed)

7.2.3 *Neighboring coal mines interact with each other*

Once the coal is mined, the stress around coal beds may initially be released and loaded onto neighboring structures. This is presumably the way that regional stress is transmitted and is a means by which the coal beds may be linked with remote regional seismic belts. Theoretically, a miner could produce a regional earthquake with a pickaxe. A slow disturbance may cause deformations, and these deformations may in turn cause transport disasters or bring about new faults or fissures through which water or gas can find its way into the mining space and cause disasters. Fast disturbances may result in quakes and directly cause roadway or transport disasters.

There were 158 disasters that occurred in different towns of the same county within 1 or 2 days, accounting for only 2.71% of the total (5825 disasters). These may be the result of neighboring coalmines interacting with each other. Disasters are seemingly caused by other disasters, and stress disturbance may play a role in this. Released stress loading onto neighboring coalmines may be an important mechanism in this process.

7.2.4 *Tectonic stress-unloaded "field" causes disasters*

If the coal on site ② in Fig. 15 are mined by the new development of the coal mines, the tectonic stress will be mainly loaded on site ① and ⑤ (unmined area). Similarly, mining on site ① will also contribute to the stress increasing on site ② and ⑤. Through this way, coal mines, tens of kilometers away, may impact on each other alternately.

The distance between disasters or earthquakes involved in a cluster series may reach 10–100 km, accounting for more than 40% of the total. This distance exceeds the mining depth by many times, and it may be far-fetched to suggest this is a result of neighboring coalmines interacting with each other. It is more plausible to suggest that these disasters are brought about by the tectonic stress-unloaded field.

7.2.5 *Mine earthquakes or rock bursts cause disasters*

Stress disturbance is speculated as the main reason, but the most direct cause may be rock bursts and mine quakes. The original stress balance is destroyed by mining and rock burst and mine quakes are just the symptoms of stress disturbance. Because the transmission of stress is adaptive, the stress disturbance is passed on among structures. On 3 November 2011, at 19:18, a M_L 2.9 earthquake occurred around Yima City of Henan Province. At 19:45, a rock burst disaster occurred in Qianqiu Coal Mine, in which 59 workers were trapped underground (rescued 48 h later). There lacks an in-site research, but it indicates that a link should be drawn between the two events.

The above analyses do not exclude or deny other traditional causative factors. In addition to those involved in cluster series, a minority of disasters have occurred in isolation. In this space–time analysis, it is undeniable that some disasters that were caused by human errors were coincidentally included into the cluster series. However, it is unreasonable to ascribe more than half of the disasters involved in the cluster series to coincidence, which, as noted, is literally a synonym for low probability. Each type of disaster has fixed causative factors, but stress disturbance is the only factor that can cause all kinds of disasters at the same time.

7.3 The relationship between earthquakes and coal mine disasters

Earthquakes and coal mine disasters are two "brothers", their common "father" may be stress disturbance. The factors that can cause stress disturbance potentially are able to bring about earthquakes and coal mine disasters. It has been reported that factors, such as air pressure (Boyer 1964; Kissel et al. 1973; McIntosh 1957), solid tide (Milne 1883), may cause stress disturbance. Accordingly, the integrated mechanism is as follows. One or more factors first bring about regional stress disturbance and regional stress disturbance subsequently causes earthquakes or coal mine disasters, by which several previously separately researching fields, such as meteorology, tectonics, mining, engineering geology, may be linked to each other.

8 Discussion

Over Continental China, except those huge sedimentary basins (for example the Ordos Basin), the majority coal mines distribute along fracture zones (Fig. 16). Modern tectonic researches indicate that bulk motion and finite deformation are the patterns of the plate movements (Tapponnier et al. 1981, 1986). Basins, as the boundaries of geological plates, are the right locations for stress or deformation to adjust. While the boundary faults of basins limit the coal seams into basins and share the common tectonic stress with coal seam. Coal seams inherently co-exist and co-grow with tectonic faults which make the tectonic structure of coal mines be an unsteady structure.

Several coalmines may not cause stress disturbances, but when the density of coalmines increases to a certain level, their combined effects cannot be ignored. The digging of more than 26,000 coal mines across China may inadvertently become a continent-wide experiment. The clustering of disasters and their coincidence with earthquakes are a reaction of the superficial crust to excessive mining. This verifies an even more important scientific point: with large numbers of coal mines dug excessively over wide areas, the superficial crust may become less stable and more likely to fluctuate, which can bring about disasters in neighboring coal mines or even interact with tectonic stress disturbances. In future, as humans explore deep into the planet, attention should not only be focused on individual sites, but on wider mining areas or tectonic stress-unloaded fields.

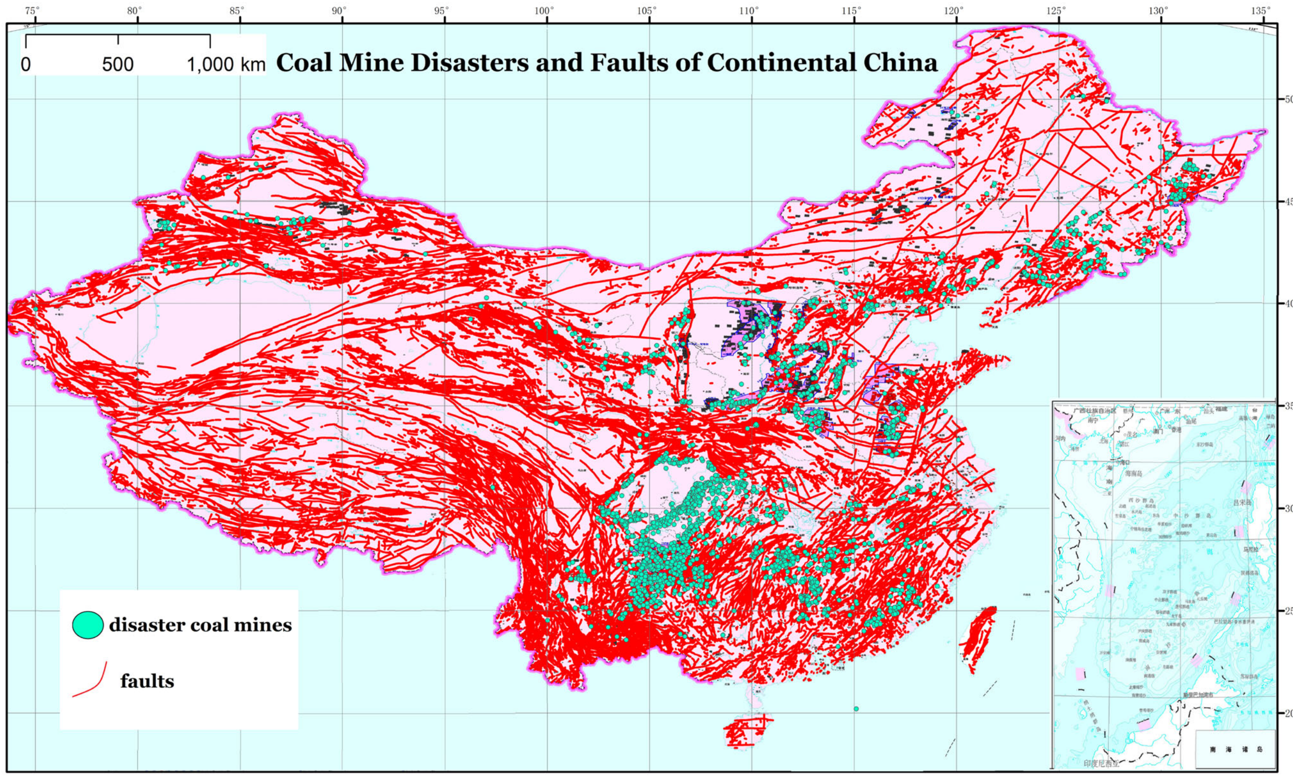

Fig. 16 Map of coal mine disasters and faults in continental China, combining the following data: 1. 1 : 10,000,000 Chinese Coal Resource Distribution Map (Chinese Geological Survey 2020); 2. 1 : 2,500,000 Chinese Metallogenic Domain Map (Geological and National Digital Data Center 2020); 3. Chinese Coal Mine Disaster Records (Chinese Coal Mine Safety Administration 2020)

9 Conclusions

It can be concluded that the cluster feature of coal mine disasters and their coincidence with earthquakes are the two primary characteristics of the space–time distribution of coal mine disasters in China.

(1) Nearly half of coal mine disasters in China have been found to occur in clusters or to be accompanied by earthquakes nearby (with M_S magnitudes lower than 5.0) and all the disaster types are involved in cluster series.

(2) Microearthquakes accompanied with coal mine disasters generally occurred 2 days before the disasters which indicates that human mining may be the main causative factor for these microearthquakes. And microearthquakes, especially those occurring around coal mine sites, may be vital geophysical evidence of stress disturbances around mining fields.

(3) Except stress disturbance, all the known causative factors are analyzed to demonstrate the authenticity and the reliability of the observed phenomena and were excluded ultimately. The clustering of coal mine disasters falls outside traditional understanding and has not been reported by previous researchers.

(4) The distances between mines are many times of the mining depth, even is as large as 100 km. Of all the causative factors of coal mine disasters, stress disturbance, the only one that can cause all kinds of coal mine disasters at one time, seems to exist among mining areas and is responsible for the cluster feature.

(5) When restricted by a space threshold of 100 km and a time threshold of 2 days, it was found that 47% of disasters were involved in cluster series and 372 coal mine disasters were accompanied by earthquakes. In addition, most series lasted for 2 days, followed in order by 1 day and 3 days. There was a sharp decrease from 4 days, but these events coincided with fatal earthquakes very well [see Supplementary II (see footnote 1)], and they are speculated to be related to regional stress disturbance.

(6) Good correspondences between earthquake and coal mine disasters have been obtained. The properties of cluster series, such as the area, the related disasters, the related earthquakes and the distance between events, are compared with the energy and the magnitude of earthquakes, and good correspondences are acquired. It indicates that the cluster series of coal mine disasters and earthquakes are

linked with fatal earthquakes and may serve as footprints of stress disturbance in future.

The paper makes the most common speculations on a given geological model, on which five affecting cases are analyzed. The cluster feature of coal mine disasters as well as its coincidence with natural earthquakes suggests widely scientific significance to earthquake research and coal mine disaster prevention:

(1) Coal mines now make the independent mining plans. All the measures are taken on the individual production. To manage stress disturbance over large areas, a comprehensive mining scheme is required.
(2) Information-sharing among coal mines and earthquake fields may be a feasible way to control or predict some stress disturbances. Information regarding earthquake activity, the mining schedule of each mine, and latest disasters can be used as precursors to predict cluster series.
(3) Taking advantage of the mechanism of stress disturbance causing disasters, a promising mutual prediction may come into being, in which cluster series may work as the stress window for the neighboring seismic belts and earthquakes of seismic belts may become "weatherglass" of coal mine disasters.

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