19th International Conference on Ground Control in Mining

August 8 – 10, 2000

Sponsors

US National Institute for Occupational Safety and Health
US Mine Safety and Health Administration
West Virginia Coal Association
West Virginia University

UTILIZING THE "ADVANCE AND RELIEVE" METHOD TO REDUCE HORIZONTAL STRESS AFFECTS ON THE MINE ROOF, A CASE STUDY

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ABSTRACT

A room and pillar coal operation in central Pennsylvania was experiencing roof cutters and long running roof falls caused by high horizontal stresses. The roof conditions created hazards for the miners, and caused several production panels to be abandoned prematurely. The mine requested assistance from the National Institute for Occupational Safety and Health (NIOSH) in applying the "advance and relieve" mining to reduce the affects of the horizontal stress during panel development.

The "advance and relieve" plan that was developed called for removing a pillar on one side of the panel as it was being advanced, thus creating a cave. The caving then relieved a portion of the horizontal stress across the panel. Because the horizontal stress direction is key to the success of this method, stress mapping as well as mining experience was used to establish the direction of the horizontal stress. Subsequent field measurements provided an estimate of the stress magnitude. Three panels were mined using this technique, and good roof conditions were achieved in all these panels.

Instrumentation was used to monitor the stress changes in the roof created by the cave. Stress relief of over 1,000 psi was measured 120 ft from the cave and to depths of 20 ft into the roof. The lateral extent of the stress relief zone across the panels appears to be about 400 to 500 ft.

This case history has provided much insight into the practical application of the "advance and relieve" method discussed in this paper.

INTRODUCTION

When ground control problems are caused by horizontal stress, there are several approaches that can be used to combat the conditions that develop. One such approach is to relieve or reduce the horizontal stress magnitude. With a reduction of the horizontal stress, less damage should be done to the rock in the immediate vicinity of the mine openings. Horizontal stress relief can be accomplished by caving or by the failure of an entry or an opening that then creates a zone of reduced stress or a stress shadow. Other mine openings driven into this stress shadow will see less horizontal stress and therefore suffer less damage. The geometry and location of the reduced stress zone will depend in part on the height and the orientation of the failure or cave with respect to the horizontal stress direction.

Longwall mining generates a cave with an accompanying zone of horizontal stress relief (*1, 2*). However development mining is usually too far from the cave to be in the stress shadow. There are also zones around the cave where stress concentrations are generated from the horizontal stress (*1, 3, 4*). In room and pillar operations, retreat mining that develops a cave will also create horizontal stress relief zones. However, unless properly sequenced, development mining may not be protected by the cave or worse, could be through zones of horizontal stress concentrations generated by the cave thus increasing the chance and severity of stress related problems.

A stress shadow can also be created by using a sacrificial opening or entry driven into the stress field in advance of the adjacent entries. With the failure of this opening, the following entries could be protected from the affects of high horizontal stress. However, mining and maintaining a sacrificial opening can be difficult due to slower development and substantial supplemental support requirements. A modification of the sacrificial entry concept was conducted as an experiment at a mine in West Virginia. In this experiment, the center entry of a 3 entry gateroad was mined in an arched configuration to a height 13.5 ft (*5, 6*). The entry was then lined with steel sets and lagging. The roof subsequently failed and created an opening with an effective height of 25 ft above the floor. The extent of the stress relief zone was at least 80 ft. This extensive stress relief zone could not be explained by the rock acting as a continuous, elastic, homogenous material. However, underground observations and numerical modeling, showed that horizontal bedding planes were a significant contributor in forming such a large stress relief zone.

Another approach that can be utilized especially in room and pillar mining is to create a cave adjacent to a panel or set of entries during development. This mining system is called the "advance and relieve" method. The first documented case of using the "advance and relieve" mining method in the U.S. was at the Sargent Hollow Mine, Wise County, VA (*7*). The mine had experienced poor roof conditions and directional roof falls associated with high horizontal stress and roof geology that was susceptible to stress damage. The mine used the system on one panel and on a portion of a second panel successfully. From this investigation, there were 4 main conclusions including: (1) the roof control problems associated with high horizontal stress could be significantly reduced by the "advance and relieve" mining, (2) a knowledge of the stress direction is critical when determining a panel orientation and a pillaring plan, (3) the degree of stress relief and the extent of the stress relief zones is a three dimensional problem, and (4) the face areas will be more quickly relieved the closer they are to the pillared out workings, however, this will reduce the safety zone that protects the working faces from the cave.

The present study was conducted at the Tanoma Mine, Tanoma Mining Company, Inc., a room-and-pillar coal operation that was experiencing roof cutters and long running roof falls caused by horizontal stress. Because these roof conditions created hazards for the miners, and caused several production panels to be abandoned prematurely, the mine requested assistance from the National Institute for Occupational Safety and Health (NIOSH) in applying the "advance and relieve" mining to reduce the affects of the horizontal stress during panel development. This paper presents information on the application of the "advance and relieve" system at the mine and discusses the important ground control issues related to the method.

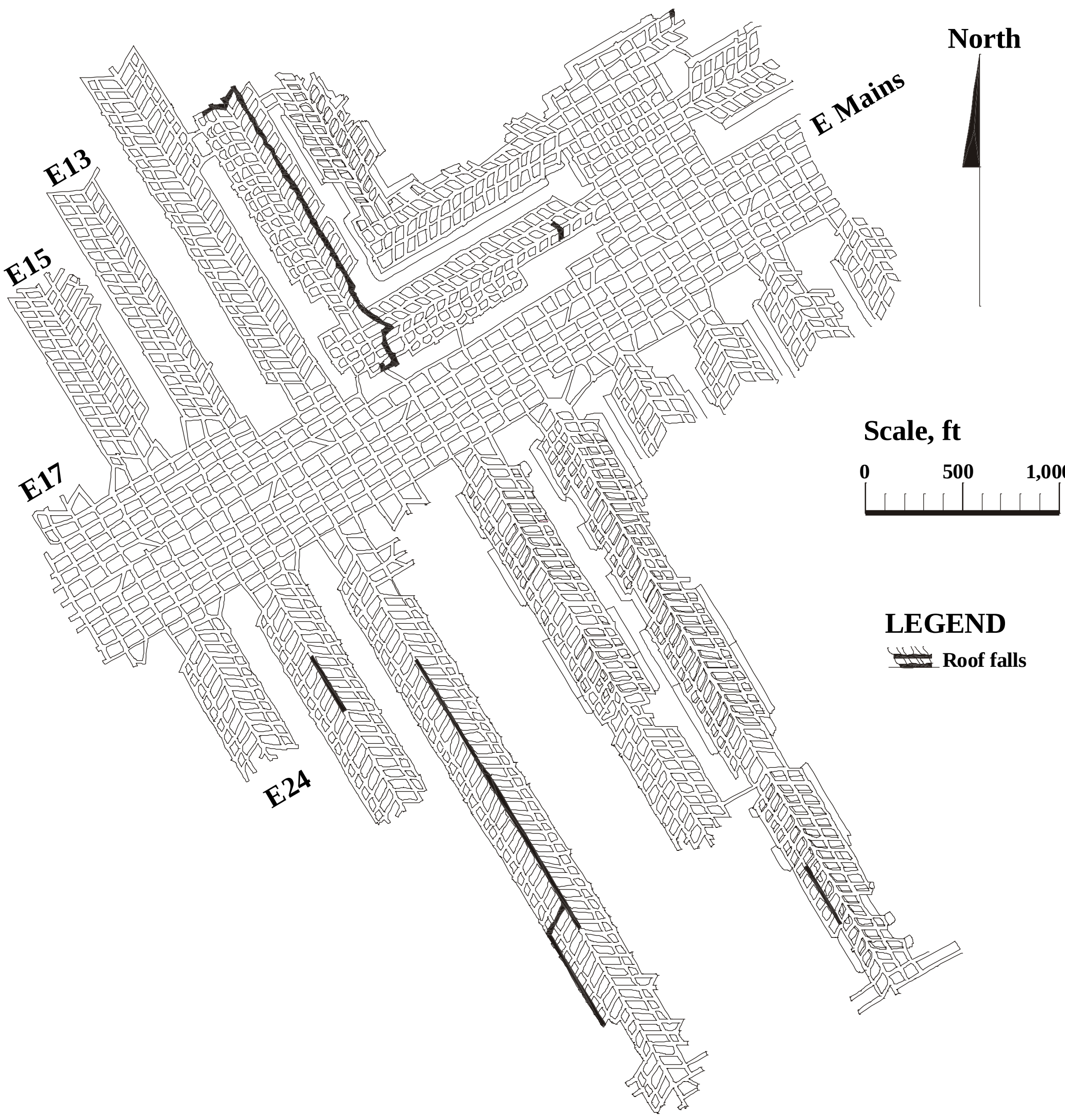

Figure 1. Plan view of E-mains and panels showing long falls

TANOMA MINE

The Tanoma Mine, is located about 10 miles northeast of Indiana, PA. For this study, the area of interest is the E mains and panels that are shown in plan view in figure 1. To date, 15 panels have been driven south off the mains generally in the S 30° E direction and 7 panels have been driven on the north side of the mains in the N 30° W direction. To develop the panels, a continuous haulage system is used with crosscuts driven at 60° angles off the entries. Panels are developed using either a 4 or 5 entry system. In the panels, crosscuts are on 60 ft centers and entries are on 80 ft centers. The entry width is 18 ft. The primary roof support is 5 ft, # 5, or 6 ft, #6 fully grouted rebar with 4 ft row spacings and 4 bolts per row. Supplemental support consists of 8 ft, #6 fully grouted rebar and 0.6 and 0.7 in diameter cable bolts with lengths ranging from 12 to 20 ft. In the mains, a shuttle car system is used for haulage and the entries and crosscuts are driven at 90° angles. The overburden depth over the E main section ranges from 600 to 900 ft. Several mines in the area have been noted for directional ground control problems related to the horizontal stress (*8, 9, 10*).

Geology

The Tanoma Mine is in the Lower Kittanning or B seam and has a coal height of 46 in. The geology of the immediate roof in the E mains and panels consists of a gray or black shale to a depth of about 20 ft. This shale is overlain by a competent sandstone that is generally 2 to 3 ft thick. In areas, the shale will become silty especially above a depth of 15 feet in the roof and near the sandstone. However, at times the sandstone may be within 10 to 15 ft or closer to the seam. Figure 2 shows a typical geologic section of the mine roof.

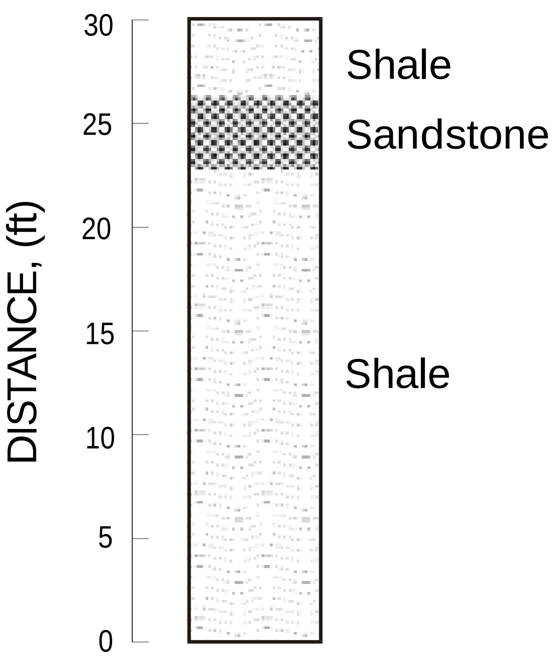

Figure 2. Roof geology in the E-mains and panels

Ground Control Problems

In the E mains and panels, the mine has experienced directional roof control problems that are related to horizontal stress. The stress damage includes long running roof falls and cutters. Roof falls as long as 2,000 ft and up to 30 to 35 ft high have occurred generally in the northwest or southeast direction (figure 1). About 95 pct of the fallen roof is in the N 30° W orientation. Figure 3 shows the amount of fallen roof normalized by the drivage in a given direction. In the N 30° W direction, over 5 pct of the drivage has failed while a little over 2 pct of the drivage has fallen in the N 40° W direction. In the other mining directions, less than 1 pct of the roof has fallen. These roof falls have occurred on both development and during retreat mining where falls occur just outby the cave. When the roof falls occurred during retreat mining, the panels or portions of the panels would often be abandoned. A little over 40 pct of the drivage is in the N 30° W direction while about 20 pct of the drivage is in both the east-west and N 30° E direction.

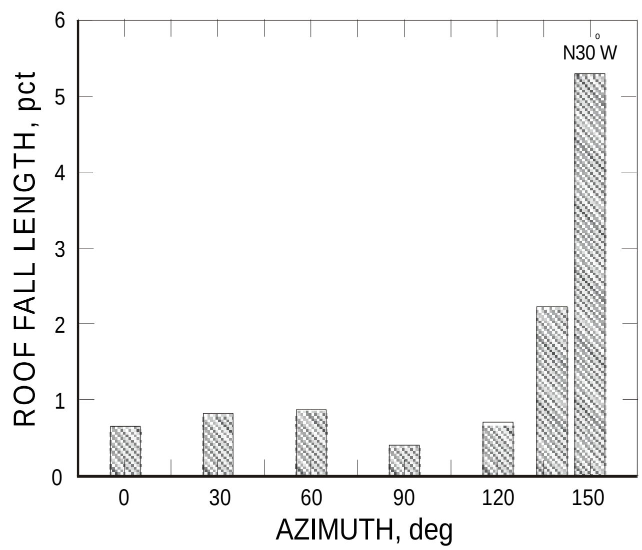

Figure 3. Direction of failed roof normalized by drivage in a given direction

Mapping of the stress damage also indicates the directional nature of the roof problem by documenting more subtle roof damage in addition to roof falls (*2*). This stress damage is in the form of cutters and gutters (figure 4). In the panels, most of the stress damage again occurred in the N 30° W entries. In one panel (E13) about 23 pct of the drivage had stress damage in the form of cutters and guttering. Ninety-five percent of this damage was in the N 30° W entries with 45 pct of the drivage in this direction suffering stress damage.

Although much of the stress damage occurred after the roof was supported outby the faces, occasionally, damage occurred during face advance or prior to installation of the primary support. However, the commencement of the roof falls varied from a few days to several weeks after an opening was mined. About 50 pct of the roof falls in the N 30° W direction occurred in the belt entry whose width is usually wider than the other entries.

Figure 4. Stress induced cutter roof failure

Direction and Magnitude of the Horizontal Stress

Initially, to determine the direction of the maximum horizontal stress, the pattern of the roof falls was used. The highest percentage of roof falls occurs in the N 30° W direction (figure 3). This would indicate a maximum horizontal stress from N 60° E. However because there is no drivage between N 30° W and north, the actual maximum stress direction could be more toward the north. Therefore, the maximum stress direction could fall between N 60° E to N 80° E. It is assumed that the maximum stress could not be any closer to the east-west direction or to the N 50° E direction because of the limited amount of falls perpendicular to those directions. Therefore, a N 70° E direction was selected as the direction of the maximum horizontal stress for the design and evaluation of the "advance and relieve" mining method.

To further define the maximum horizontal stress orientation and determine the stress magnitude, in situ stress measurements were also made using both hydraulic fracturing and overcoring with the USBM 3 component borehole deformation gage (*11*, *12*). The hydraulic fracturing was done with a minifrac system from an underground borehole in the roof (*4*). These measurements were made in the sandstone at a depth of 26 ft in E 24 panel on the south side of the E mains. The horizontal stresses in the sandstone from this measurement were the maximum horizontal stress, P= 6,410 psi from N 87° E, and the minimum horizontal stress, Q= 3,870 psi from N 3° W.

Overcoring stress relief measurements were made at a site in E mains just outby the entrance to E15 panel. Measurements were attempted at depths from 15 to 23 ft. Only one measurement in the shale was successful. The measurement in the shale was at a depth of 17 ft and the calculated stresses were P = 1,975 psi from N 78° W and Q = 1,710 psi from N 12° E. An elastic modulus of 3.4 million psi are used to determine the stress. In the sandstone, the core disced during overcoring.

Clearly a substantial stress was measured in the sandstone that is further indicated by the core discing (*13*). The magnitude of the horizontal stress in the shale is much higher than the vertical stress that could be expected at a depth of 700 ft while the ratio of the maximum to minimum stress is only 1.1. However, without confirming measurements, these results may just reflect a local stress condition. Because of the directional nature of the roof falls and the mapped stress damage features, the maximum horizontal stress was assumed to be N 70° E for design purposes.

THE "ADVANCE AND RELIEVE" METHOD

Because of the extent of roof falls and stress damage, the mine decided to try "advance and relieve" mining. This mining system would be used on 3 panels on the north side of E mains, panels E15, E17, and E19 (figure 1). The "advance and relieve" method involved the extraction of a pillar and a portion of the barrier on one side of the panel during development. Figure 5 shows a portion of the E15 panel with the right side of the panel being pillared. The pillar and barrier were mined just outby the faces. With the pillar extraction, a cave was created along the right side of the panel. In this panel layout, the faces were driven 1 to 2 crosscuts ahead of the cave.

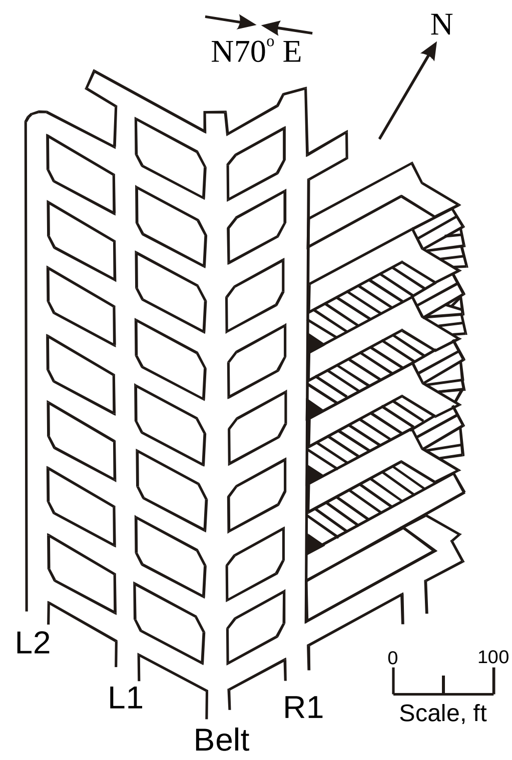

Figure 5. Plan view of E15 panel showing "advance and relieve" pillaring

Panel Layout and Pillar Plan

The panels and cave were developed in the N 30° W direction and therefore at a 100° angle or nearly perpendicular to the maximum horizontal stress from N 70° E. With this panel direction, to maximize the zone of protection that could occur in front of the cave, pillaring was conducted on the right side of the panel.

However, with this panel layout, the faces would still not be stress relieved because the stress shadow lagged one or two crosscuts behind the faces. Figure 6 shows a plan view of panel E15 with the assumed stress pattern that develops around the cave in two dimensions. Because the roof falls and much of the stress damage did not occur immediately, stress relief of the faces was not critical.

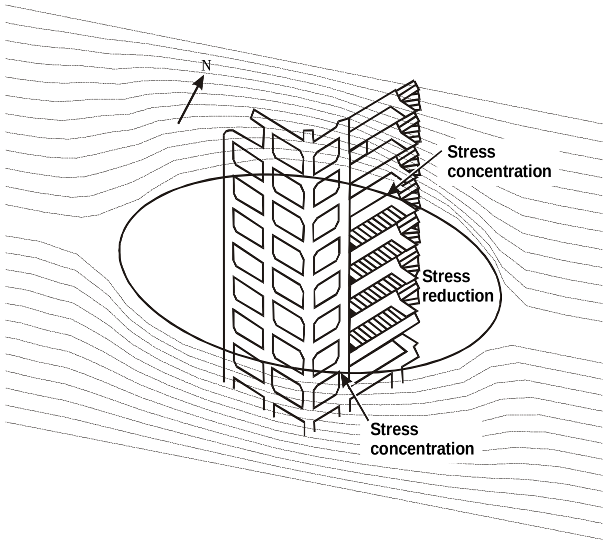

Figure 6. Plan view of stress distribution around pillaring and cave in panel with reference to a N 70° E direction of the maximum horizontal stress

In E15, the "advance and relieve" mining did not begin until after the panel had been advanced 900 ft. During panel development, the two left side entries are designated L1 and L2 with L2 adjacent to the barrier , the belt is in the center while the first entry to the right of the belt is the R1 entry. The R1 entry was adjacent to the cave (figure 5). The first pillar that was outlined by the "advance and relieve" system was not mined. This allowed for the modification of the panel layout from the original 5 entry to the 4 entry configuration with extension of mining into the barrier.

Figure 7 shows the original extraction plan. The plan called for the pillar to be extracted from a room developed from the R1 entry. This original panel layout had crosscuts on 60 ft centers with the length of the extracted pillar of approximately 100 ft. The room length and extent of extraction into the barrier was controlled by the reach of the continuous haulage system which was 258 ft.

A cut back entry at the end of the room was mined and supported to outline the pillar. This allowed for adequate ventilation and complete pillar extraction. Once the cut back was completed the mining sequence was to first cut into the barrier then extract the pillar. The pillar was then mined from the barrier toward the R1 entry. Only a small pillar stump about 10 to 15 ft wide was left along the R1 entry next to the cave. With this system, a cave quickly developed that was about 100 to 120 ft wide that extended from the pillar stump to the barrier. At several intersections the cave did extend into the R1 entry. However, with this plan, the cut back entry was very difficult to mine because the entry was subjected to severe roof damage from the horizontal stress concentration. Figure 8 shows the stress concentration that developed around the cut back entry. After 6 pillars were mined using this plan, a second pillaring plan was developed to address this issue.

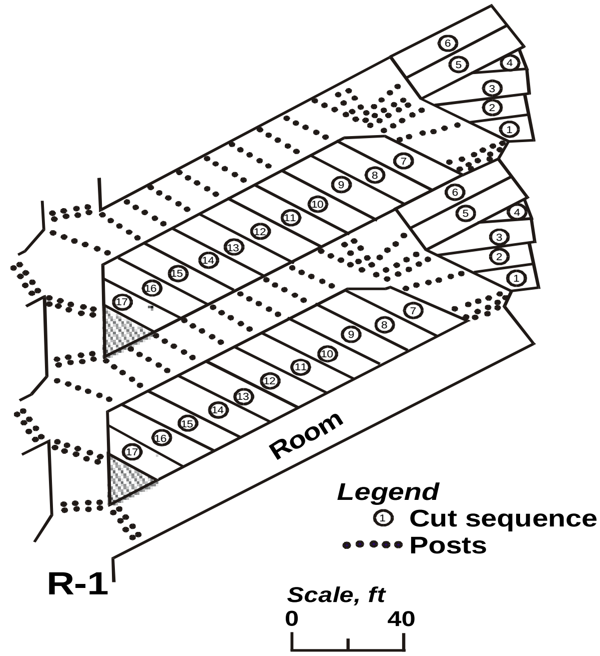

Figure 7. Original pillaring plan used in E15 panel

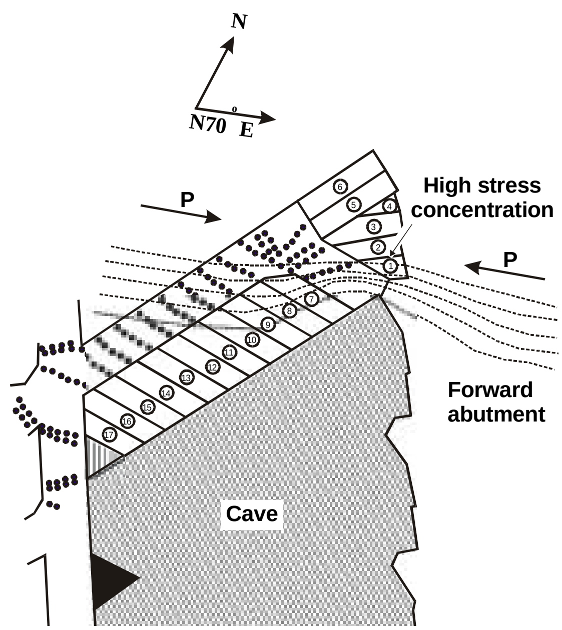

Figure 8. Forward stress abutment and concentration with respect to the original pillaring plan

Second Pillar Plan

The second pillar plan that was adopted and used for the remainder of panel E15 and the adjacent panel E17 is shown in figure 9. Instead of making a cut back entry, a notch parallel to the

R1 entry was cut into the pillar from the outby room prior to the pillar extraction. This notch allowed for a cut through of the pillar during the early stages of pillaring for ventilation and allowed for the full pillar width to be mined. Normally the notch would be bolted with only 2 rows of bolts inby the rib line. With this second pillaring plan, the horizontal stress appeared to be concentrated near the notch. Figure 10 shows the stress concentration developed around the notch. During pillar extraction, the cuts that mined into the notch, cuts 4 and 5 resulted in the roof caving from the notch inby to the barrier. After this cave, there were few problems encountered with the extraction of the remainder of the pillar.

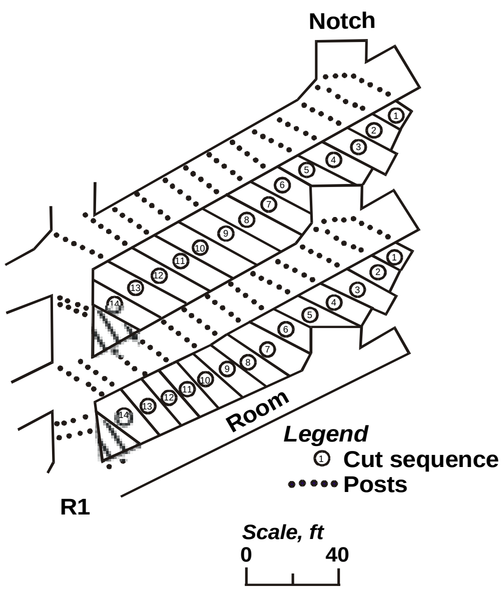

Figure 9. Second pillaring plan used in E15 and E17 panels

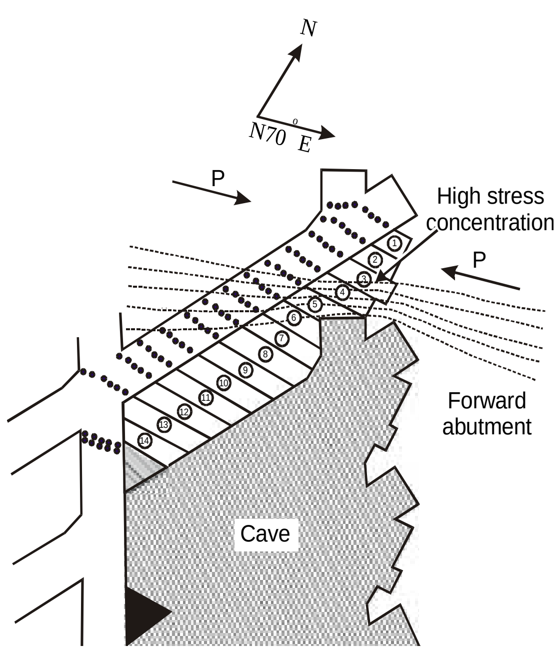

Figure 10 Forward horizontal stress abutment and concentration with respect to the second pillaring plan

After this second plan was adopted, another adjustment was made where a bigger pillar stump with an average width of 30 ft was left along the R1 entry. With the larger stump, the R1 entry was kept open, where previously the roof had caved in some of the intersections.

This new pillaring plan was now used for the rest of panel E15 encompassing 16 pillars and the adjacent E17 panel where 25 pillars were mined (figure 11). With E17, pillaring began just 250 ft inby the mains and 650 ft outby the start of pillaring in E15. Again, a pillar and a standing room were left outby the cave.

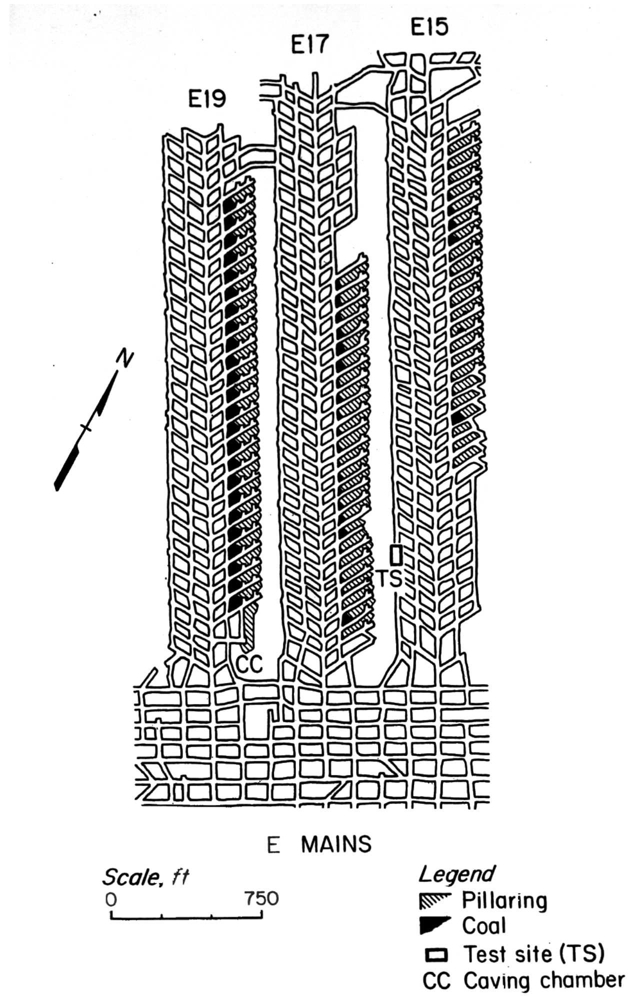

Figure 11. Plan view of panels E15, E17, and E19 showing location of test site

Floor Heave

With the start of "advance and relieve" pillaring in both panels E15 and E17, significant floor heave developed. Over the panels the floor consisted of 1 to 2 ft of shale underlain by 4 to 5 ft of fireclay while the overburden averaged 700 ft. Figure 12 shows typical floor heave that occurred. Systematic roof to floor convergence measurements were made in the intersections of the belt, L1 and L2 entries along the length of each panel.

Figure 12. Floor heave experienced in E15 panel.

The maximum floor heave occurred in both panels during the first 800 ft of "advance and relieve" pillaring. In E15 the average heave rate in this panel section was 0.24 in/day, while in E17 the average rate was 0.38 in/day. These rates were maintained for periods of up to 40 to 60 days before leveling off. In places, 20 to 30 in of floor heave resulted. This floor heave occurred across the panel width and was not confined to the area adjacent to the cave. Figure 13 shows the pattern of floor heave over time across the E17 panel 200 ft inby the start of pillaring. The accelerated rate of floor heave shown in figure 13 after 115 days is the result of retreat mining in the panel. The variable initial rates between 20 and 30 days may reflect the failure of the hard shale layer.

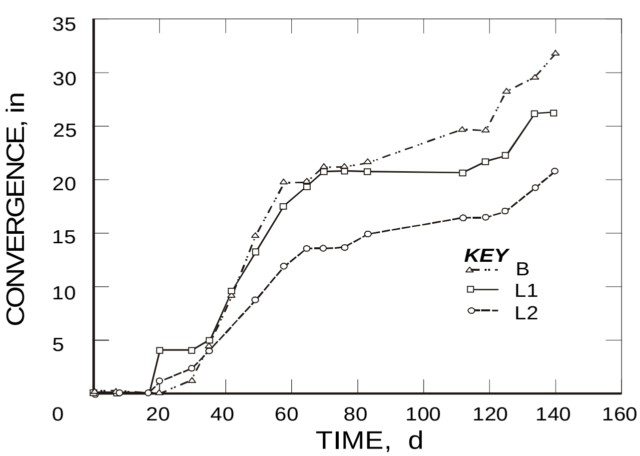

Figure 13. Floor heave rates across E17 panel

Because of the floor heave, an evaluation was made of the pillar stability and the pillar loads using Analysis of Retreat Mining Pillar Stability (ARMPS) (*16*). In the panels, the stability factor of the pillars between the belt and R1 entry was 1.16 while the average stress on these pillars were 2,900 psi. For these pillars, the crosscut spacing was 60 ft and entry spacing was 70 ft. The entry spacing for the pillar between the belt and the L1 entry was 80 ft.

The heave necessitated removal of the floor in sections of the panels in both the belt and the L1 travel way outby the face. Because of the floor heave problem, the pillaring plan and pillar and panel design in the E19 panel were altered with the new design discussed below.

Panel E19

To address the floor heave issue, a third pillaring plan and a new panel design were developed and implemented in panel E19. The size of the pillars in the panel were increased by extending the distance between crosscuts to 70 ft. Instead of a pillar stump as was left in E15 and E17, a pillar was now left between the cave and the R1 entry that was on average 40 ft wide. Figure 14 shows this third pillaring plan. A double notch was used to assure that a cut through was made during pillaring for both ventilation and for caving. Besides the change in pillar dimensions, the width of the caved zone was decreased to about 80 to 90 ft.

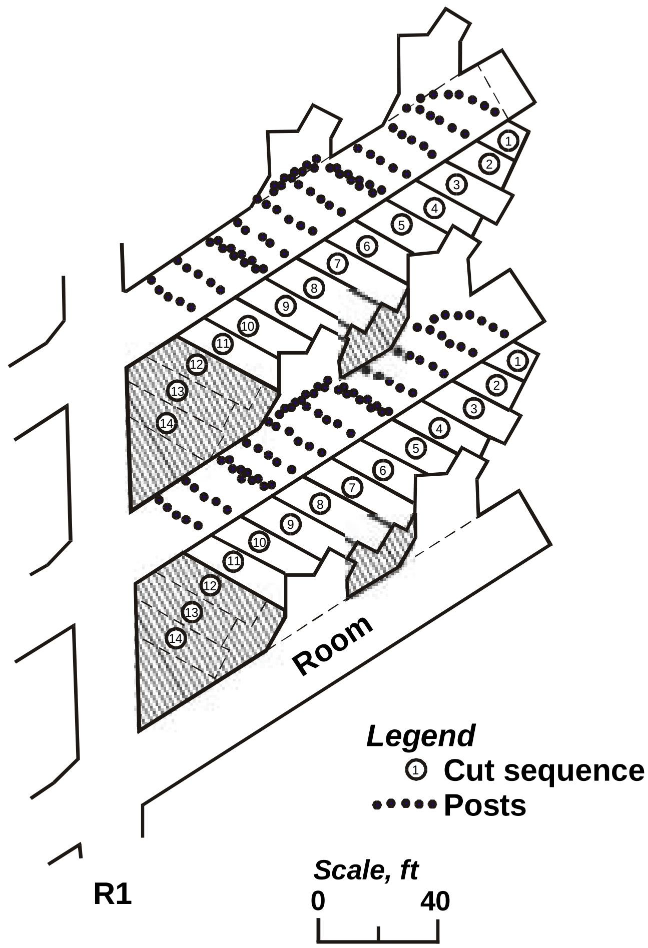

Figure 14. Pillaring plan in E19 that was changed because of floor heave

Using the ARMPS analysis, the pillar between the R1 and belt now had a stability factor of 2.1, with an average vertical stress of 1,800 psi. The pillar adjacent to the cave had a stability factor of 1.7 with an average vertical stress of 2,200 psi. The larger pillar along the cave prevented the R1 entry from falling so that the entry remained open for ventilation. Although floor heave still occurred in E19, the average rate of floor heave was only 0.12 in/day.

In the panel during "advance and relieve" pillaring no stress damage was observed. Also, caving was not as complete as before and lagged further outby the pillaring. Typically the cave stayed behind the pillar line by about 3 to 5 crosscuts. Therefore, inby the cave, a large mined out area 90 ft wide by to 200 to 300 ft long remained open.

HORIZONTAL STRESS ABUTMENTS AND REDUCTION ZONES

Monitoring of Stress Changes from the Cave

The horizontal stress changes that occurred from the pillaring in E17 were measured by instruments placed at a test site in the L2 entry of E15 panel. Figure 11 shows the location of the test site with respect to E17 where the distance from the cave to the instrumentation was 120 ft. Two types of instrumentation were used, the USBM 3 component borehole deformation gage and the CSIRO hollow inclusion cell (*11, 14*). The borehole deformation gages were located at depths of 2, 5, 10, and 15 ft and the CSIRO cells at 5 and 20 ft in the roof. The 20 ft cell was in the sandstone roof unit.

Figure 15 shows the stress changes with time as the panel approached, then passed the test site for the gages at 2 and 10 ft. The cave front position is also indicated on the graphs. On this figure, the largest stress reduction is ΔP and the smallest ΔQ. The orientation of the stress changes are given as the azimuth to the smallest stress reduction component ΔQ. A minus value represents a stress reduction while a positive value represents a stress increase. Although the data is not shown, at the 20 ft depth there was a stress reduction of 1,200 psi after the cave had passed the test site with an azimuth direction of 233°.

Forward Horizontal Stress Abutment

With cave initiation, a horizontal stress abutment was created in front of the cave (figures 6 and 8). The damage in the cut back entry which required a pillar plan modification was one indication of this abutment. Even with the second pillaring plan, the outer half of the room used to extract the pillar in front of the cave suffered stress damage.

This forward horizontal stress abutment can be seen by the increase in stresses as the cave front approaches and passes the test site. At 120 ft from the cave, stress increases ranged from 200 to 800 psi. This stress increase began when the cave was 200 ft outby the test site. At the 2 ft level, the roof could not sustain this added stress which quickly dropped to show a stress reduction. At other depths, the stress concentration although dropping from a peak remained higher than the original stress conditions in the direction just sub parallel to the cave.

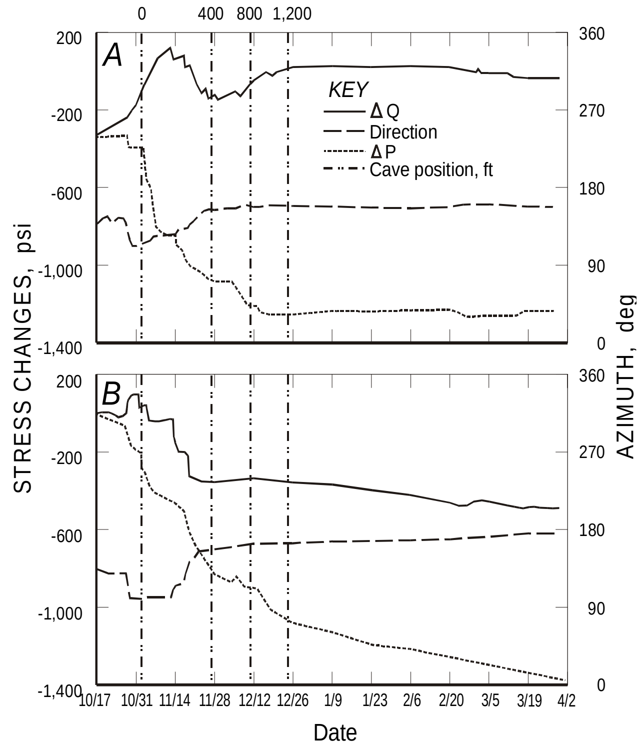

Figure 15. Horizontal stress changes measured at the test site. (a) 2-ft depth and (b) 10-ft depth. The azimuth direction is to ΔQ

Some roof damage did occur in the faces inby the cave especially in the R1 entry where a cutter would normally develop from the crosscut at the cave front and progress inby toward the face of R1. About 74 pct of R1 received some stress damage in E15. This again was a sign of the forward horizontal stress abutment.

For the first 1,000 ft of "advance and relieve" pillaring in E15, this stress damage was largely confined to the R1 entry. However, in the last 300 ft of the pillared section of the E15 panel, cutters and guttering were seen in the other three entries. This damage occurred both at the face and outby the face in portions of the L2 entry that were not yet in the stress shadow. After the "advance and relieve" pillaring was halted, this damage continued inby for the rest of the panel (a distance of another 400 ft). In this section, guttering and severe roof damage occurred mainly in the faces. A roof fall did occur in the belt entry 100 ft inby the cave. Both the E11 and E13 panels that were adjacent to E15 were terminated at the edge of this zone because of severe roof damage and roof falls. However, no roof falls occurred in the entries adjacent to the cave and the stress damage did not appear to get any worse. No roof control problems occurred during retreat mining in E15.

Rear Horizontal Stress Abutment

Roof damage in the entries and crosscuts in the panels just outby the cave was probably caused by the rear horizontal stress abutment. This abutment did not advance with the mining, but essentially remained stationary. In E15, the damage consisted of cutters developed in the R1 entry from the cave outby for a distance of approximately 200 ft. This stress damage was parallel to the length of the cave.

Stress damage also occurred in the crosscut just outby the cave. A cutter ran across the belt entry then into the crosscut from the belt entry to the L1 and L2 entries. This was a narrow zone about 10 to 15 ft wide of fairly severe roof damage that crossed the entire panel at a right angle (figure 16). This damage zone ran both in the N 30° E and east-west crosscuts with an orientation sub parallel to the direction of the maximum horizontal stress.

Figure 16. Rear abutment stress damage in the L1 entry

To migrate the damage, cribs and posts were set as supplemental support along with cable bolts in the R1 entry and across the panel along the narrow zone of damage. Similar, though not as severe damage was seen outby the cave in E17. Again supplemental support was used to control the stress damage. In E17 with the start of the cave 200 ft inby, the damage approached but did not reach the mains.

In E19, to moderate the effects of the rear abutment, a caving chamber was mined just outby the area where the pillaring began (figure 11). This chamber involved mining into the barrier from the R2 entry for a distance of 100 ft prior to the start of the pillaring. This created a chamber that was 100 ft long and 50 ft wide. This chamber caved very readily as did the initial 100 to 200 ft of the pillared section. The "advance and relief pillaring then began just inby this caving chamber with the cave in the chamber initiating the cave in the pillared section. There was still outby damage in the R1 entry for a distance of about 50 ft while the roof fell in the crosscut between the caving chamber and the R1 entry. However, the damage did not extend across the panel as occurred in E15.

Stress Reduction Zone

Stress relief began when the cave was across from the test site and was competed to a large extent when the cave was about 500 ft inby. With the cave passing, there was significant stress reduction in the shale below the sandstone in the direction of the cave that ranged from 800 to 1,200 psi. Based on the stresses measured in the shale, this would represent between a 40 and 60 pct reduction in the applied horizontal stress. At the 2 ft level, there was stress relief in both directions though the reduction parallel to the cave was only about 300 psi. Even in the sandstone at a depth of 20 ft, there was a stress reduction of 1,200 psi that represents about a 20 pct reduction in the horizontal stress.

Further evidence of the stress reduction is suggested by the fact that no roof falls occurred in E15, E17, and E19 panels adjacent to the caves during development about 4,000 ft of panel length. During retreat mining in the panels, no roof falls or roof control problems were encountered indicating that the workings were stress relieved.

Although there are no quantitative measurements as to the extent of the stress reduction zone that developed, there are a number of qualitative indicators that can be used to approximate the distance. In both the E15 and E17 panels, there was no increase in damage or any roof falls in the L2 entry as compared to other entries. Because of the lack of damage or any change of damage which occurred in the L2 entry, it appears that some stress relief is occurring in that entry, a distance of 220 to 250 ft from the cave. Further, in E13 panel, the panel adjacent to E15, almost 33 pct of the L2 entry suffered stress damage including roof falls. Another indication of the extent of stress relief is that the stress damage in E17 was limited to the R1 entry and pillar crosscut outby the E15 pillaring. Little damage was seen inby where the E15 "advance and relieve" pillaring had begun. The distance from the cave in E15 to the R1 entry in E17 was about 500 ft. During retreat mining of panel E13, in early December, test site instrumentation monitored 100 to 200 psi of stress change as the pillar line past. The distance from the E13 cave to the test site was about 400 ft.

Cave Height

Because the cave height in part controls the size of the stress relief zone, it is important to establish the geometric relationship between the cave height and stress reduction zone. Obviously, no direct measurements could be made on the cave height. However, to obtain an estimate of the cave height, measurements on the height of a long fall that had occurred in the N 30° W direction were made. The fall height from the top of the mined opening was about 30 to 32 ft resulting in a total opening height between 35 to 37 ft. This is assumed to be the height of the cave in the "advance and relieve" section. The height of the cave will be limited by the bulking of the caved material and not by the width of the cave as long as the cave width is sufficient to develop the failure (*15*).

DISCUSSION

Stress Reduction Zone

Clearly there is a directional roof control problem caused by the high horizontal stress at the mine with a N 70° E direction for the maximum horizontal stress being assumed. With the "advance and relief" method and a panel and cave direction of N 30° W , the angle of the horizontal stress with respect to the cave was 100° or nearly perpendicular to the maximum horizontal stress. This created a stress reduction zone that protected or shadowed most of the panel behind the cave from the affects of the maximum horizontal stress. Figure 17 shows the stress reduction zone generated by the cave.

A significant stress reduction was achieved with caving that ranged from 800 to1,200 psi at a distance of 120 ft from the cave. This level of stress relief may represent a reduction of up to 50 pct of the maximum horizontal stress. More stress relief would occur closer to the cave while the amount of stress relief will diminish with distance. Underground observations indicate that once the openings were in the stress shadow, minimal stress damage occurred to the mine roof. Further, no roof falls occurred in the "advance and relieve" sections yet there was nearly 18,000 ft of drivage shadowed by the caves in three panels. This allowed for retreat mining in the stress relieved sections with no roof control problems or roof falls.

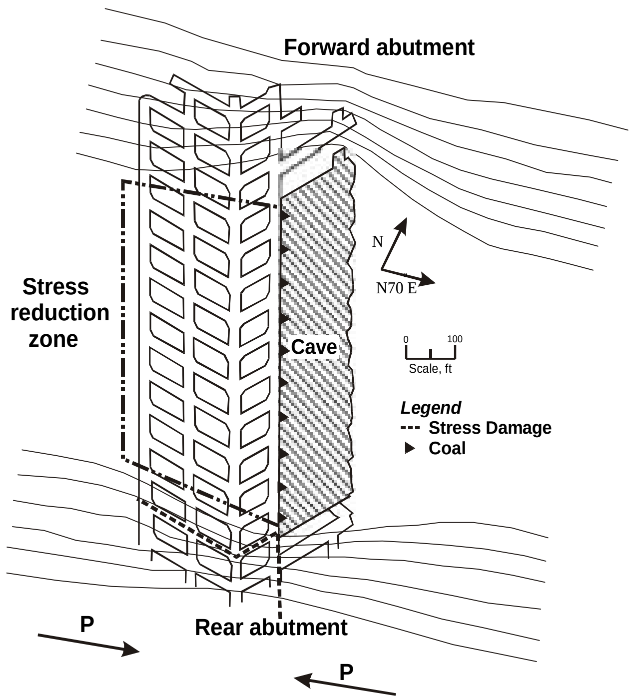

Figure 17. "Advance and relieve" panel with cave showing the forward and rear abutments and stress reduction zone

The width of the stress relief zone from the cave appears to be between 250 to 500 ft. With a cave height of only 35 to 37 ft this stress reduction zone was 7 to 14 times the cave height. Further, the extent of the stress relief can not be explained by the response of a continuous, homogeneous, elastic material. This implies that much of the stress relief must come from movement and slippage along bedding planes or other discontinuities (*5, 6*). The extent of any stress relief zone will determine the width of the panel or mining that can be effectively protected.

During this investigation, because of the cave orientation with respect to the stress field, the faces were not relieved immediately but fell into the stress shadow 1 or 2 crosscuts behind the face. In much of the development in the 3 panels, shielding the faces was not critical since immediate stress damage did not occur in the advanced workings. When this damage did occur at the faces such as at the end of E15, the damage was limited because the roof was exposed to the high stresses for only a short time. Once behind the cave, the openings suffered no further roof damage.

With the no roof falls during retreat mining, the stress concentration that usually developed in front of the pillaring appears to be absent or greatly reduced by the stress relief generated on development. Prior to "advance and relieve" mining, sections of panels could not be mined during retreat mining because of roof falls caused be the stress concentration generated by the retreat cave.

Forward and Rear Horizontal Stress Abutments and Pillaring Plans

As the stress reduction zone was created, both forward and rear horizontal stress abutments were developed. Figure 17 shows the location of these stress abutments with respect to the cave. The forward stress abutment results from the concentration of the horizontal stress in front of the cave. Because of this stress concentration, localized roof damage occurred in the faces adjacent and forward of the cave. However, the location of this damage was generally predictable though requiring at times longer bolts to be installed. Also, these areas were subjected to these stress conditions for only a short period of time which minimized the damage that could be done.

Because of the forward horizontal stress abutment, adjustments to the original pillaring plan had to be made. The first pillaring plan was not successful because of the difficulty in trying to mine an entry across and into the stress concentration (figure 8).

With the second plan, the ground control problems resulting from the stress concentration were minimized. The stress concentration was still on the inby half of the crosscut and in the notch where stress damage in the form of cutters and guttering still occurred (figure 10). However, the intervening coal pillar between the notch and the crosscut reduced the combined affects of the two openings on the stress concentration. When the barrier and pillar were now mined, a portion of the horizontal stress concentration was now over a section of the pillar to be extracted. This concentration was located near the notch and was seen between cut sequence 4 and 5 with the roof cave initiating when these cuts were taken. However, instead of being a problem for development, the stress concentration now assisted in generating a cave. Once the cave occurred at this stress concentration point, there were few problems with the mining of the rest of the pillar.

A rear horizontal stress abutment was also created that was similar to the forward abutment except that this rear abutment was stationary (figure 17). Essentially, the stress concentration once fully developed was not limited in time in causing stress damage. As a result, the damage of the rear abutment appeared to be more severe than that resulting from the forward abutment. Two zones of damage developed, one outby and parallel to the cave in the R1 entry and the other zone a narrow band that ran across the panel, perpendicular to the cave. The damage parallel to the cave in the

R1 entry was probably caused by the concentration of the maximum horizontal stress. However, the stress damage across the panel may have in part been caused by the minimum horizontal stress.

Supplemental support in the form of cribs, posts, cable bolts and longer primary support was required in both zones to control the damage. Because of the outby damage parallel to the cave, when designing the panel, a sufficient distance must be left between the start of the cave and the mains to prevent damage to the mains. In E17 a distance of 250 ft appeared to suffice. This distance allowed the damage and the stress concentration to dissipate before reaching the mains. The caving chamber in E19 seems to have reduced the rear abutment stress damage. Apparently, the rear abutment stress was shifted into the barrier pillar between the end of the chamber and the mains.

Cave Height and Width

The panel width that can be protected is dependent on the extent of the stress relief zone and this is in part a function of the caving height. However, the cave height is to a large degree controlled by material bulking and not by the cave width (*15*). Usually, the cave will reach a height that is 2 to 10 times the mining height with the higher heights achieved in weaker shales (*17*). The cave width is only important in that this dimension must be sufficient to allow the full cave height to be achieved through the failure of the roof. In the case of Tanoma Mine, a 20 ft wide entry was able to generate the full cave height, however a larger width is required to consistently initiate and propagate the cave. A width of 100 to 120 ft appeared to be adequate for generating a cave that reached a maximum height in two of the panels. In E19 panel, a caving chamber 50 ft wide readily caved but in the pillared section a span of 80 ft did not cave easily. The difference may be the result of the caving chamber being affected by the full magnitude of the horizontal stress, while the cave in the "advance and relieve" section was in a stress shadow generated by the pillaring both on advance and on retreat from both E15 and E17 panels.

Floor Heave

Whether the floor heave is the result of the vertical or horizontal stress is not known for certain. However, with the significant change in floor heave rates in E19 where the cave size was reduced, the pillar size increased and another pillar added, suggests that the floor heave may have been caused by the vertical stress. In this case, the third pillar plan and panel design reduced the floor heave rate by at least 50 pct.

With a weak floor, floor heave must be considered when adopting the "advance and relieve" method because the openings will be subjected to the floor heave for extended periods of time. This additional time will allow for more floor heave to occur. Further, this floor heave developed well outby the face and was worse at the start of the panel. This is just the opposite of what occurs during retreat mining where the largest amount of floor heave will develop between 2 to 3 crosscuts outby the pillar line where the exposure time limits the floor heave.

CONCLUSIONS

The "advance and relieve" mining system was an effective way to minimize stress damage and to prevent roof falls caused by high horizontal stresses both on development and on retreat. With this system a significant reduction in the horizontal stress in the panel behind the cave was achieved. However, a knowledge of the horizontal stress direction is important to understand what stress will be reduced and where the location of the stress concentration zones will be in the panel. In this case, the maximum horizontal stress was nearly perpendicular to the panel and cave and resulted in the stress relief zone encompassing most of the panel behind the cave. Because of the orientation of the stress field with respect to the cave, stress relief did not occur at the faces but occurred one or two crosscuts behind the face as the cave was advanced. Since, roof falls and severe stress damage usually did not occur immediately, this situation was acceptable.

With the creation of a stress reduction zone, forward and rear horizontal stress abutments were also generated. The forward abutment which moved with mining required the development of a pillaring plan that could be used in the high stress concentration zone. There was also some increased damage in the workings adjacent to and ahead of the cave. The rear horizontal stress abutment was stationary and therefore resulted in more severe stress damage necessitating the use of supplemental support. This damage was localized and in predictable locations.

The extent of the stress relief zone was 7 and 14 times the cave height. The development of such a large zone of reduced stress must rely on the movement along bedding planes and other discontinuities and not on the elastic response of the rock mass. The cave height and therefore the extent of the stress relief zone will be limited to a large degree by the bulking of the caved material and not necessarily by the cave width. The success of this technique depends on the extended dimensions of the stress relief zone that can shadow the entire panel width and even beyond to adjacent development.

With a weak floor, floor heave may occur and therefore must be considered. The panel adjacent to the cave, especially at the start of the pillaring, will be subjected to the increased vertical abutment stress for an extended period of time. This results in the development of a large amount of floor heave that can impact mining. Retreat mining will usually not have the same effect because of the limited exposure time. However, a modified pillaring plan and panel design was able to reduce the heave rate significantly.

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