



Controlling Crosscut Damage in Response to Excessive Levels of Horizontal Stress: Case Study at the Subtropolis Mine, Petersburg, OH

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Abstract

The Subtropolis Mine is a room-and-pillar mine extracting the Vanport limestone near Petersburg, Ohio, at a depth of approximately 59.4 m (190 ft). In February of 2018, mine management began implementing a new layout to better control the negative effects of excessive levels of horizontal stress. Almost immediately, the conditions in the headings improved. Conversely, and as expected, stress-related damage concentrated within crosscuts. Over the last 18 months, the mine operator has diligently experimented with different techniques/methods to lessen the impact of the instabilities in the outby crosscuts. The range of controls used by the mine operator include angled crosscuts, crosscut offsets, increase distance between crosscuts, arched crosscuts, cable bolted crosscuts, altered blasting pattern, and windows. A window is used to resist roof deformation by leaving a strong brow of roof rock within the crosscuts. A window reduces the crosscut dimensions vertically and, in some applications, horizontally. With each application of engineering controls, conditions were monitored and analyzed using observational and measurement techniques. In every case, the advantages in ground conditions were weighed against its impacts to haulage, ventilation, and other mining considerations. This paper examines how each engineering control was implemented and assessed. All these controls are based on well-established geomechanics principles, but experience has shown that local modifications are needed to deal with the unique local conditions such as geology, mining method, mine equipment, and in situ stress conditions.

Keywords Ground control · Limestone · Horizontal stress · Stress control layout · Crosscut · Windows

1 Introduction

The Subtropolis Mine has experienced significant ground control issues related to excessive levels of horizontal stress. These experiences are evident when examining the current mine map showing numerous layout changes implemented to minimize hazardous conditions (Fig. 1). Evidence of excessive levels of horizontal stress includes:

- Chevron fractures and half-moon concave fractures

- Cutter roof failure and oval-shaped roof fall oriented at right angles to the direction of horizontal movement
- Consistent directional offset trends within vertical test holes

In January of 2018, the operator determined that 9 of their 15 existing production headings were experiencing roof failures related to excessive levels of horizontal stress. A decision was made to implement a different mine layout to mitigate unstable ground conditions. The new stress control mine layout focused on driving the headings in the direction of highest horizontal stress and associated lateral movement. Iannacchione et al. [1] reported the orientation of the principle plane of horizontal stress to be N 35-deg W. Almost 2 years later, the new orientation has provided clear evidence as to how this stress control layout minimizes the occurrence of roof instabilities, thereby increasing worker safety.

In general, the headings have been free of cutter roof failures and oval-shaped roof falls except in the intersections next to crosscuts with roof damage. These intersections have

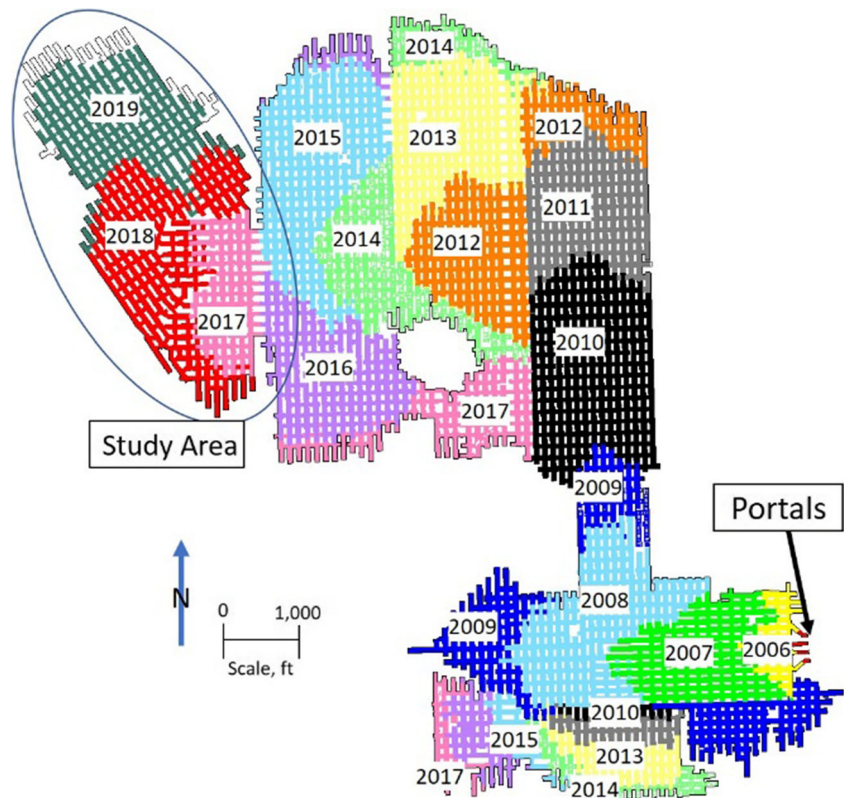
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Fig. 1 Subtropolis Mine Map displaying mining progression and new orientation in study area



shown some signs of stress damage, including chevron fractures and cutter roof. As has been noted in previous work [2–5], typically headings that are developed in the direction of principal horizontal stress have less damage than crosscuts that are perpendicular to the principal horizontal stress direction. These conditions have been found to be dependent on a bi-lateral horizontal stress field; the strength and competence of the roof, rib, and floor strata; and the mining method. It is more desirable to have the headings stable because of the long-term importance within underground mining operations. This layout uses rectangular pillars that allow for greater amounts of headings driven in the direction of principal horizontal stress. The headings serve as long-term haulage and access points to the working faces. The crosscuts on the short side of the rectangular pillars have minimal drivage lengths. The complication comes in the working face area where crosscuts become a critical means of moving equipment and ventilation between the multiple advancing faces.

This research project focuses on engineering controls used to stabilize ground conditions impacted by excessive levels of horizontal stress. Conditions of the underground entries were monitored and assessed. The degree of instabilities within the roof, ribs, and floor were compared to the engineering control used in the crosscuts. The success of every control was weighed against its impacts to ground conditions, haulage, ventilation, and other mining considerations. Lessons learned from this study can help other underground limestone mines mitigate potential instabilities and improve the safety of miners in similar conditions.

2 Damage Prevention Techniques in Crosscuts

The stress control layout relies on rectangular pillars with the long axis of the pillars parallel to the principal horizontal stress direction. The entries on the long side of the pillars are referred to as headings. At the working face, headings represent the direction of mining into the reserve. Headings also become the long-term access to the working faces and the primary means to move product, supplies, and personnel to those areas. At Subtropolis, the standard production pillars are from 12.2 (40 ft) to 18.3 m (60 ft) in length by 9.1 m (30 ft) wide. Mining height averages 4.9 m (16 ft). Headings are 12.2-m (40 ft) wide, and crosscuts are 9.1-m (30 ft) wide. The Vanport seam at Subtropolis ranges from approximately 6.3 to 6.9 m (20 to 22 ft). The primary roof support pattern at this mine consists of five, 1.5-m (5 ft) long fully grouted combination resin bolts to a row, 2.4 m (8 ft) apart, with 2.4 m (8 ft) between each row. The secondary roof support pattern includes 2.4-m (8 ft) long fully grouted cable bolts, four bolts per row, spaced between the primary fully grouted bolts. The secondary roof support pattern is routinely used in crosscuts and within the headings adjacent to crosscuts. The Subtropolis pillar design limits the length of drivage in the crosscut direction, where shear failures from compressive forces could cause roof instabilities.

One design option is to offset the rectangular pillars, so that the crosscuts are not aligned. Offsetting the crosscuts forms a barrier to shear-induced failure and from extending beyond

the adjacent intersection. This design option was difficult to implement, when hauling to a centralized crusher that requires front-end loaders to transport stone across a 286.5-m (940 ft) wide mining front. It is more effective to transport in a straight line versus weaving through offset crosscuts. There is the added problem of increased transport time, wear and tear on vehicles, and, most importantly, increased risk of accidents (Fig. 2a).

Another design option allows the crosscuts to be aligned but uses an arched roof and/or secondary support in the crosscuts. An arched roof is inherently more stable than a rectangular roof where stress concentrations can be critical (Fig. 2b). Initially, the arches were used throughout the mine, because offsetting the crosscuts negatively impacted ventilation. Several running crosscut shear failures occurred where arched roof was used. In practice, it was difficult to develop a competent arch roof in the overlying Vanport limestone with standard blasting techniques. The blasting pattern, direction of shot, and delays had to be re-configured.

Lastly, if control measures such as increased secondary support or arched roofs are necessary, then increasing the distance between crosscuts would help reduce development costs. Unfortunately, increasing crosscut offset distances puts additional burdens on the mine's ventilation and haulage systems. It should be mentioned that angular crosscuts were tried

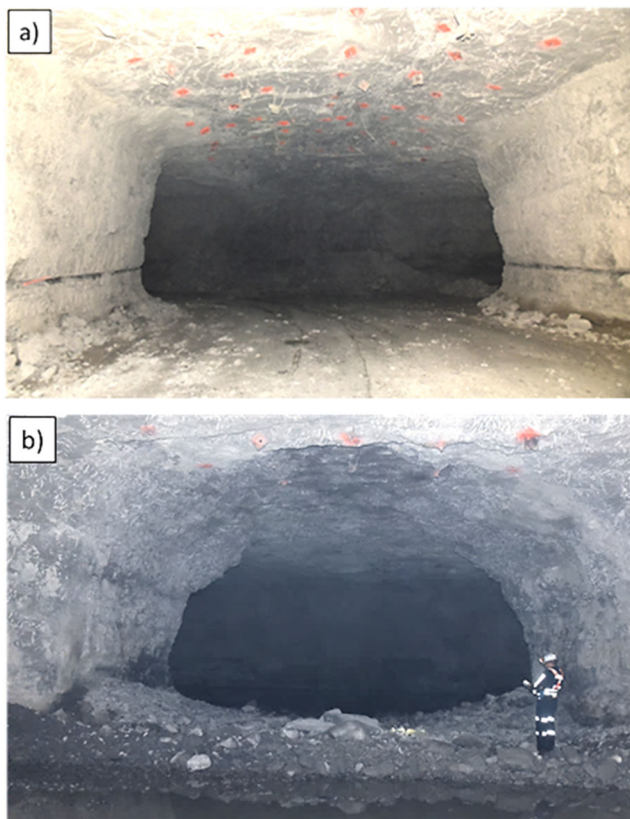


Fig. 2 **a** Example of a typical offset crosscut. **b** Example of an arched roof crosscut

once during the study. The results of this one test were discouraging, not significantly improving ground conditions while causing haulage issues and increasing secondary support requirements.

3 Effectiveness of Windows

Currently, the operator implemented an engineering control technique called windows. Windows are used to resist horizontal movements or deformation that occur parallel to the maximum horizontal stress direction (Fig. 3) or perpendicular to the direction of stress failures. A window is developed by leaving an increased thickness of roof rock in the crosscuts, thus reducing the crosscut dimensions vertically.

3.1 Window Development

At Subtropolis, the height of the openings under the windows is approximately 3.05 m (10 ft). The operator decides to offset the windows, thereby limiting stress damage propagation in the crosscuts (Fig. 4a). Developing windows in an aligned crosscut pattern (Fig. 4b) would enhance haulage; however, this strategy is not ideal for controlling the propagation of stress damage in the crosscuts.

The operator experimented with half-windows to strengthen the crosscuts and continue with the offset pattern despite the haulage difficulties. A half-window occupies one-half of the crosscut width. At least two half-windows failed violently, most likely due to the reduced cross-sectional area resulting in excessive stress levels. To date, no full windows have failed although there have been incidents where the edges of the windows experienced minor instabilities (Fig. 5). As a result, the operator stopped using the half-windows.

The current engineering intervention implemented at the mine is full windows in a staggered orientation and only



Fig. 3 Example of a full-crosscut width window

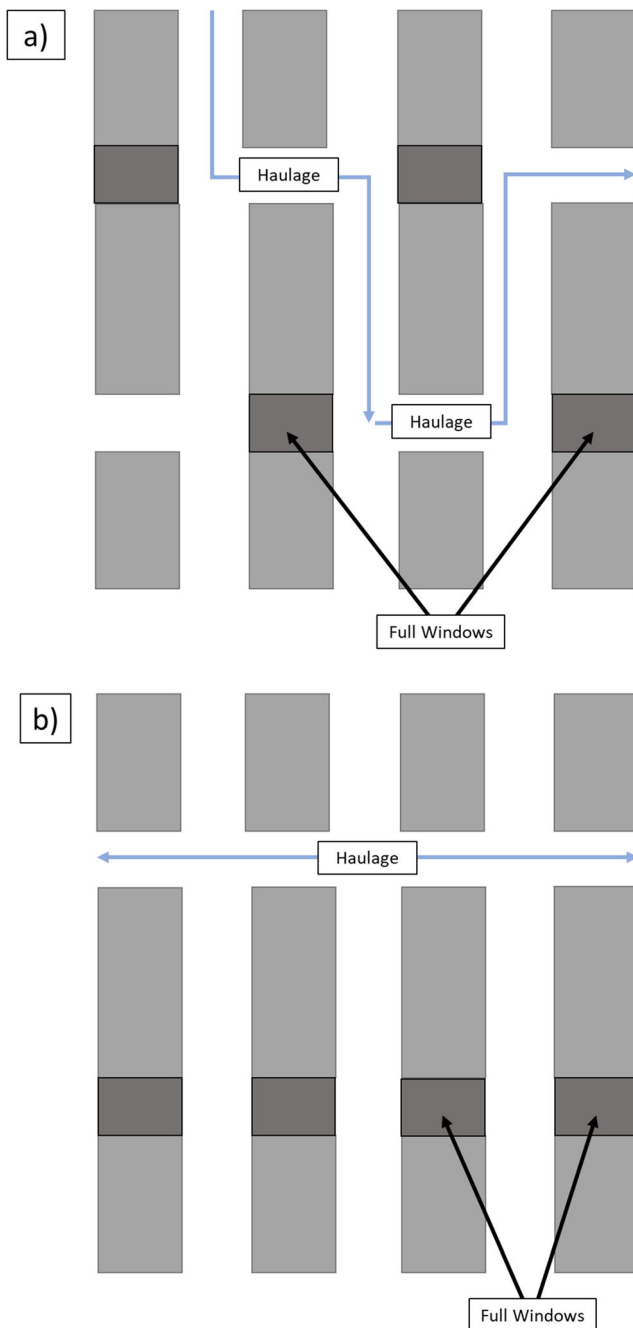


Fig. 4 a Windows in an offset pattern. b Windows in a crosscut aligned pattern

removing them in critical locations to enhance haulage. The operator has experimented with two different variations of developing the full window. One variation of development is to drill in at a right angle and shoot in three stages. This variation takes additional time to develop. To optimize development, the operator now angle drills from either side of the crosscut, thus reducing the shots from three to two (Fig. 6a and b). This configuration results in narrower ventilation openings but benefited from additional pillar support of the limestone



Fig. 5 Example of partial failure of a full window

layers in the window brow. Support window brows cannot be accomplished with rock bolts due to equipment restrictions.

Once the operator established the full window offset in this manner, and the mining front progressed, instabilities in the crosscuts typically subsided.

In order to analyze the windows' performance in high-stress conditions, this study focused on three roof instabilities and found that window performance was in part due to the thickness of the overlying limestone roof member.

3.2 February 2019 Roof Fall

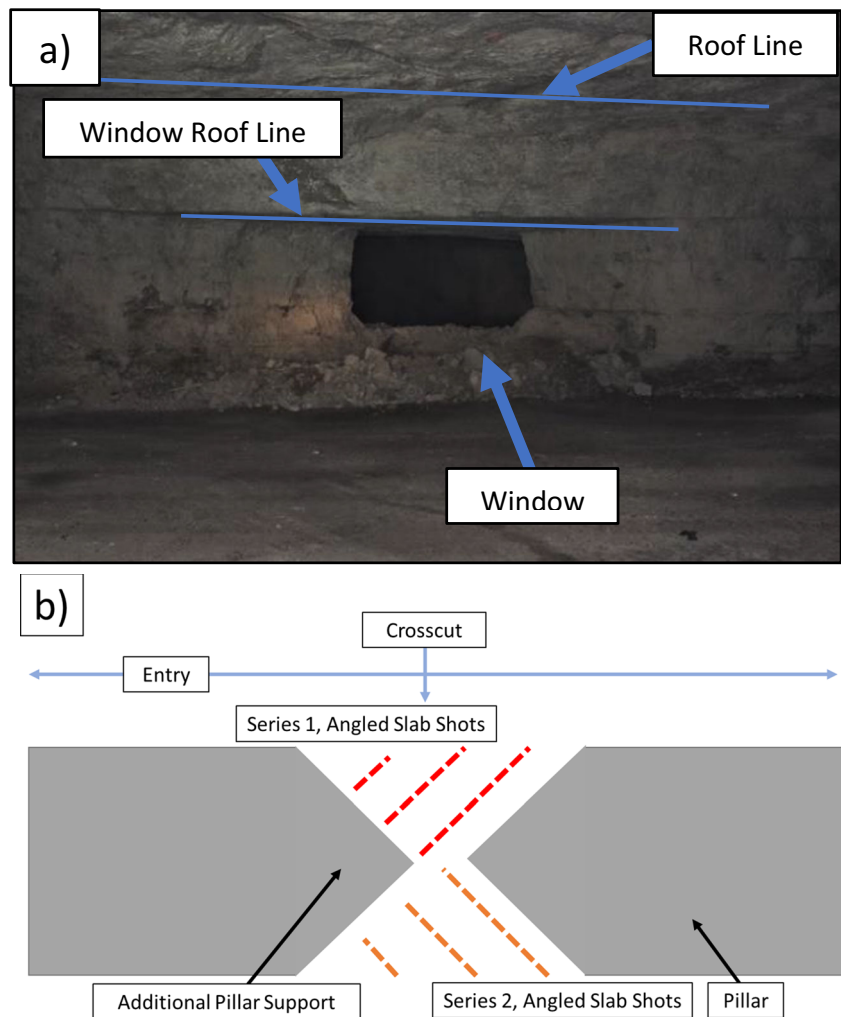
In February of 2019, a roof fall began in crosscut 4 between entries 15 and 21 (Fig. 7). Roof instabilities in the form of shearing were observed on February 5, 2019. Additional shearing was observed on February 19, 2019. The roof shearing in the crosscuts was occurring approximately 30.5 m (100 ft) outby (behind) the face. Minor roof damage was observed in the headings.

The windows in this area remained stable under these high-stress conditions; however, two windows were partially damaged. The window between entries 17 and 18 in crosscut 4 was damaged when 3 inch of the bottom of the window fell out. The second damaged window was between entries 19 and 20 in crosscut 4. This window was damaged when the front edge fell out. Conversely, another window in crosscut 3 between entries 16 and 17 arrested the shear propagation through the crosscuts.

3.3 March 2019 Roof Fall

In March of 2019, a roof fall occurred in crosscut 2 between entries 19 and 21. The limestone caprock thickness reduces from approximately 1.5 m (5 ft) to approximately 1.2 m (4 ft) (Fig. 8a). Oval-shaped falls and chevron fractures are associated with changes in the limestone caprock thickness. The

Fig. 6 **a** Example of a full window with two angled slab shot patterns initiated from either side of the crosscut. **b** Plain view of a full window under window roof line with two angled slab shot patterns initiated from either side of the crosscut



origin of the chevron fractures is currently being studied but is thought to occur in headings where stress concentration is occurring. In this area, the stress failure began in the intersection of entry 21, crosscut 2, and propagated towards existing oval-shaped falls in entry 20. The half-window in crosscut 2 between entry 19 and 20 was observed to be under considerable stress. A 20-degree fracture was moving diagonally through the pillar rib to the top of the half-window. At some point, the half-window failed dramatically. The roof failure began to extend into headings 19, 20, and 21 of crosscut 2. The half-window in crosscut 2 between headings 17 and 18 was observed to be under considerable stress. The combination of window placement and large concrete cribs placed next to a half-window in entry 18 after instabilities began, successfully stopped the propagation of the roof fall.

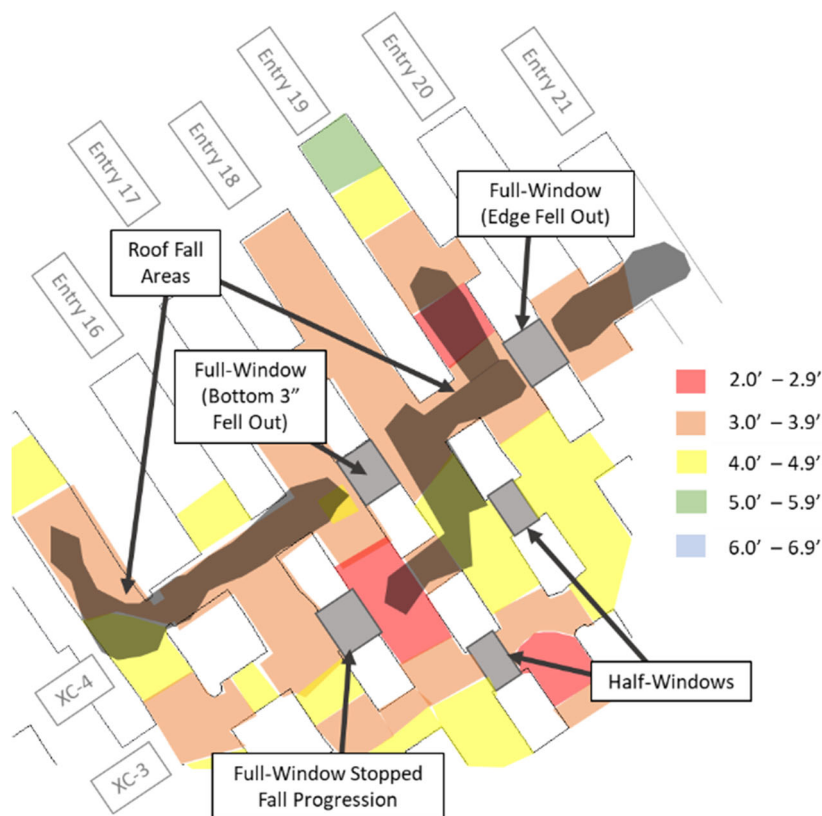
Iannacchione et al. [1] report that these stress-induced failures were initiated by a concentration of stresses in the barrier to the east of this section (Fig. 8b). This study also found that the limestone caprock thinning was occurring in this area. The stress conditions in this barrier pillar between the old 3 N workings and the new workings grew larger as the new

workings mined closer to the old workings, indicating that the stress was undergoing redistribution from the barrier pillar to the surrounding workings.

3.4 July 2019 Roof Fall

In the late July of 2019, a roof fall occurred in crosscut 4. It began when a half-window failed at entry 2, crosscut 4. The roof fall continues to fail through August 19, 2019, and is still active as of September 25, 2019 (Fig. 9). The failed window was located in the eastern-most portion of the new workings where horizontal stress may be concentrating at the end of the entry approximately 24.4 m (80 ft) away. Another window in crosscut 3, between entries 6 and 7, failed violently 8 months earlier when a running failure zig-zagged through poorly developed arches. This half-window failed and developed into an arch. Other windows around the fall are full windows. Each of these full windows remained stable. In fact, one window at the edge of the fall area in crosscut 4, between entries 5 and 6, seemed to stop the fall from progressing further down the

Fig. 7 February 2019 roof fall area, displaying limestone caprock thickness and window type



crosscut. Instead, the fall moves down the far side of entry 5 approximately 6.1 m (20 ft) (Fig. 9).

The limestone caprock in this area of the mine had shown high concentrations of stress-induced fractures that reduced the thickness of the roof to under 1.2 m (4 ft) thickness. The combination of shear stress damage and associated thinner limestone caprock may have contributed to this fall. However, the implementation of full windows in an offset orientation helped to stop this fall from propagating further.

4 Conclusions

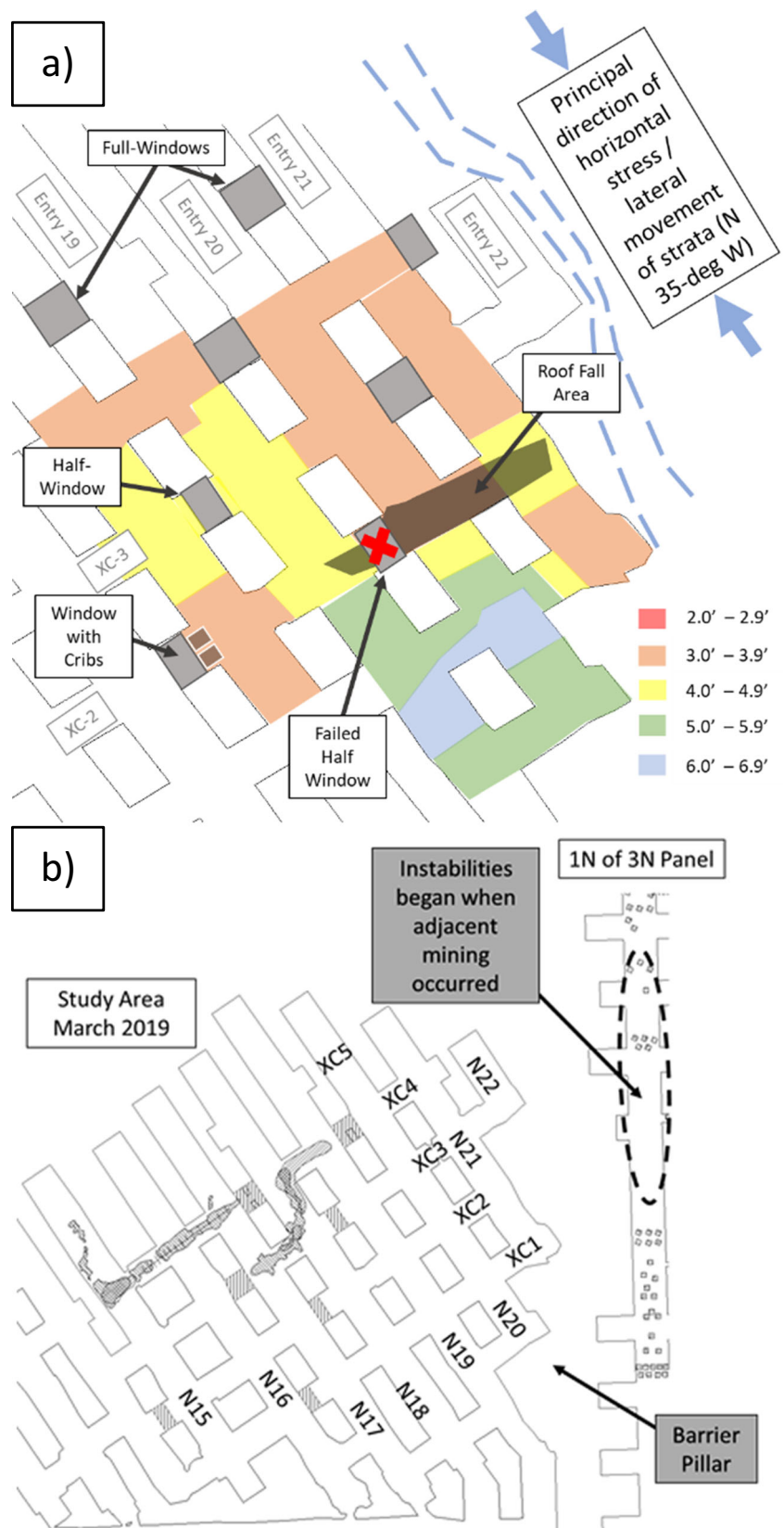
The Subtopolis Mine has been dealing with high horizontal stress since mining began in 2005. The operator has initiated an assortment of engineering interventions to help mitigate associated ground control issues. These interventions have resulted in numerous mine layout changes and adjustments to the heading orientation, pillar size and shape, and rock reinforcement. In February of 2018, the operator decided to utilize the stress control layout design which requires the headings to be driven into the direction of the maximum horizontal stress field. This action has been shown to reduce stress-induced damage within the headings as the rectangular pillar shape concentrates drivage in lower stress conditions. However, the stress control layout concentrates stresses in the

crosscuts. Here again, the rectangular pillars effectively reduce the drivage in higher stress conditions.

Several engineering interventions have been initiated at the Subtopolis Mine to help mitigate stress damage in the crosscuts, including offsetting the pillars, creating arches, cable bolting, narrowing crosscuts, increasing distance between crosscuts, and changing the orientation of the crosscuts. Some of these techniques proved more effective than others. For example, offset crosscuts reduced the potential for the propagation of stress-induced failures. However, this control negatively impacted haulage near the working faces. Another example is increasing the distance between crosscuts. This control would produce less drivage in the high-stress crosscut direction. In this case, the ventilation near the production faces was negatively impacted by lower airflows.

The goal of this study is to identify the means to reduce damage within the crosscuts and still maintain ventilation and haulage requirements. The implementation of windows in the mine design brought the operator closer to this goal. The operator determined that offsetting the windows was ideal, that the half-windows did not perform as well as the full windows, and that the two sets of angled slab shots were the most effective and efficient way to develop the windows. These angled slab shots also produced a self-supporting beam for the window area. Once these control measures were implemented in the mine design, damage to the crosscuts lessened.

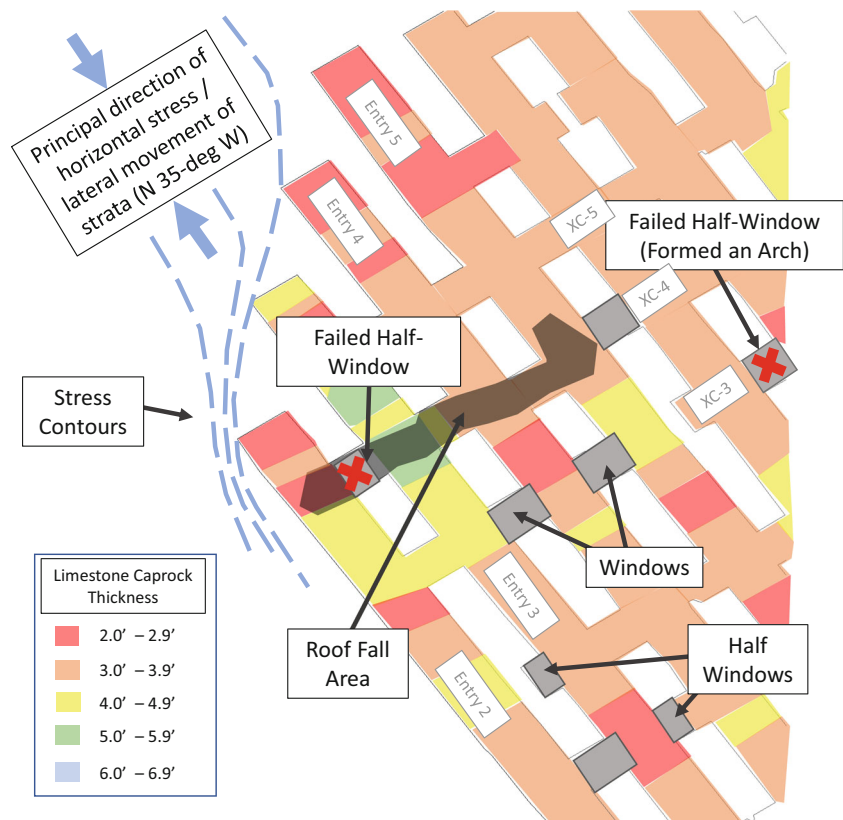
Fig. 8 a March 2019 roof fall area, displaying limestone caprock thickness and window type. b 1 N of 3 N panel location in relation to study area



It is important to note that at the same time this mine design was changed, and damage to the crosscuts lessened; the

caprock thickness increased to an average thickness of close to 1.2 m (4 ft). The overall mining front is currently flatter, and

Fig. 9 July 2019 roof fall area, displaying limestone caprock thickness and window type



the stress-blasting damage to the back has been reduced. The irregular fractures that developed in the high-stress areas often resulted in 0.6 m (2 ft) less of limestone caprock in these areas. There were several areas near the roof falls described in this report that contained caprock thickness at little more than 0.6 m (2 ft). Previous research at other underground limestone mines indicated that stress in the roof beam is not sensitive to the beam thickness until the beam is reduced to 0.6 m (2 ft) [6]. The associated increase in stress levels within the thinner roof beam can initiate failure of the limestone beam that is capable of damaging the overlying shale. The authors of this paper suspect that a similar situation is occurring at the Subtopolis Mine. This may also account for the improvement in conditions when the limestone caprock thickness increases, especially when implemented with the offset full windows. The brows in the windows take a portion of the load that was carried by the limestone caprock. The windows effectively increase the caprock thickness, possibly lessening the stress effects in the roof and resisting the propagation of stress-induced failure through the crosscuts.

Overall, the offset full window design has been effective in controlling damage in the crosscuts caused by high horizontal stress. Once the design was implemented, roof stability improved which has contributed to safer conditions for miners at this operation. As mining continues at Subtopolis, monitoring

of the caprock may be of use in addition to the continued implementation of the current window design in this heading orientation.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Disclaimer The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

Statement of Informed Consent This study was conducted with the collaboration of, and consent to publish from, East Fairfield Coal Company.

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