# Safer mine layouts for underground stone mines subjected to excessive levels of horizontal stress

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## Abstract

***Excessive levels of horizontal stresses cause ground-fall hazards in underground mines in the Appalachian Basin. At an underground stone mine in Pennsylvania, a modified stress-control mine layout is reducing the hazardous conditions associated with excessive horizontal stresses. A microseismic monitoring system is in place to measure levels of rock stability and provide information on the effectiveness of the design technique. The microseismic data is supplemented with frequent and extensive mapping of roof falls and roof rock damage. Findings to date show that the stress-control layout provides more stable conditions, resulting in a safer environment for the mine workers.***


## Introduction

The U.S. National Institute for Occupational Safety and Health (NIOSH) continues to study the impact of different mine layouts to control the damaging effect' and resultant hazardous conditions of horizontal stress in underground stone mines, Successful stable mine designs need to be identified and communicated to the underground stone industry, so that safer working conditions for miners can be achieved. As underground stone production increases, so will the need to develop and use safe mine layouts to minimize hazardous ground conditions. Excessive levels of horizontal stress are present in many parts of the earth's crust and have often been produced by tectonic plates pushing towards one another. Residual stresses from these events have been retained in rock, even at low overburden (Bickel, 1993).

The study was conducted at an underground stone mine in southwestern Pennsylvania. There, excessive levels of horizontal stress were known to exist and such stresses have been observed to cause roof falls. At this mine site a traditional room-and-pillar and a new stress-control layout were in use. The ability of these two mine layouts to control ground was accomplished by mapping roof falls and roof damage areas and by monitoring seismic activity with a 12-channel microseismic system.

## How can horizontal stress affect roof stability?

At the mine, the measured N60°E horizontal stress field (Iannacchione et al., 1998) matched reasonably well with the regional east-northeast stress field found in other mines within this region (Fig. 1). Additionally, maximum values of horizontal stresses ranged from about 10 to 35 MPa (1,400 to 5,000 psi), with an average of about 25 MPa (3,600 psi). This range in values of horizontal stress is 10 times greater than the stress produced from the overburden weight in this part of the mine.

The effects of excessive levels of horizontal stress on roof rock stability have been discussed by several researchers (Emery 1964; Parker, 1966; Parker, 1973; Gale 1986; Mark and Mucho, 1994; Mucho and Mark, 1994; Iannacchione et al., 1998). Mining perpendicular to the orientation of the maximum levels of horizontal stress can concentrate that stress in the immediate roof rock. When stress levels exceed the strength of the roof rock, beams within the roof can buckle and fail in shear (Fig. 2). Traces of failure planes often appear as low-angle shears approximately $15^0$ from horizontal and oriented perpendicular to the direction of the maximum levels of horizontal stress.

In some mining situations, the shear planes can occur with enough frequency to coalesce, forming a semilinear trend tens-to-hundreds of meters in length across a mining section. Major shear zones can result in large roof falls that are often oval in shape, with the long axis perpendicular to the orientation of the maximum levels of horizontal stress (Fig. 3). Typically, these falls show stress concentrations along the axial ends of the oval, oriented perpendicular to the maximum stress direction (Fig. 3). Elevated stress levels are also found in the solid rock above the caved area. It is not uncommon for this oval-shaped type of fall to grow vertically and horizontally over the course of days, weeks and even years, depending on conditions.

Another recognized characteristic of a roof fall caused by horizontal stress is the zone of reduced stress adjacent to the long axis of an oval-shaped roof fall. These areas of stress reduction are commonly referred to as stress shadows (Fig. 3). The directional nature of the roof falls and adjacent stress shadow zones provide essential information for determining layouts aimed at reducing this type of ground fall hazard. The potential for additional roof instability is highest when mining perpendicular to the direction of maximum horizontal stress and lowest when mining either parallel to the direction of maximum horizontal stress or ill the stress shadow areas adjacent to the long axis of a roof fall.

**FIGURE 1**

**Measured horizontal-stress conditions in mines in western Pennsylvania, eastern Ohio and northern West Virginia (Mark and Mucho, 1994; lannacchione el al., 1998).**

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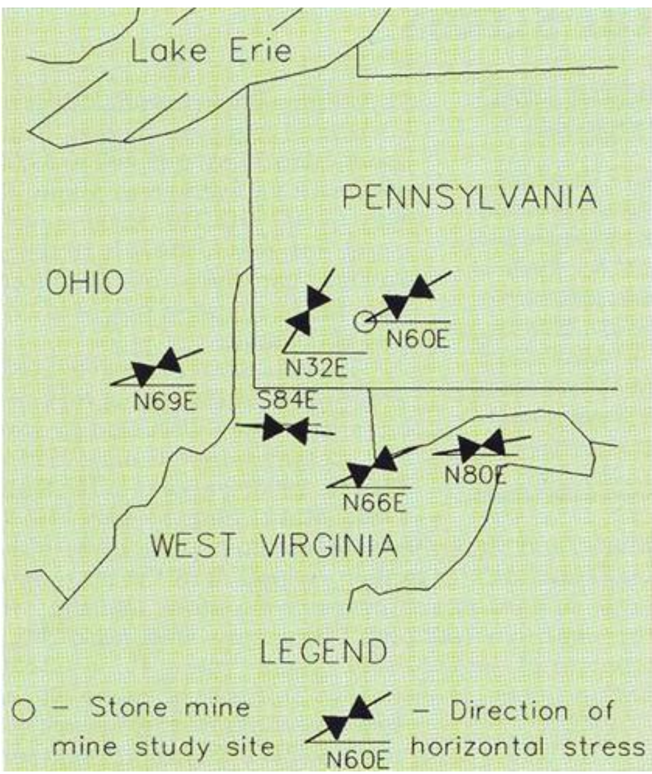
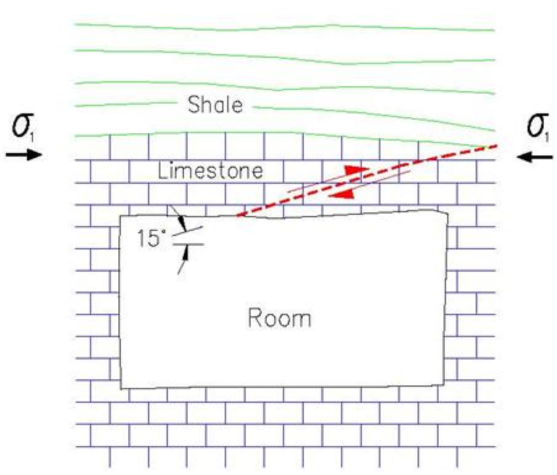



**FIGURE 2**

**Low-angle shear failure in limestone roof beam caused by excessive levels of horizontal stress.**




### Identifying stress-related damage

Large, directional roof falls that are often oval in shape typically indicate excessive levels of horizontal stress. Horizontal stress also causes roof falls of lesser magnitude. Mapping falls in relation to the direction of mining provides some of the information necessary to determine if a series of fails were induced by horizontal stress,

Figure 4 demonstrates how a progression of roof falls can occur as mining advances. Roof falls associated with excessive horizontal stress typically occur as mining advances into virgin rock perpendicular to the orientation of maximum stress. Once the fall occurs, stress is temporarily relieved. The process is illustrated in fig. 4. During mining in Area 1, a fall occurs after mining advanced to the east in the direction perpendicular to the stress field. As mining advances to the south towards Area 2, the stress relief or shadow from the fall in Area 1 provides temporary stability. Then, a mining continues southward, the stress levels again build or concentrate until relieved by Fall 2. The pattern is repeated in Areas 3 and 4.

NIOSH personnel have observed this pattern or progression of falls at a number of mines. With this knowledge, decisions on changing mine layouts can be made to minimize the instabilities induced by horizontal stress. Conversely, without this information, it is often difficult to recognize a pattern because damaged roof zones appear to occur in a random fashion across a mining section.

### How can mine layouts control stress-related damage?

One potentially safer way to room-and-pillar mine in a directional stress field is to advance a greater percentage of faces parallel to the direction of maximum horizontal stress, while minimizing the percentage of faces driven perpendicular to this direction (Fig. 5). In a stress-control layout, headings are oriented in a more favorable direction while crosscuts are in the less favorable direction.

Mining in this fashion should help to lessen the overall amount of roof rock damage by:

- Maximizing the number of headings driven parallel to the direction of maximum horizontal stress. The roof rocks in these headings have lower stress levels.
- Lessening the number of crosscut driven perpendicular to the stress field minimizes the amount of mining where stress levels are the greatest.
- Driving the crosscut faces only into an existing heading. This reduces the potential for high stress concentrations in those faces.
- Offsetting crosscuts to create only three-way intersections. This is helpful in that if failures develop, the roof falls developing perpendicular to the maximum stress direction will quickly encounter the barrier formed by the rib of an adjacent pillar.

- Maintaining a wedge-shaped mining front parallel to the direction of maximum horizontal stress. This will help to evenly distribute the stress concentrations along the entire mining front.

### How can a mine layout be evaluated for safety and effectiveness?

As discussed, the orientation and spacing of headings and crosscuts will affect the stability of the roof rock when excessive levels of horizontal stress are encountered. It is critical to use the layouts that provide the safest working conditions for miners in the underground stone industry. Unfortunately, there are currently no widely accepted guidelines available for evaluating mine layouts in these conditions.

Methods to evaluate safe mine layouts consist of the following two categories: observational or qualitative and measurement or quantitative. Observational technique' consist of mapping roof rock instabilities through time. Measurement methods consist of assessing characteristics that are indicative of rock failure. These characteristics could include stress changes, rock deformations and/or microseismic or acoustic emissions.

In this study, observation and measurement techniques were used to evaluate the effectiveness of two different mine layouts subjected to excessive levels of horizontal stress. The observational technique used consisted of mapping stress-related failures and roof fall at regular intervals (usually every two weeks) and placing this information on working mine maps. The measurement technique consisted of monitoring the quantity of seismic emissions emanating from the mine as faces were advanced. It is known that as rock fails in tension or shear, it emits audible sounds. In 1975, Hardy examined this concept when he stated, "In geologic materials, the origin of acoustic emissions/ microseismic activity is not well understood, but it appears to be related to processes of deformation and failure, which are accompanied by a sudden release of strain energy." Microseismic monitoring systems can be designed and placed in such a way as to locate the source of energy release associated with roof failure

**FIGURE 3**

**Probable stress redistribution patterns around oval-shaped roof falls, concentrating stress above and along the axial ends and reducing stress (stress shadow) adjacent to the long axis of the rooffall.**

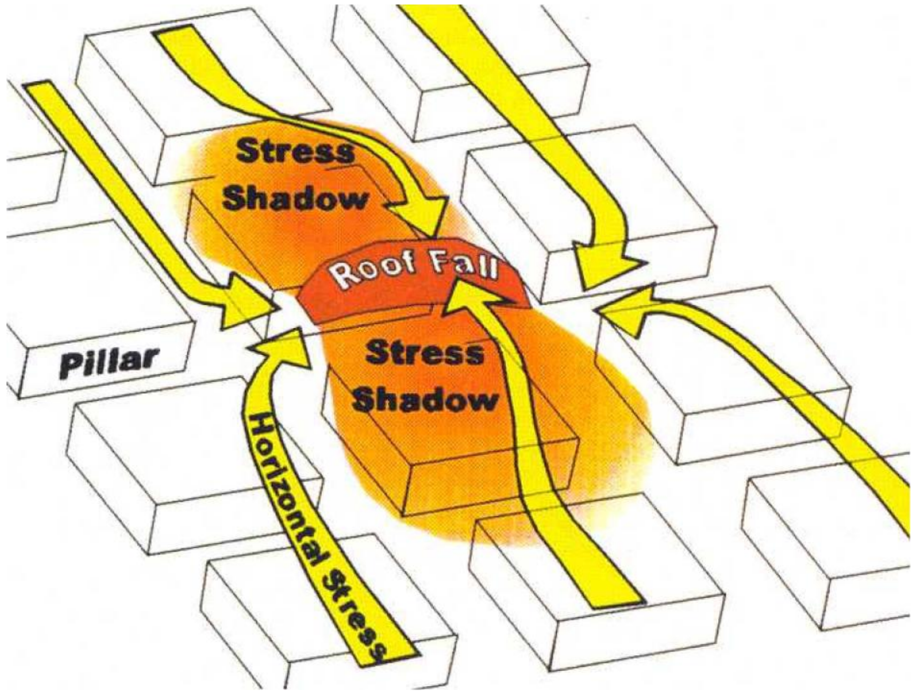
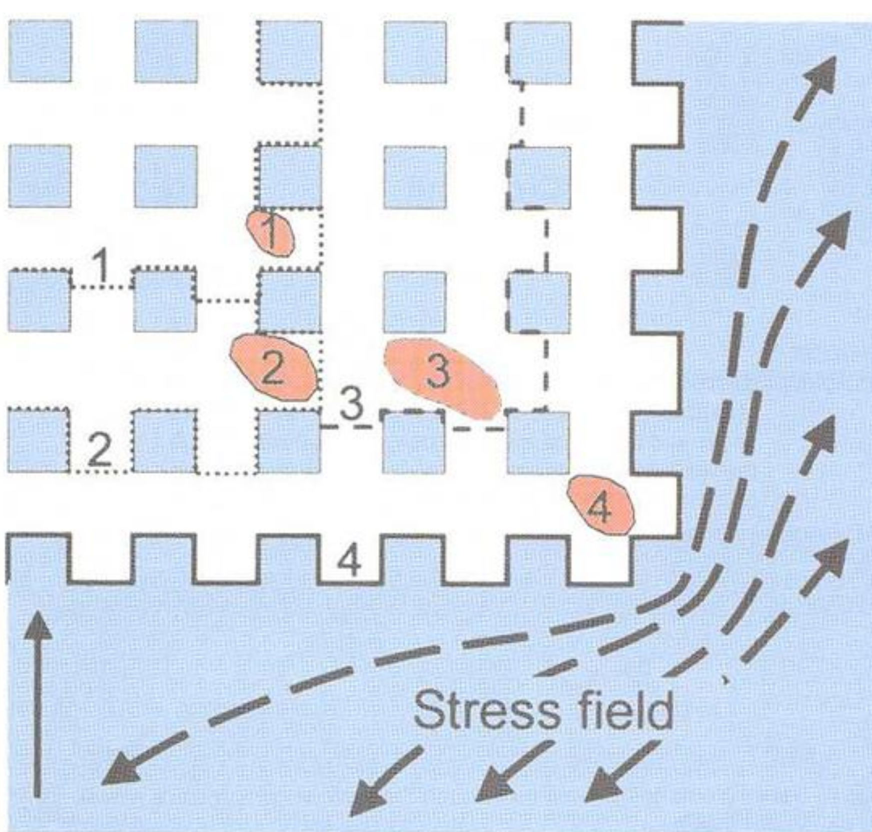



**FIGURE 4**

**The likely location of successive roof failures at four face positions during room-and-pillar mining in a directional stress field.**



(Fig. 6). With this tool, the relative quantity of roof damage can be assessed continuously as mining progresses.

## Working hypothesis

This study evaluated pillar design and room orientation as a tool to reduce the hazardous effects of excessive horizontal stress conditions in underground stone mines. The study is based on the following working hypothesis:

Roof strata subjected to excessive levels of horizontal stress often fail in shear and tension. This failure is often of high enough intensity to produce seismic energy (acoustic emissions) that can be recorded by a properly tuned microseismic system. If two different mine layouts are used in similar geologic and overburden conditions, the layout that concentrates less stress around working faces will produce less rock failure and. hence, less microseismic activity. Therefore, the layout with significantly fewer roof falls and less microseismic activity should, in general, invite less roof-strata damage and less loose rock that could potentially injure miners.

**FIGURE 5**

**Mine layout with a high percentage of rooms driven parallel to the maximum stress direction this layout should lessen overall roof damage. Staggered crosscuts reduce the potential for running roof falls.**

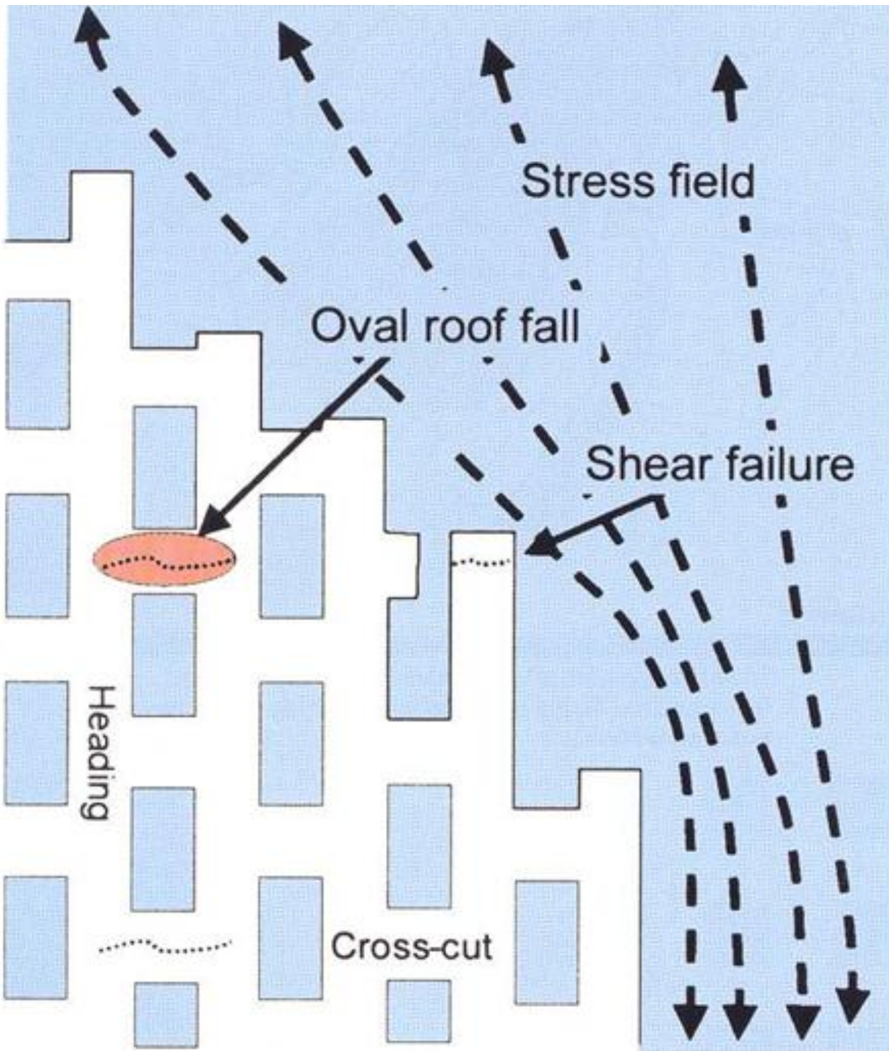
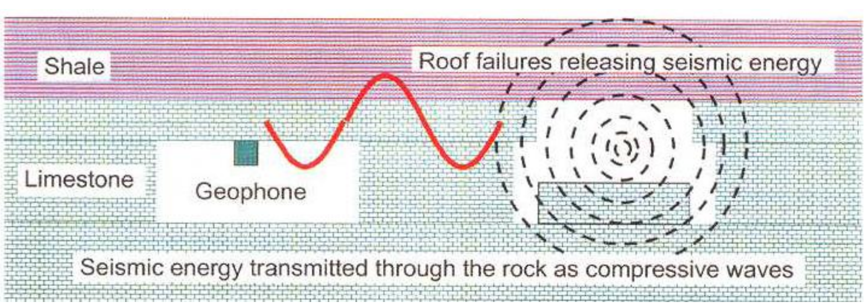



**FIGURE 6**

**Idealized example of how strain energy is released by shear and tensional rock failures, transmitted through the rock as a compressive wave and captured by a microseismic system's geophone.**




## Test mine site conditions

The southwestern Pennsylvania study mine site produces crushed stone from the Loyalhanna (limestone) Formation. Roof falls found at this mine fit the characteristics of those caused by excessive levels of horizontal stress as discussed previously. Roof instabilities typically start with the development of compression zones. These zones consist of low-angle shears oriented approximately 30°W. When roof falls occur, many of them are oval in shape, with the long axis oriented approximately N30°W. In the northeastern section of the mine, these roof falls follow this same northwesterly direction (Fig. 7). All of these failure patterns indicate a strong horizontal stress field oriented at approximately N60°E. Additionally, hydrofracturing tests at tile site measured the maximum stress direction to be 60°E to N75°E (Iannacchione et al., 1998).

In February 1998, mine management initiated a new mine layout to lessen the degree and frequency of roof instabilities at the mine site. This stress-control mine layout was designed to advance the majority of the faces parallel to the maximum horizontal stress direction in the northeast section of the mine (Fig. 7). Two lead headings were driven N60°E in advance of the other headings to the left and right Crosscuts were generally driven N30°W or S30°E only after the adjacent 60°E headings had been advanced past the breakthrough point. Only three-way intersections were used, so that the crosscuts were offset. Pillars were rectangular in shape with the long axis oriented N60°E. Pillars, 27.4 m (90 ft) long, were designed to provide a solid, continuous rib to hinder propagation of the directional failures in the 30°W direction.

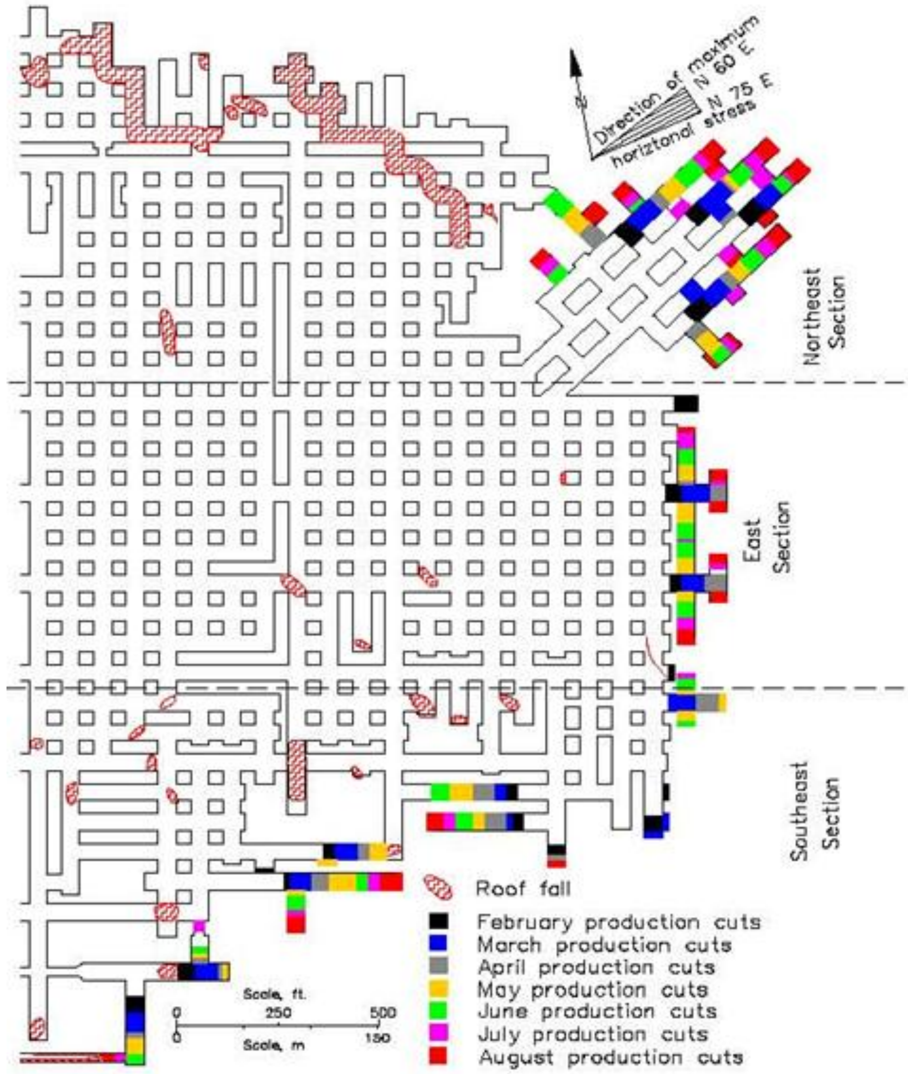
Along the east section of the mine, two north-south trending headings were driven to outline a row of ventilation barriers and to prepare set-up entries for turning all headings in the N60°E direction. While the east section used a mining plan similar to that used in the southeast section, it lacked sufficient crosscut development to be considered as similar to the southeast layout.

In the southeast section of the mine, mine management decided to continue with the traditional room-and-pillar mine layout until the east and south mining fronts could be straightened to facilitate the turning of the entries in that part of the mine. Rooms were driven 10°E and N50°W on 24.4-m (50-ft) centers outlining 10.7-m (35-ft) square pillars. The decision to continue with the traditional mine layout in an area close to the new stress control mine layout provided a good opportunity to compare the two designs.

NIOSH installed a microseismic system during the winter or 1999-2000 and began monitoring microseismic activity on Feb. 9, 2000. The locations of the faces that were mined from February 2000 until August 2000 are shown in Fig. 7. The microseismic system consisted of data-acquisition devices, filtering and analysis equipment, 12 geophone sites located throughout the area of interest, and cables connecting the geophones to the instrument trailer.

**FIGURE 7**

**Mine layout at the start of the field study on Feb. 9, 2000, and the location of roof falls that occurred during the study. Also shown are the direction of the maximum horizontal stress and the faces mined during the study.**




### Roof falls and microseismic activity

During the study period, four significant roof falls occurred. Three of them occurred in the southeast section, one each during February, March and May. The fourth fall occurred in the southeast corner of the east section during June-July (Fig. 8). The northeast section did not have any roar falls and experienced only minor instabilities in the immediate roof.

During this same period, the microseismic system recorded approximately 1,443 events, after data associated with blasting, electrical surges or mining activity such as Ian, equipment and drill vibrations were filtered out. A more complete analysis of all the microseismic activity is planned and may help to further determine how stresses interact with mining to cause roof rock failure.

While the location and magnitude of any individual event can have some degree of error associated with it, the accumulated data can and do show significant trends. Of the 1,443 events, 1,302 were located within one of the three sections shown in Fig. K. Of these, 194 (15%) occurred in the northeast section, 275 (17%) occurred in the east section and 833 (64%) occurred in the southeast section. Much of the activity in the southeast section is clustered around the three (February, March and May) roof falls. However, significant activity also occurred in a wide band extending from behind to well in front of the working faces. Microseismic activity in the east section was largely evident along the eastern mining front, with much of it clustered around the June-July roof fall in the southeast corner. The northeast section was characterized by little microseismic activity, with a weak clustering in the unmined limestone between the new and traditional mine layouts.

Another (actor to consider in conjunction. with microseismic activity is mining face advancement, referred to in this paper as the activity rate. At this mine, most microseismic activity was associated with excessive stress levels that induced rock deformation and failure. Increases in rock deformation and failure were, in turn, caused by advances in mining. Therefore, normalizing microseismic activity to face production provides one way of testing part of this study's hypothesis - "the layout that concentrates less stress around working faces will produce less rock failure and hence. less microseismic activity." During the study period, 138 faces were blasted in the northeast section, 71 in the east section and 130 in the southeast section (Fig. 7). The activity rates for each month during the study period and corresponding to each section in the study area are shown in Fig. 9. In general, the activity rate for the southeast section is highest, followed by the cast section. Additionally, the months of February, June, July and August show the highest activity rates for the southeast section. Except for August, these are the months when roof falls were occurring in the east and southeast section.

The activity rate from the northeast section averaged 1.32 microseismic events per production blast, with a standard deviation of 0.68. In the east section, the activity rate had an average of 3.94 with a standard deviation of 3.21, while the southeast section had an average of 7.67 with a standard deviation of 4.57. Clearly, the roof fall and microseismic data show that the amount of roof rock instabilities in the new stress control layout was significantly lower than that in the traditional room-and-pillar layout. Because of the significantly lower seismicity and observed roof falls, the authors believe that the working hypotheses are validated - this stress control mine layout produced significantly fewer roof Calls and less microseismic activity and, in general, less roof strata damage. Less failed rock reduces the potential for falls of ground and, therefore, makes for a safer working environment for the miners.

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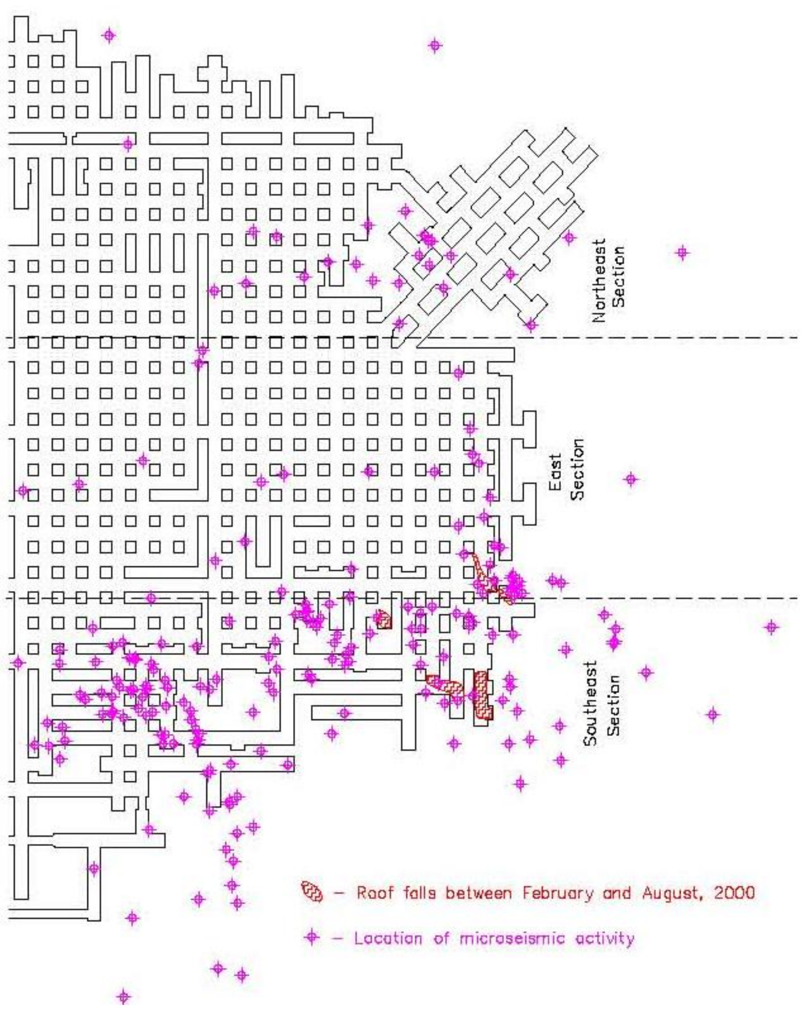
**FIGURE 8**

**Locations of 1,302 microseismic events recorded from Feb. 9 through Aug. 31, 2000, and contained within the northeast, east and southeast sections.**




## Summary and conclusions

Observational methods in the form of roof-rock damage mapping were conducted during the mining of both a stress control and a traditional room-and-pillar layout. During the study period, (our roof falls were observed. All of them occurred within the east and southeast sections, where the traditional room-and-pillar layout was used. Additionally, both the frequency and rate of microseismic activity were much less in the stress-control layout than in the traditional room-and-pillar layout. The stress-control layout that was successfully demonstrated in this study has the following attributes:

• It increases the total proportion of headings driven in the favorable direction with lower stress levels.
• It lessens the total proportion of crosscuts driven in the less-favorable direction with elevated stress levels.
• It drives crosscuts generally *into* an existing heading .
• It offsets crosscuts to create more stable, three-way intersections • It reduces the potential for running roof falls by offsetting crosscuts in the less favorable direction .
• It maintains a wedge-shaped mining front parallel to the maximum horizontal stress field.

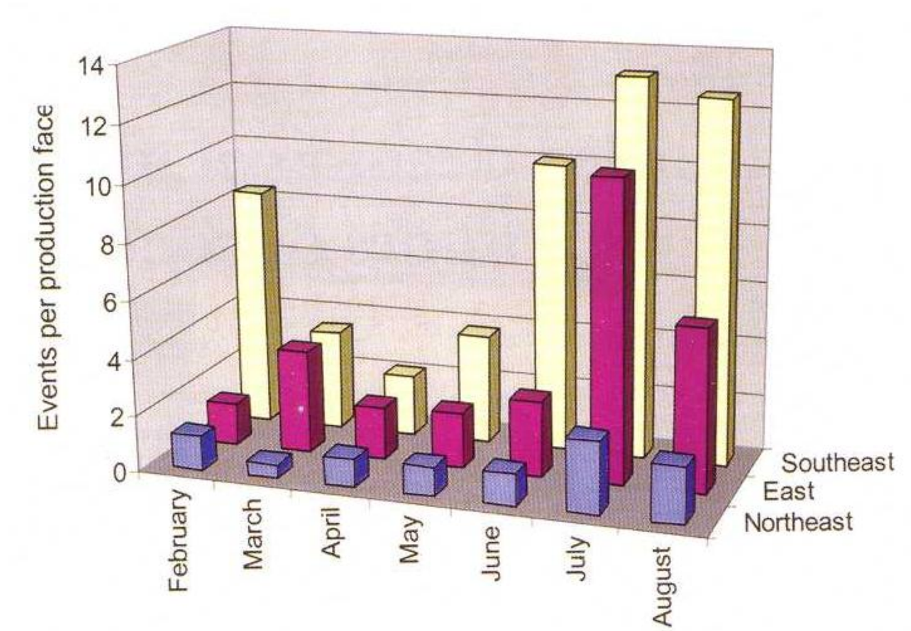
All of these attributes help to lessen horizontal stress concentrations in the root and reduce the potential for roof rock failures.

This NIOSH field study has shown that there is less observable roof failure, and microseismic activity from the northeastern stress-control layout than from the eastern or southeastern traditional room-and-pillar layout. The amount or mining from the northeastern portion of the mine in this study was at least equivalent to the production from the eastern and southeastern portions of the mine.

Therefore, the observations and measurements support the working hypothesis that the stress-control design employed here does not damage the roof rock as much as the traditional room-and-pillar design. It then follows that it is a safer design from the standpoint of reducing falls of ground. The stress-control layout should have 'widespread application for protecting underground stone miners where excessive levels of horizontal stress exist. •

**FIGURE 9**

**Histogram showing the microseismic activity rates for the three mining sections.**

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