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Evaluation of seismic potential in a longwall mine with massive sandstone roof under deep overburden

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Abstract

A recent seismic event was recorded by a deep longwall mine in Virginia at 3.7 ML on the local magnitude scale and 3.4 MMS by the United States Geological Survey (USGS) in 2016. Further investigations by the National Institute for Occupational Safety and Health (NIOSH) and Coronado Coal researchers have shown that this event was associated with geological features that have also been associated with other, similar seismic events in Virginia. Detailed mapping and geological exploration in the mining area has made it possible to forecast possible locations for future seismic activity. In order to use the geology as a forecaster of mining-induced seismic events and their energy potential, two primary components are needed. The first component is a long history of recorded seismic events with accurately plotted locations. The second component is a high density of geologic data within the mining area. In this case, 181 events of 1.0 M_L or greater were recorded by the mine's seismic network between January, 2009, and October, 2016. Within the mining area, 897 geophysical logs, 224 core holes, and 1031 fiberscope holes were examined by mine geologists. From this information, it was found that overburden thickness, sandstone thickness, and sandstone quality contributed greatly to seismic locations. After the data was analyzed, a pattern became apparent indicating that the majority of seismic events occurred under specific conditions. Three forecast maps were created based on geology of previous seismic locations. The forecast maps have shown an accuracy of within 74%–89% when compared to the recorded 181 events that were 1.0M_L or greater when considering three major geological criteria of overburden thickness of 579.12 mor greater, 6.096–12.192 m of sandstone within 15.24 m of the Pocahontas number 3 seam, and a longwall caving height of 4.572 m or less.

Keywords

Seismic; Mapping; Deep overburden; Massive sandstone

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

1. Introduction

In the United States, the tracking of mining-related seismic events has been growing significantly in recent years, especially after the Crandall Canyon Mine collapse in 2007 that resulted in 9 fatalities. This event and other similar mine events have led to a substantial increase in funding by government agencies and mining companies in an effort to better understand the science behind these large seismic events. There is no doubt that seismic events have the potential to be hazardous to both mine worker safety and mine production. Unfortunately, in most cases, not enough information is known to establish a link between the seismic locations and the geological and mining parameters that drive them.

This paper describes a collaborative study by the National Institute for Occupational Safety and Health (PMRD) and Coronado Coal researchers into the history, challenges, and mapping of 181 seismic events that were 1.0 M_L or greater and were caused by massive sandstone beds in close proximity to the Pocahontas No. 3 coal seam at a deep longwall mine in southwestern Virginia. Mining-induced seismicity has a long history in coal mining and has been tracked since the 1920s in Europe [1]. Although many subsequent research efforts have been performed in various types of mining, much is not understood about mining-induced seismicity in U.S. coal mines.

Recently, large seismic events occurring in conjunction with mining activity are coming back into the public spotlight; some of these events have been large enough to have been felt on the surface in surrounding residential areas, causing concern. Generally, these events are large magnitude events of greater than 3.0 M_L. This was the case in July 2016 when a mining-induced event occurred at the longwall operation in southwestern Virginia. This event was measured at 3.7 M_L on the local magnitude scale by the seismic network at the mine and at 3.4 M_L on the moment magnitude scale by the United States Geological Survey (USGS). A few local residents felt the vibrations resulting from the event and reported it to local news stations and the USGS. Upon reviewing the lithology in the vicinity of this event and the other 180 events that were 1.0 M_L or greater that have occurred since 2009, the key similarities among these events became apparent.

2. Previous studies

A previous study conducted at the same mine in Virginia theorized that the geology and seismic activity are linked [2]. Another study mentioned that near-seam massive sandstones and overburden over 609.6 m could have been the major contributor to a large seismic event that occurred in February 2005 [3].

Two studies were carried out in 1989 and 2011 to investigate the seismicity induced by longwall mining at the same mine area in Virginia. Bollinger examined seismic activity with one geophone, so he was not able to triangulate the location of the source [2]. However, the researcher notes that seismic activity increased by a factor of seven when the longwall was in operation, and rock bursts and cavings of the strong sandstone beds in the immediate roof were the cause of seismic activity during longwall shutdowns. Warren used the mine seismic network to locate and study events based on the longwall location [4]. A significant observation noted by the researcher is that there are two distinct types of events that occurred during the longwall mining process. The first type is small gob-forming events at the longwall face that usually register in the negative range of the local magnitude scale. The second type is seismic events that occur in the roof strata overlaying the gob of the adjacent panel from the longwall face. These events are the largest type of seismic events encountered at the mine and have been recorded as large as a 4.3 M_L, which have caused injury to personnel and significant damage to mining operations.

3. Geographic and lithologic information

The longwall mine is located in Buchanan County, Virginia, and operates in the Pocahontas No. 3 seam within the Lower Pennsylvanian Series of the Pocahontas formation. The Pocahontas formation is approximately 213.36–274.32 m thick in the study area and consists of sandstone, sandy shales, shales, clysa, and coal. These rock intervals occur in what are known as cyclothems, which are sequences of cyclic depositional environments based on sea level [5].

The mine is in the Appalachian Plateau physiographic province; however, the faulted and folded Valley and Ridge province is in close proximity to the mining area to the south [5]. The mine is within the Virginia overthrust area, and the major fault within the mining area is the Keen Mountain fault, which is a strike-slip fault with compressional overthrusting [6]. The fault has caused a few mining difficulties in the past, and future mining should not be directly affected by the Keen Mountain fault. However, the fault has caused additional minor thrust faulting within the coal seam, and this condition has created thinning and thickening sequences of the seam, which negatively impacts local roof control. The coal seam averages approximately 1.8 m in thickness but can range anywhere between less than 0.6 m and greater than 3.048 m, depending on local geologic conditions.

The roof geology consists of various sequences of silty to sandy shales, sandstones, and coal. Shales usually make up the immediate roof followed by sandstone and then the Pocahontas No. 4 coal seam, which is on average 15.24 m above the top of the Pocahontas No. 3 seam. The immediate roof shales can range from 0 to 3 m of thickness; however, on rare occasions the thickness can exceed 6 m. The sandstones above the immediate roof shale are unnamed but have been referred to as Sandstone 1 (the first encountered sandstone above the Pocahontas No. 3 seam) and Sandstone 2 (the second sandstone unit encountered after small shale lenses above Sandstone 1 [5]. In limited areas, sandstone 1 is not present and is replaced by a larger interval of silty shale. The shale lens between Sandstone 1 and 2 that typically ranges 0.3–1.5 m can be absent, resulting in the two sandstones acting as one massive unit (Fig. 1).

The sandstone units are typically medium to massively bedded, and fine to medium grained with few micaceous streaks, sparse coal debris, shale streaks, and iron nodules (Fig. 2). Where these sandstones become massive, potential longwall caving issues may be present [5]. Axial and diametral compressive strengths of the sandstone averaged 174.76 and 132.05 MPa, respectively, and the maximum strength was 241.31 MPa for axial tests and 218.56 MPa for diametral tests.

4. Seismic activity

The combination of deep overburden in excess of 579.12 m and massive sandstone lithology creates conditions conducive to mining-induced seismic events. Seismic events of 3.4, 4.3, and 3.4 occurred in 2005, 2006, and 2007, respectively, which caused a fire propagated by a reversal of ventilation due to damaged stoppings. This prompted the mine to install a surface seismic monitoring network, consisting of seven stations, in January 2009. These stations are in a radial pattern around the active panels to provide the best magnitude and epicenter results, which are typically accurate within 91.44 m.

Significantly change the pillar stability factor, which, in turn, could affect the longwall-induced stresses in the sandstone. The original pillar design employed was 27.43 m × 39.62 m × 15.24 m centers in a 4-entry development, which yielded an analysis of longwall pillar stability (ALPS) factor of 0.54—less than ideal for an overburden of 701.04 m. The new pillar design was 15.24 m × 51.81 m × 15.24 m centers, which yielded an ALPS stability factor of 0.95—acceptable for the typical strong sandstones and shales in the immediate roof geology of the current mining area. Such a significant improvement in the pillar stability factor serves two purposes: (1) with patterned standing support in the #1 and #2 entries, the #2 entry stays open behind the longwall face on the tailgate side, enabling the mine to keep the tailgate on intake from start to finish; (2) with the 51.81-m-wide pillars remaining stable between panels, the overriding of stresses between panels is reduced, and the gateroad pillars serve to separate the individual panels [5]. Since the change of the global mine design in 2008 no events above 3.7 M_L have occurred, and mining operations have been unaffected by further seismic activity. Each station relays raw data to a central point above the mine where the data is stored on a computer. The computer relays the data via secured internet using satellite telemetry to the Virginia Tech Seismological Observatory (VTSO), where data can be automatically or manually analyzed if necessary. Since the seismic network became operational in January 2009, it has recorded 181 seismic events of magnitude 1.0 M_L or greater in addition to thousands of smaller events less than 1.0M_L (Fig. 3).

The seismic events from 2005 to 2007 prompted an extensive effort to collect geotechnical data by the mining company to identify hazardous mining areas and institute changes in the mine design. This geotechnical effort identified discrepancies in the global stability design and resulted in modifications to the pillar design and the reduction of the longwall panel width from 304.8 to 213.36 m wide, which improved the stability factor of the roof sandstones by 700% [5].

Because the original pillar widths were subcritical compared to the depth of cover present, changing the pillar design the mine typically has 5 or 6 longwall panels per district. After the 5th or 6th panel, a solid barrier measuring 3764.28 m × 91.44 m, on average, is left in place before the next district is started. Looking at the historical seismic data, it has become clear that the blocks of coal left between districts have a positive effect on reducing seismic activity. Only three of the recorded 181 seismic events occurred within the first longwall panel of a new district. The majority of the events occurred within the center three or four panels of the district under certain geological conditions, which is consistent with the traditional “square area” concept.

Mining hazard maps were created to combine four geologic criteria that showed geological variability that could affect longwall-induced stresses in the sandstone and abutment stresses in the gateroad pillars (Fig. 4). The geologic criteria in descending importance were overburden depth, longwall caving height, interval to sandstone above the Pocahontas No. 3 seam, Sandstone 1 thickness, and sandstone quality determined by fracturing. The caving height was calculated by a thorough and conservative geologic approach examining weaknesses in the strata, such as cracks, mica laminations, shale lenses, and coal streaks. The strata were examined by three methods: fiberscope, geophysical logs, and corehole information. Each geologic method searched for the first layer of weakness within 4.57 m of the immediate roof strata. If the weak layer of rock was below 4.57 m from the top of the roof, then it was considered poor caving because the amount of gob would not be enough to support the massive sandstone layers above [5].

In July of 2016, a magnitude 3.7 M_L seismic event occurred in roof strata above the gob adjacent to the active longwall panel. The event caused no damage to the mine but was strong enough to be felt by the miners underground and local residents on the surface. After reviewing the original hazard maps, it was clear that the event was thousands of meters away from the nearest hazard area previously defined. The hazard map was intended to highlight areas that could cause problems to mining operations at the longwall face rather than to track potentially seismic zones of interest. Only 8 of the total 181 events that occurred from 2009 through October 2016 were within the mining hazard map boundary.

5. Seismic mapping

It was evident after the July 2016 event that a seismic forecasting map would be invaluable to the mining operations to determine where and with what possible magnitude events could occur under different geological conditions. Many geological factors were examined. These factors were determined through observations from 1031 fiber scoped holes, 224 cored holes, and 897 interpreted electronic logs to find common themes centered on the seismic events (Fig. 5). After much consideration, three factors stood out amongst all the data related to seismic events 1.0 ML or greater. Overburden, the amount of sandstone within 15.24 m of the top of the Pocahontas No. 3 seam, and caving height was common themes surrounding almost every event. The lithology information could be modeled and mapped using minescape geological mapping software. Minescape deploys an interpolator known as finite element method (FEM) and is based on a series of gridded triangles to forecast the probability and magnitude of an event if a particular panel was mined.

As found in the previous work, overburden depth was found to be the strongest correlating factor in determining possible seismically active locations [5]. Over the history of the total 181 events that were 1.0 M_L or greater since July 2016, only 47 (26%) occurred under overburdens of less than 579.12 m. If the 91.44-m accuracy of the seismic array is taken into account, then up to 89% of seismic events 1.0 M_L or greater have occurred under overburden depths of 579.12 m or greater. The seismic network provides an accuracy within 100 m if the event provides a good signal to multiple towers on the surface. If the events that are within 50 m of the 579.12-m overburden contour are considered, then only 19 of the 181 events are outside the 579.12-m contour. Under less than 579.12 m, the seismic events seem to follow a more random pattern and could not be logically correlated to mining or geologic parameters. When all events are considered, the first criterion for creating a seismic forecast map based on global stability is the 579.12-m-and-above overburden contours. The 579.12-m-and-above overburden contour map represents the first stage of the possibility of forecasting a seismic event 1.0 M_L or greater, but additional factors are needed to understand where larger events could take place (Fig. 6).

The second factor to determine an increased likelihood of seismic potential based on previous case histories is the thickness of sandstone 15.24 m above the Pocahontas No. 3 seam. The previous mining hazard map only covered the Sandstone 1 thickness and not the Sandstone 2. During the research of the events, it became evident that there was very little correlation between the Sandstone 1 thickness and the recorded events. However, if the Sandstone 1 and Sandstone 2 were viewed as one unit, the thickness within the first 15.24 m provided a strong correlation with the location of seismic events 1.0 M_L or greater. A total sandstone thickness of 6.09–12.19 m within the first 15.24 m of roof, in particular, provided the strongest correlation because, if the total sandstone thickness was greater than 12.91 m, it would be too strong to break and would bridge across the longwall panel. In contrast, any sandstones that were less than 6.09 m thick should readily break behind the face support to form gob and provide a cushion to support any massive sandstones higher than 15.24 m in the roof, thus preventing a seismic event. When sandstone thicknesses of 6.09–12.19 m were combined with an overburden of 579.12 m or greater, the mapping resulted in a 72% accuracy (46 of 64 events) of forecasting larger seismic events in the range of 1.5 M_L or greater. The forecasting accuracy could be as high as 85% when taking into account the 100-m accuracy of the seismic network. The combination of 6.09–12.19 m of sandstone thickness with 579.12 m or above of overburden represents a moderate potential for seismic activity (see Fig. 6).

The third factor is 4.57 m or less of caving height in the gob, which was adopted from previous work [5]. Due to a bulking factor of approximately 50%, a caving height of 4.57 m or greater should cushion the massive sandstones above and prevent seismic events. However, if the caving is less than 4.57 m, the void in the gob will contribute to a more likely scenario for a possible event. Caving height also provides an indirect measurement for sandstone cavability. If a sandstone is highly laminated, then it is more likely to cave than a massive sandstone. This provides a way to differentiate poor quality sandstones from massive sandstones identified in the second factor.

When the three criteria were combined, a seismic potential map (Fig. 6) was created to show the greatest probability of a large seismic event. Elevated potential of seismic activity is shown in brown. The areas of elevated seismic hazard include those areas in which all events with magnitudes of 3.0 M_L or greater occurred since the installation of the seismic network in 2009 (two total), and the seismic events of magnitude 3.4 M_L or greater that occurred at the longwall face in 2005, 2006, and 2007. The elevated potential areas correctly forecasted all five 3.0 M_L and greater events that have occurred since 2005.

The subsequent hazard map was created by overlaying the three identified critical geologic criteria on a single map (Fig. 6). This map may then be used to forecast areas of elevated seismic potential. If the area is only blue, then overburden depth is the only identified risk factor present. Yellow indicates that the overburden is 579.12 m or more, and it also has 6.09–12.19 m of total sandstone thickness within the first 15.24 m of mine roof. The areas that are brown meet all three risk criteria—overburden, critical sandstone thickness, and caving height of 4.57 m or less—and represent the areas that have the highest potential for a large seismic event of 3.0 M_L or greater (Fig. 6).

6. Conclusions

The forecast map of elevated seismic potential that was created from the geologic data and seismic history will continue to be reviewed and updated with respect to new seismic events. The current hazard map successfully forecasted high-risk areas with an accuracy of 74%–89%. This accuracy is based on analysis of 181 recorded events that were of magnitude 1.0 M_L or greater, overburden depths 579.12 m or greater, and using the current 91.44 mepicenter accuracy of the 7-station surface array. Accuracy of 72–85% was achieved for moderate seismic potential areas with seismic events of magnitude 1.5 M_L or greater. In the areas that have a high potential for seismic events of magnitude 3.0 M_L or greater, 100% accuracy was achieved; however, this accuracy used a small sample set of only five events. Additional monitoring sites are needed underground to provide better resolution for the hypocenter location for maintaining vertical control of the data. Currently, NIOSH and the Virginia Tech Seismological Observatory (VTSO) are working together to see if underground geophones can be tied into the existing surface system.

With the ability to realistically forecast large seismic events, mine management at the Virginia location was able to establish and effectively deploys a seismic mitigation plan to safeguard miner safety and health. The seismic mitigation plan uses the seismic forecast map to inform management and miners where the potential for significant seismic activity could take place. When mining into these forecasted high-risk areas, mine management will hold safety briefings to the crews to discuss ventilation and reporting procedures that must be taken in case an event of magnitude 3.0 M_L or greater occurs. Any event has the potential to cause injury or ignition, but large-scale magnitude events are particularly likely to cause global failures that will impede ventilation and escapeways. The seismic forecast map allows the mine to make informed decisions regarding future mine plans, if necessary, to maximize safety and production many years into the future.

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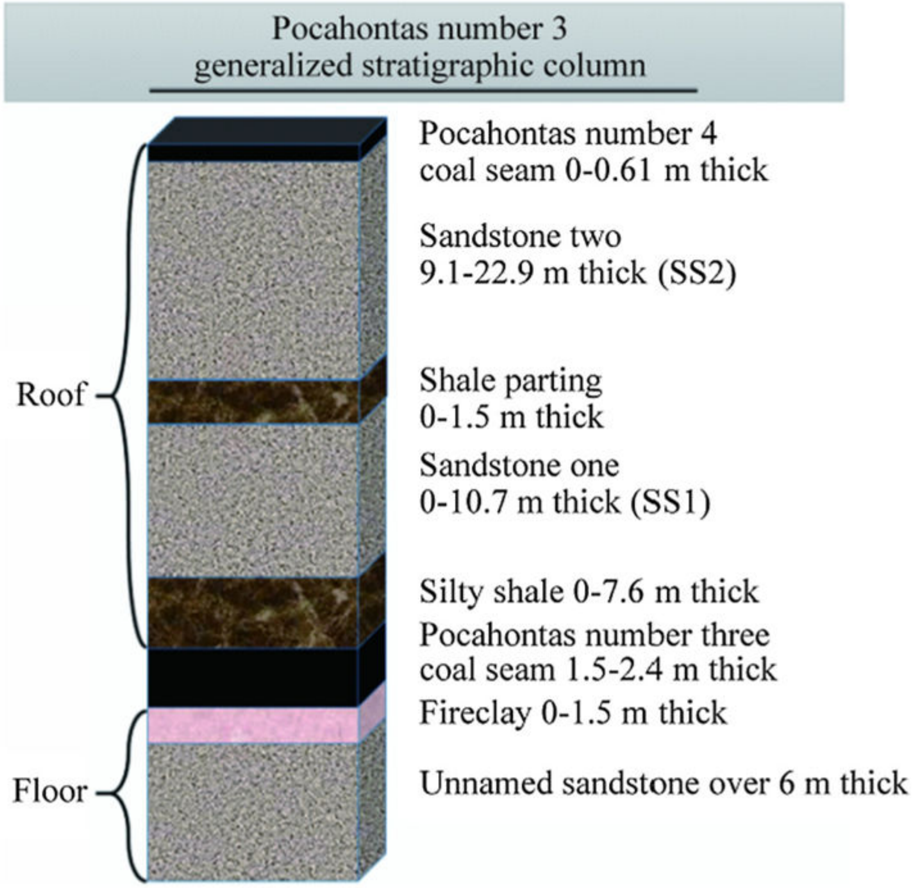

Fig. 1.
Generalized stratigraphic column.

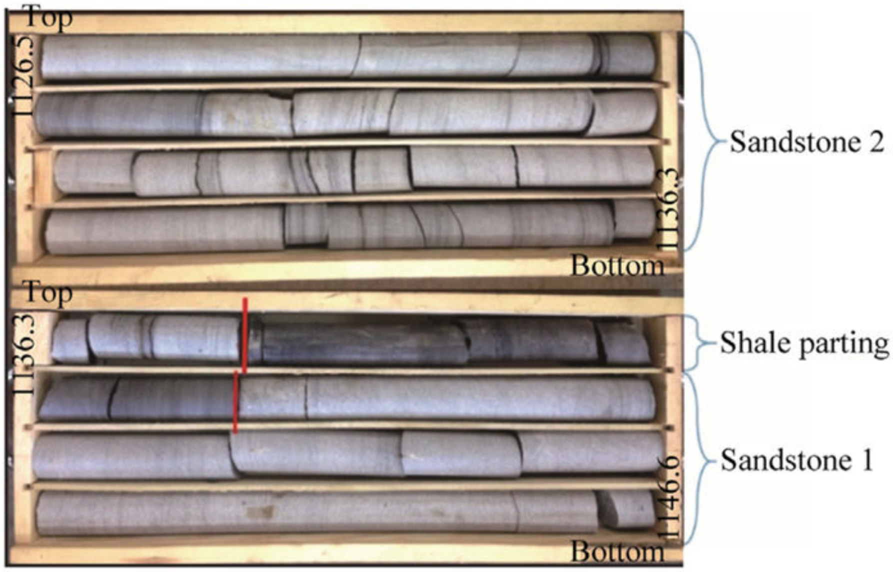

Fig. 2.
Core from Sandstone 1, shale parting, and sandstone.

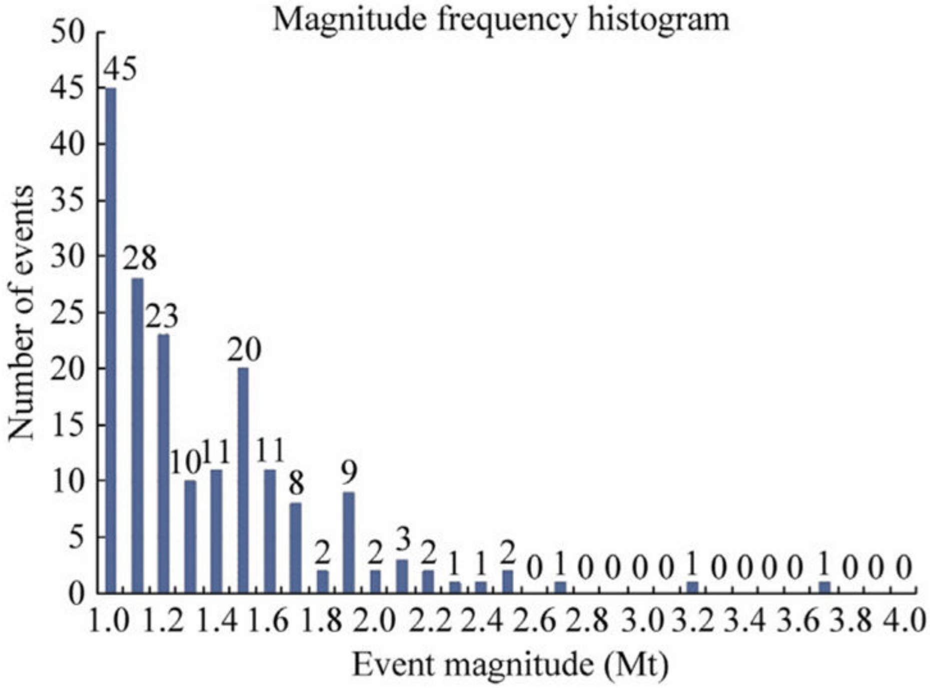

Fig. 3.
Magnitude frequency histogram.

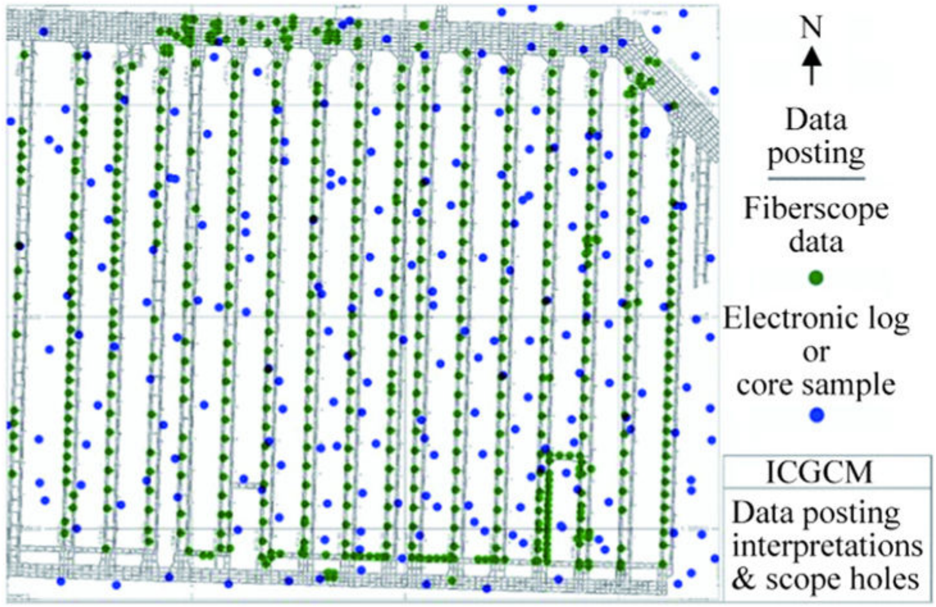

Fig. 4.
Geological data points.

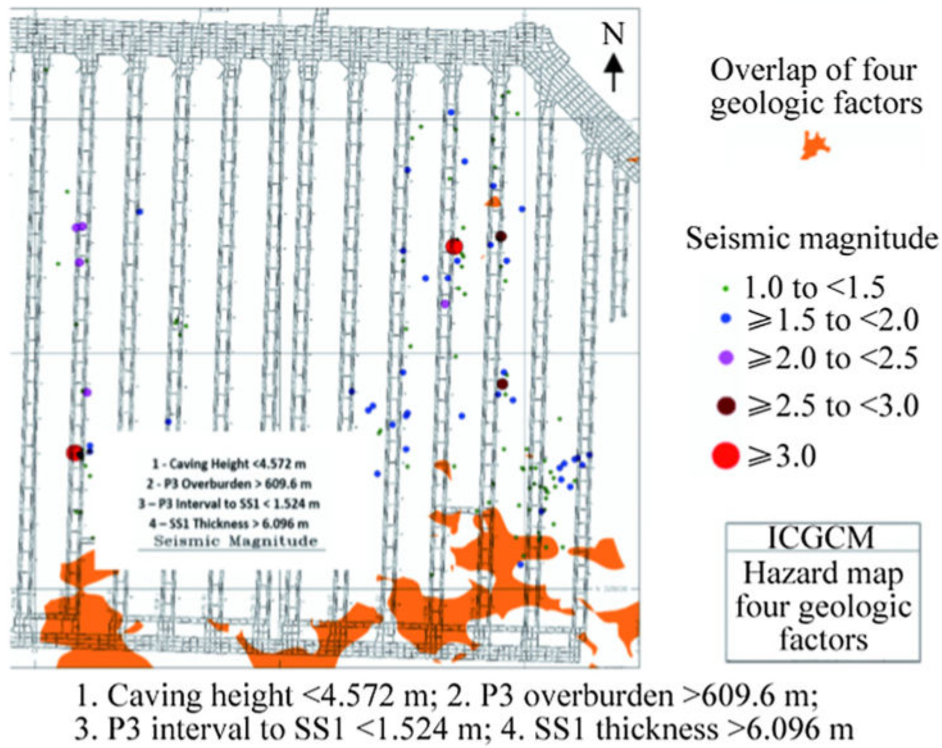

Fig. 5.
Mining hazard map.

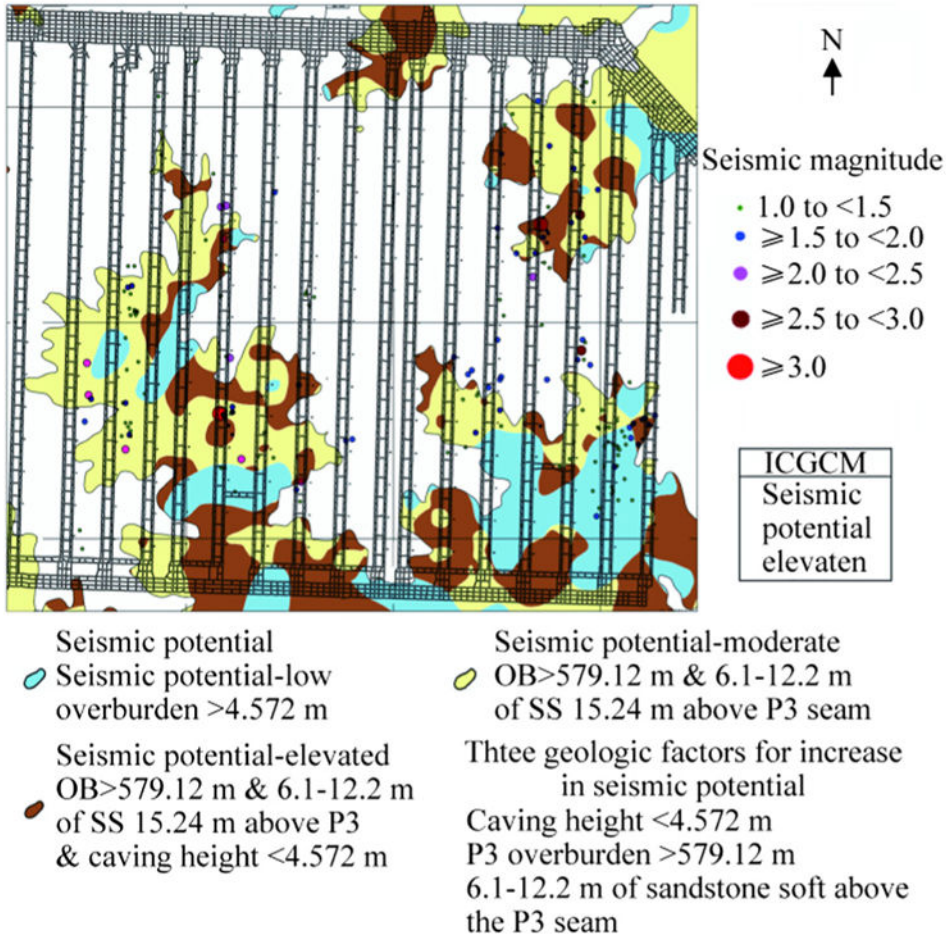

Fig. 6.
Seismic potential map.