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The Advance and Relieve Mining Method: A Horizontal Stress Control Technique

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ABSTRACT

Sacrificial entries, roof slotting, and other tactics have been used to combat high horizontal stresses during roadway development in U.S. coal mines. In Australia, the "pillar extraction on the advance" mining method has been successfully employed as a horizontal stress control technique. The concept of advancing and relieving mine workings through pillar extraction developed from observations that some mines experience difficult ground conditions when advancing and retreating the first panel in a new reserve. However, conditions dramatically improve in subsequent panels. Apparently, the creation of a gob area stress relieves the adjacent panel workings. After much debate and close scrutiny, the first U.S. roof control plan to advance and relieve was approved in 1998, for the Sargent Hollow Mine in Wise County, VA. The major concern was that this mining practice places section personnel inby of the gob. The tentative approval permitted barrier pillar slabbing and removal of the adjacent development pillar during panel development. The intent of the plan was to provide a "stress shadow" for the advancing faces and outby workings to reduce the excessive number of roof falls. Sargent Hollow successfully extracted their first panel by pillaring on advance and retreat mining using posts. Mobile roof supports were employed to extract pillars while advancing the second panel. This paper summarizes Sargent Hollow Mine's experiences with the advance and relieve mining method.

INTRODUCTION

Several U.S. coal mine operators have come to the realization that underground mining conditions are highly dependent upon roadway orientation. For example, in the Eastern U.S., virtually all longwall panels are oriented approximately east-west, and very rarely north-south. Another situation, sometimes referred to as "first panel syndrome," has also plagued numerous longwall and room-and-pillar mines. With first panel syndrome, extremely adverse ground conditions are experienced when developing and retreating the first panel in a new reserve. However, at many of these operations, favorable ground conditions were experienced in subsequent panels. Over the past two decades, researchers have determined that adverse ground conditions associated with both of these phenomenon are caused by high horizontal stresses (*1, 2*).

In mine workings subjected to high horizontal stresses, many operators have also experienced roof damage in the entry which intersects the horizontal stressfield first. However, satisfactory ground conditions were encountered in the adjacent entries. This fact, coupled with first panel syndrome, indicates that horizontal stresses can only be fully transmitted through intact rock. Roof falls, fractured ground, and gob areas apparently stress relieve or "stress shadow" nearby workings (*3*). Based on these observations, mine operators have employed sacrificial entries or caving chambers (*4*), roof slotting, and other tactics to stress shadow adjacent workings. As the name "sacrificial" implies, the entry which enters the stressfield first, sustains roof damage and is sacrificed for neighboring entries (figure 1). This strategy has been employed to help insure stability in headgates, tailgates, and other critical entries. With roof slotting, a cutting machine is used to cut a vertical slot into the roof near mid-entry. This technique was tried at a Northern West Virginia operation. The 15-cm (6-in) wide slot closed 7.5 cm (3 in) within two days after cutting it. In an Illinois coal mine, the 15-cm (6-in) wide slot converged 7.5 cm (3 in) within 7 days of cutting it (*5*). The pillar extraction on the advance mining method has also been employed to combat ground control problems associated with high horizontal stress in Australia (*6*). With this method, pillars on one side of the panel are extracted as the panel is developed. The intent of the plan is to stress shadow the advancing faces and outby workings in order to reduce the occurrence of roof falls.

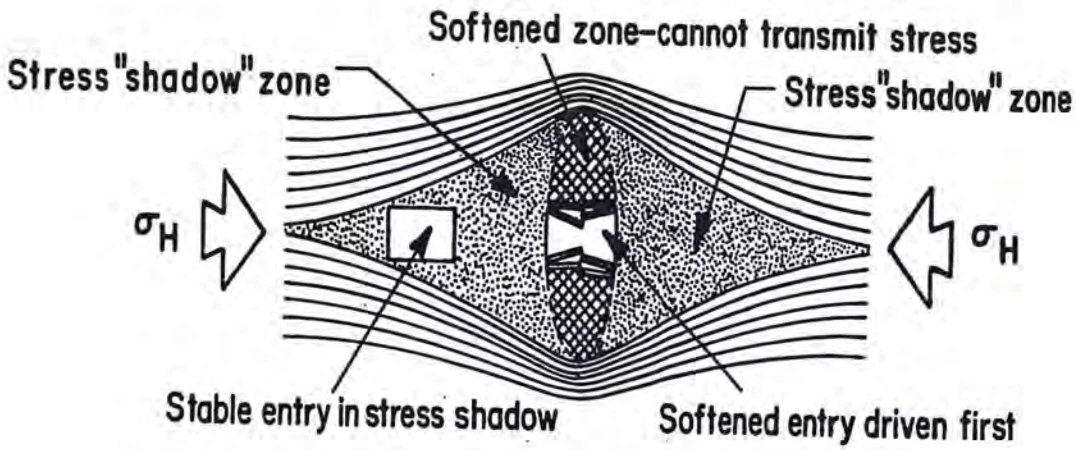

Figure 1. Development of a stable entry in the stress shadow of a sacrificial entry (2).

Over the past two decades, researchers from the National Institute for Occupational Safety and Health (NIOSH) and the former U.S. Bureau of Mines have investigated the problems associated with high horizontal stresses in underground coal mines (*7*). During this time, numerous case histories documenting successful and unsuccessful mining designs and methods to mitigate stress related problems have been determined (*2, 8*). Another opportunity to collect an unique case history developed when a series of unintentional roof falls and related injuries occurred at the Sargent Hollow Mine. At the request of the mine operators and the Mine Safety and Health Administration (MSHA), NIOSH personnel conducted underground geotechnical evaluations to determine the causative factors of these falls. The initial mine visit indicated that the weak roof strata was being subjected to and damaged by high horizontal stresses. After discussions, the mine operators and the Virginia Department of Mines, Minerals, and Energy (DMME) personnel, and Sargent Hollow Mine operators expressed an interest in employing the novel advance and relieve mining method. Subsequently, the mine operators requested NIOSH assistance in determining the maximum horizontal stress direction, and also to both monitor and evaluate the mining methods effectiveness. It was readily apparent that if this mining method proved to be successful in reducing the occurrence of stress related roof falls, that its applicability to other mines facing similar conditions might prove to be wide ranging.

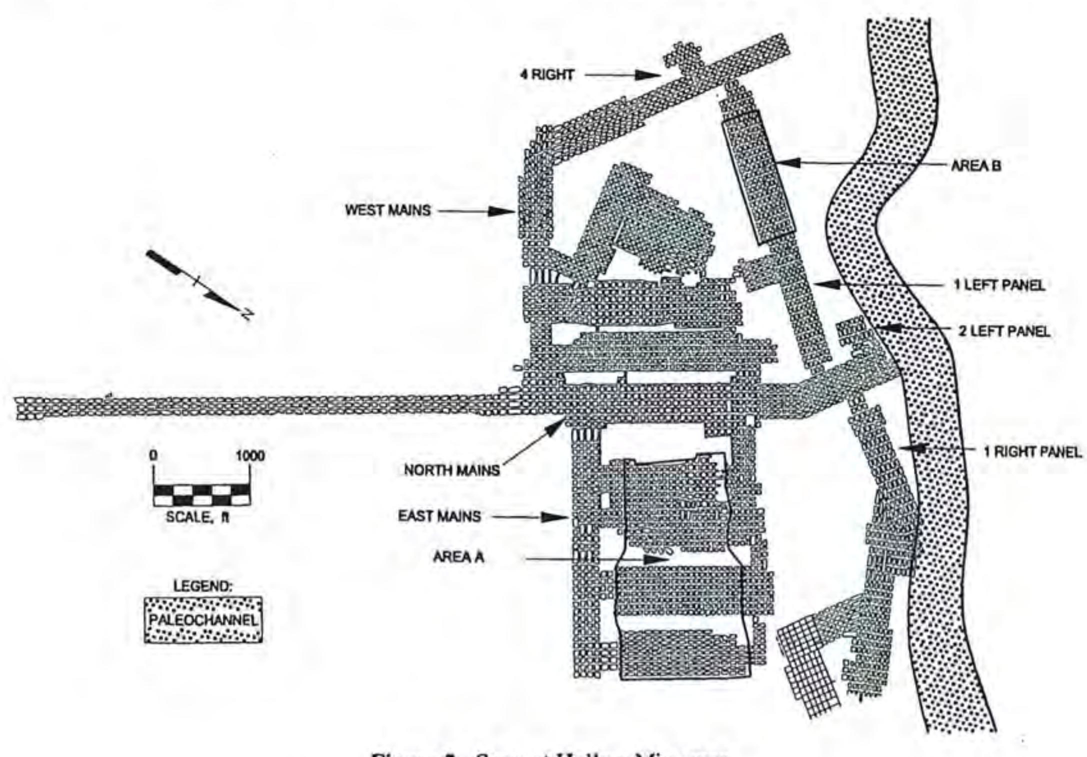

Figure 2. Sargent Hollow Mine map.

MINE SETTING

Sargent Hollow mine is located in Wise County, VA. The mine is extracting the 1.1-m (42-in) thick Blair Coalbed. The Blair Coalbed is notorious for having poor roof conditions, and several operators have been unsuccessful in their attempts to mine adjacent reserves. In order to access the mineable reserves, mine operators drove four, 1,525-m (5,000-ft) long mainline entries (figure 2) from the highwall through coal and rock. The roof rock at Sargent Hollow is highly variable. In portions of the mine, the immediate roof is a rooted mudstone (underclay) overlain by a 2.5-10-cm (1-4-in) thick rider coal. In other areas of the mine, a more competent shale occurs immediately above the coalbed. The Coal Mine Roof Rating values (*9*) for the former is typically in the low 30 range, and in the low 40's for the latter. Considerable channel activity also occurred contemporaneously with both peat and roof sediment deposition at Sargent Hollow Mine. This activity is evidenced by in-seam partings (splits), alternating thin layers of sandstone, shale, and coal (stackrock), and paleochannels (washouts or wants). Each of the above mentioned roof rock types, except for the massive sandstone channel deposits, are highly susceptible to horizontal stress damage. This was evidenced by the frequency of unintentional roof falls, and the regular occurrence of cutter roof failures (figure 3), ribline guttering, and stress roof potting. High horizontal stress conditions were also suggested by "first panel syndrome" which occurred in the first of a series of panels driven off the East Mains (figure 2, Area A). Overburden in Area A ranged from 91 to 206 m (300 to 675 ft). Under the deepest cover, the Analysis of Retreat Mining Pillar Stability Factors (ARMPS SF) were 1.1 or greater (*10*).

Figure 3. Cutter roof failure.

ADVANCE AND RELIEVE MINING METHOD

Due to the high frequency of unintentional roof falls and related injuries, discussions were held with roof control specialists from MSHA, DMME, and NIOSH to consider the advantages and risks associated with an advance and relieve mining method. The overlying concern was that if a gob fall over-rode the breakers into the working faces, the incident could jeopardize the safety of section personnel. Although a similar concept had been successful in Australia, it had never been formerly tried in the U.S. On June 2, 1998, a tentative approval, pending results of an in-mine evaluation by MSHA and DMME, to advance and relieve was granted to Sargent Hollow Mine. The test site was located in 1 Left Panel off the North Mains (figure 2, Area B). In 1 Left Panel, eight entries were driven on 15.2-m (50-ft) centers as shown in figure 4. The crosscuts were driven on 21.3-m (70-ft) centers, and the roadways were approximately 6.1-m (20-ft) wide. Because of the section's ventilation plan, entries were advanced from right (number 8 entry) to left. In the roadways, primary support consisted of 1.8-m (6-ft) tensioned rebar bolts (# 6 rebar grade 60) which were installed with a 0.6-m (2-ft) equivalent of grout. In the intersections of number 1 and 2 entries, and other areas where conditions warranted, 2.4m (8-ft) tensioned rebar bolts (# 6 rebar grade 60) were used. Cover over 1 Left Panel varied from 198 to 274 m (650 to 900 ft).

NIOSH personnel stress mapped (*8*) several miles of underground workings to determine the horizontal stressfield direction. Knowledge of this direction is critical in order to determine an optimum panel orientation and correct pillar plan (figure 4). Based on this mapping, the maximum horizontal stress (σ_H) direction was determined to be ENE, which is in agreement with the regional stressfield (*11*). Figure 4 illustrates one preferred panel orientation with respect to the horizontal stressfield, to maximize the workings being advanced into the stress shadow zone. As indicated in figure 4, the number 1 entry will intersect the stressfield first, and therefore, pillaring should be conducted on the left side of the panel to produce the stress shadowing effect. Figure 5 depicts the approved timber plan and cut sequence for Sargent Hollow's advance and relieve plan. As shown on figure 5, five lifts, outby to inby, were taken from the number 1 entry to slab the barrier pillar. Similarly, three lifts are then removed from the adjacent development pillar from the number 2 entry. A final lift is then taken from the development pillar from the inby crosscut. Prior to barrier and production pillar extraction, the roof control plan stipulates that the working faces must be developed at least two crosscuts inby the area to be pillared, as shown in figure 4.

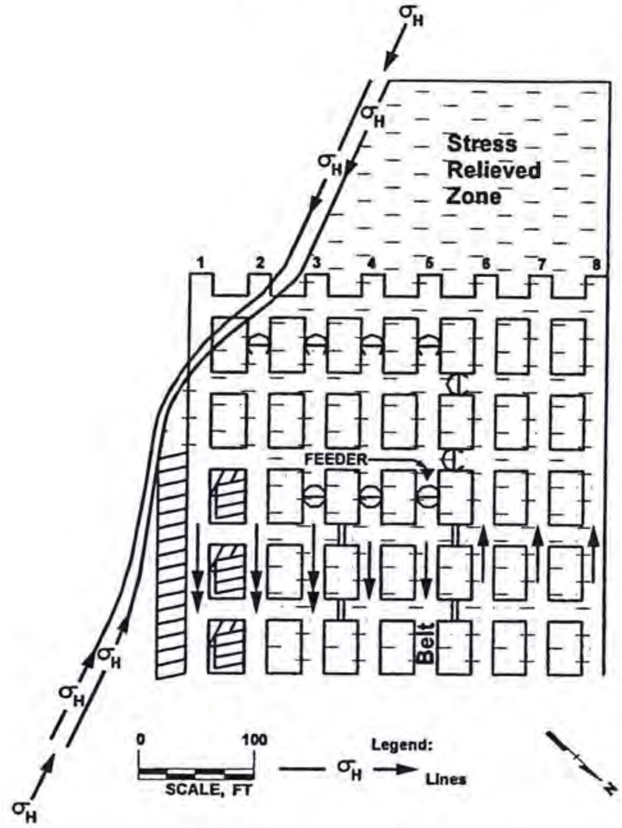

Figure 4. Layout for 1 Left Panel showing stress relief zone.

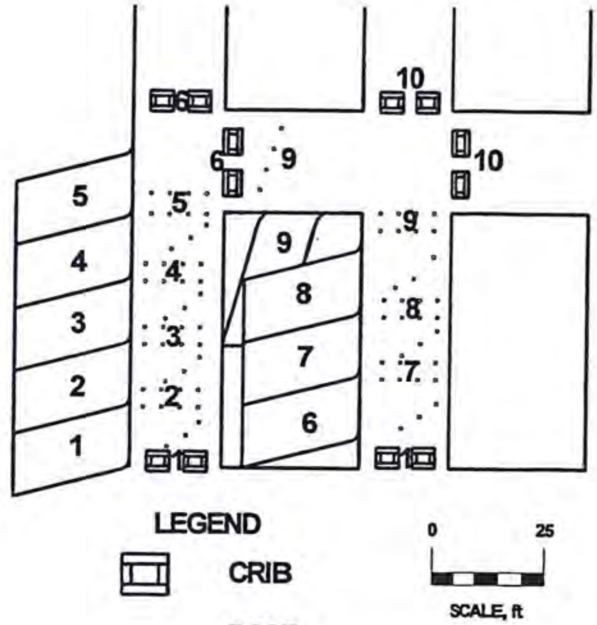

Figure 5. Timber plan for 1 Left Panel.

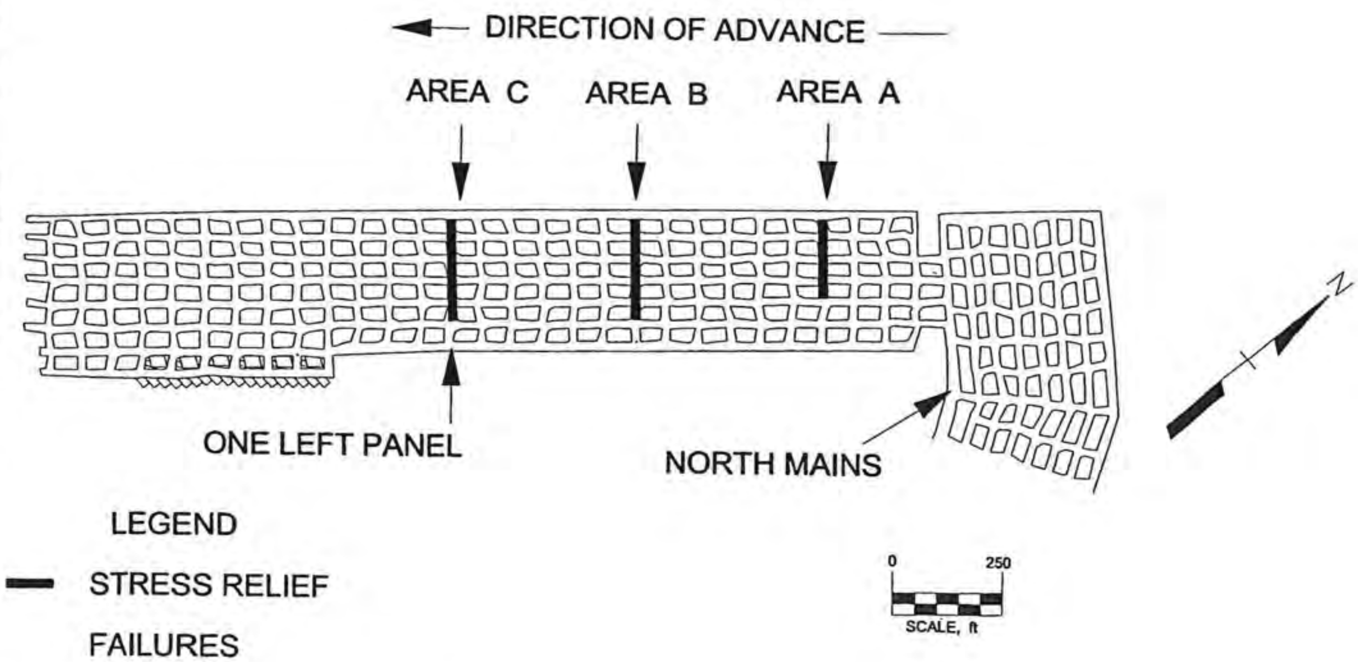

Figure 6. Crosscut stress relief failures in 1 Left Panel.

As was expected, the number 1 entry sustained considerable damage on development, causing difficult conditions during barrier slabbing because the entry was located in a stress concentration. Conversely, excellent ground conditions were generally encountered on the right side of the panel, especially in the number 8 entry, because the workings were advanced into the stress shadow zone. One interesting note is that prior to instituting the advance and relieve plan, 1 Left Panel experienced incremental increases in loading after each successive row of crosscuts were established. The section continued to load up until it had been advanced eleven crosscuts, at which time, the workings located eight crosscuts outby began deteriorating and breaking up (figure 6, Area A). The area was immediately spot bolted using 2.4-m (8-ft) bolts, and the crosscuts were heavily cribbed. Some cribbing was also necessary in the adjacent entries. Tension cracks and cutters continued to develop, and excessive roof spalling also occurred. The roof appeared to be broken up and failed, and was most probably resting on the heavily loaded cribs. Shortly afterward, the entire section appeared to be stress relieved. The section was advanced eight more crosscuts and the same pattern of loading conditions and roof damage occurred again. This time the damage occurred in the workings located six crosscuts inby of the first area affected (figure 6, Area B). When the scenario repeated itself a third time (figure 6, Area C), it became obvious that some type of periodic horizontal stress buildup was developing. Periodic horizontal stress buildup, in one form or another, has also been observed in other coal mine operations. NIOSH personnel were on the section to observe the next cycle. However, the outby crosscut workings did not load up or fail as was expected. The most likely explanation was that the newly implemented advance and relieve plan had de-stressed the outby workings. In fact, the pillaring had been started just two crosscuts outby the crosscut location of where the next damaged workings were expected. The ground control problems which occurred in the number 1 entry and in the crosscuts were bothersome, but not overwhelming. After the advance and relieve mining method was implemented, overall mining conditions at Sargent Hollow improved, and the roof control plan was approved for further use.

After intersecting 4 Right Panel off the West Mains (figure 2), 1 Left Panel was retreat mined. An ARMPS SF of 1.0 or greater was maintained during panel retreat. Development of 2 Left Panel (figure 2) began in October 1998. Even more favorable ground conditions were anticipated in this panel because of the stress shadowing provided by the adjacent gob in 1 Left Panel. However, rapidly changing geological conditions proved to be the unknown variable at Sargent Hollow. A thick in-seam parting and poor roof conditions associated with a nearby paleochannel were encountered, and mining was terminated in the 2 Left Panel. Mining then began in the 1 Right Panel (figure 2). Once more, very favorable mining conditions were experienced with the advance and relieve mining method. Two of the reasons for this success was increased pillar recovery and more rapid panel advance due to mobile roof support (MRS) usage. MRS's were used in lieu of turn posts and cribs during pillar extraction (*12*). Observations of the gob area where the timber plan had been used in 1 Left Panel (figure 5) indicated that only partial caving was occurring in the immediate roof rock to an approximate height of 1.5 - 1.8 m (5-6 ft). It was obvious that the pillar remnants, posts, and cribs were inhibiting complete caving. With MRS's, only eight entry breaker posts are required to slab cut the barrier per crosscut, and total of 16 entry and crosscut breaker posts are necessary to extract the production pillar (figure 7). It was evident from observations back into the gob that more complete and higher roof caving was occurring in the 1 Right Panel. In fact, roof caving intersected the sandstone paleochannel at one location. Gob caving was so complete that the channel was broken into large units, some of which were 1.8-m (6-ft) thick. Figure 7 indicates the cut sequence for pillars driven on 28-m (90-ft) crosscut centers.

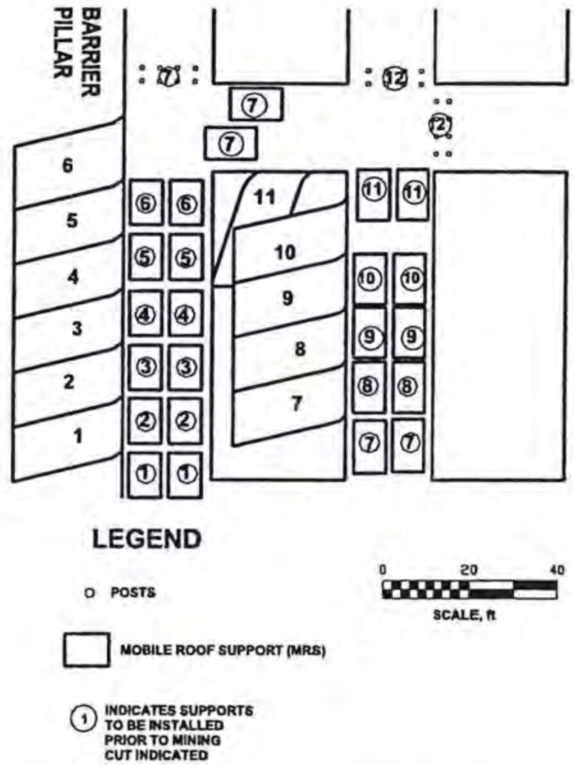

Figure 7. Approved plan for single development pillar extraction using MRS's.

Development continued in 1 Right Panel until another thick in-seam parting and poor roof conditions associated with a nearby paleochannel were encountered. The panel was then reoriented to a direction adjacent and parallel to the trend of the parting and the channel (figure 8, Area A). During this realignment, barrier and production pillar extraction were halted. As a result, the section began experiencing severe loading, and additional time was lost setting cribs. In an attempt to stress relieve the workings, a modified roof control plan approval was granted to extract the pillars shown on figure 8 in Area A. Unfortunately, pillar removal failed to mitigate the problem, and four large falls occurred over a 24-hour period. After turning the panel, the advance and relieve plan was reinstated. Semi-favorable mining conditions were encountered for the next four rows of crosscuts. At this point, difficult ground conditions started occurring in the number 1 entry and pillar recovery was incomplete. In January 1999, Sargent Hollow received an approval which allowed for the extraction of the barrier and two production pillars on advance (figure 9). The reasoning behind this plan was that enhanced stress shadowing would occur on the section because a wider pillared out area would induce higher roof caving. Because of the location of the power center, it was necessary to develop another entry on the left side of the panel to provide the additional pillar to be removed. A less favorable panel orientation with respect to the maximum horizontal stress direction coupled with the time required to develop the additional heading proved costly. As previously mentioned, pillar recovery was incomplete immediately outby, and the number 1 entry was already beginning to load up. By the time pillaring could begin, section personnel deemed it unsafe to try to recovery the two pillars next to the barrier as shown on figure 8, Area B. This only aggravated the problem and the section began experiencing severe loading immediately outby of the working faces. Cutters and tension cracks started ripping the roof, and the pillars began spalling and popping indicating that they were taking weight.

Section personnel continued to address the problem by cribbing extensively until conditions permitted barrier and production pillar extraction. Within a matter of minutes after extraction was completed, NIOSH and mine personnel observed a noticeable improvement in ground conditions, giving further credence to the advance and relieve plan. It became readily apparent after this experience that mining operations must remain on cycle, failure to systematically stress relieve the workings through pillar extraction invited unnecessary problems. It is important to note that after 1 Right Panel was reoriented, optimum directional mining with respect to the maximum horizontal stressfield was diminished because the section was driven approximately parallel to the maximum horizontal stressfield. This less than desirable orientation reduced the number of working faces being advanced in the stress relief zone, and also placed the crosscuts in an unfavorable direction (nearly perpendicular) with respect to the stressfield. The adverse conditions encountered underground confirmed that this mining direction produced unacceptable results. The cover over 1 Right Panel ranged from 190 to 297 m (625 to 975 ft).

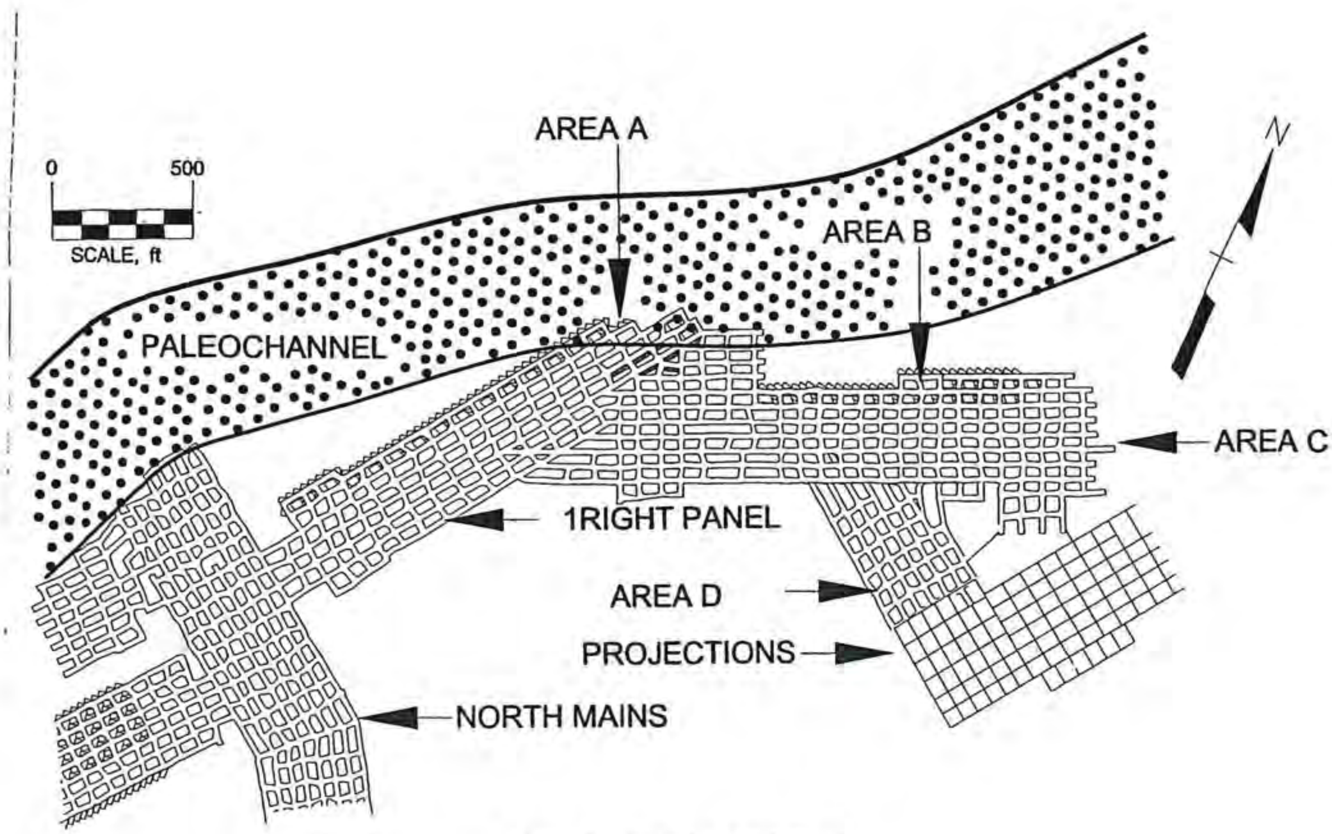

Figure 8. Layout for 1 Right Panel.

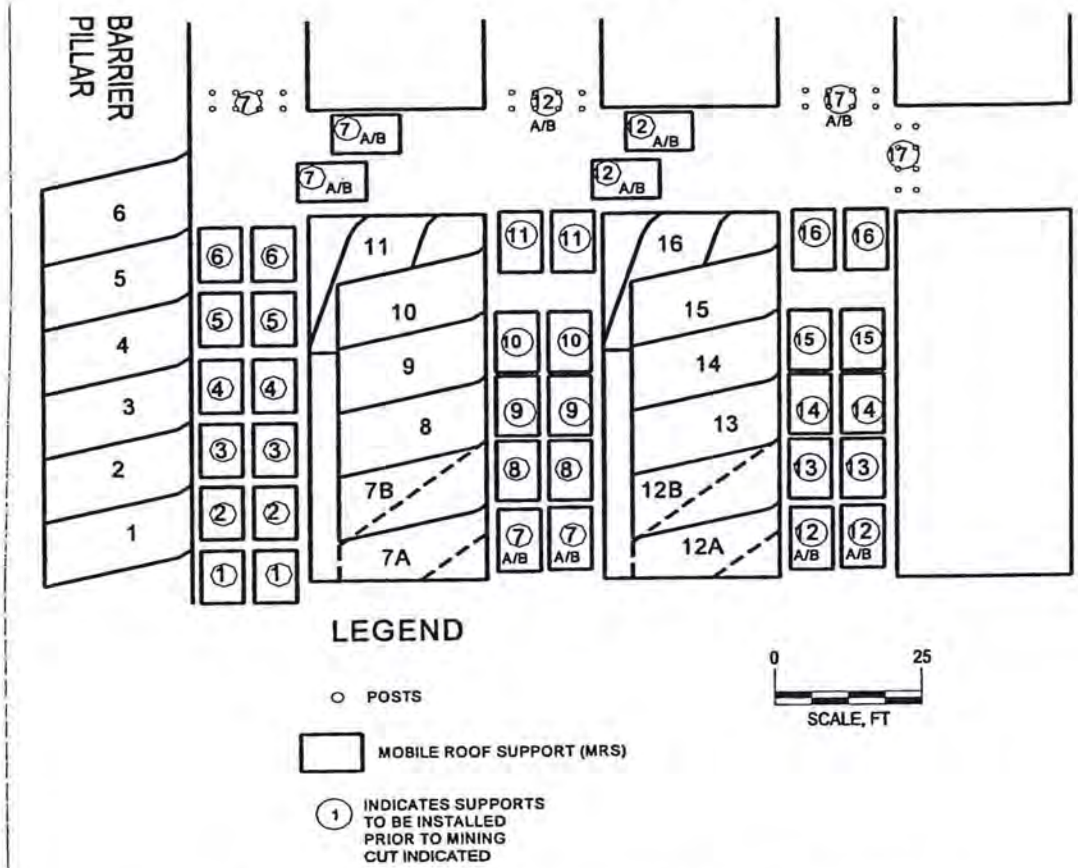

Figure 9. Approved plan for dual development pillar extraction using MRS's.

It should be indicated that MSHA personnel also conduct an independent underground study of the advance and relieve plan conducted at Sargent Hollow Mine (*13*). The most significant findings of this investigation include:

1. Difficult mining conditions occurred in several areas where the depth of cover exceeded 850 ft. It is probable that vertical stress also contributed to poor ground conditions.

2. Barrier and single pillar extraction may have been beneficial in improving ground conditions at Sargent Hollow Mine. It is not clearly evident that the favorable mining conditions which occurred in the areas where the advance and relieve mining method was used were due solely to stress relief. Changes in roof lithology and/or higher pillar stability factors in low cover areas could have been the primary factors for improved conditions.

3. Roof deterioration index and stress mapping indicated that conditions worsened when dual production pillar extraction was employed. Dual pillar extraction might be detrimental. One reason for this might be added abutment load transfer.

DISCUSSION

Difficult ground conditions associated with a paleochannel in the roof was most probably a key factor in halting 1 Right Panel development (figure 8, Area C). In fact, oppressive mining conditions occurred in each location where the channel was encountered (2 Left Panel, North Mains development, and 1 Right Panel, Area A). Poor mining conditions in proximity to paleochannels are attributable to two factors. First, channel margin geology is typically composed of weak rock types (*14*) which are extremely susceptible to high horizontal stresses. Second, there is a general consensus that where the roof strata are subjected to high horizontal loads, that stress concentrations occur along the stiffer sandstone intrusion (*15*). Although this has not been confirmed by direct measurements in the U.S., British work indicates that horizontal stresses are higher in stiffer strata such as sandstone (*16*). Many coal mine operators have experienced problems with channels similar to those at Sargent Hollow, even where dealing with small channels. As shown in figure 8, Area D, 1 Right Panel was reoriented away from the channel margins to access the reserves. After the panel is turned, the advance and relieve plan will be reinstated in a more favorable orientation with respect to the maximum horizontal stressfield. In order to keep the section advancing in a timely manner, only one production pillar will be removed on development. Where the mining was terminated in 1 Right Panel (figure 8, Area C), the cover was 297 m (975 ft) and the pillars had an ARMPS SF of 1. Although this stability factor is lower than the suggested 1.5, analyses of case histories in the ARMPS data base in other mines where the overburden exceeded 200 m (650 ft) indicate that pillars with equivalent stability factors have provided satisfactory ground conditions. NIOSH is currently investigating this and other issues pertaining to deep cover pillar recovery.

As indicated earlier in the paper, NIOSH and mine personnel stress mapped miles of workings to determine the maximum horizontal stress direction. Micro stress damage features such as bolt hole shifting and cutter and pot orientations were inconclusive in determining the maximum horizontal stress direction in both 1 Left and 1 Right Panels. The ENE compressional stressfield which was identified in 1 Left Panel was based on two macro features. Namely, the failed roof zones which primarily occurred in the crosscuts. The other factor which was used to establish the orientation was the stress concentration damage which developed in the number 1 entry. These same two stress damage macro features were also observed in 1 Right Panel (figure 8, Area B), where the sections orientation had been changed approximately 25° as compared to 1 Left Panel. Based on the differing orientations of the macro stress damage features in 1 Left and 1 Right Panel after reorientation, it appears that the maximum horizontal stress direction may not be well defined over this portion of the mine property. As previously indicated, in order to maximize the workings being advanced into the stress shadow zone, the panel should be correctly oriented with respect to the maximum horizontal stressfield. The above mentioned facts suggests that maximum stress shadowing may not have occurred in the working faces. However, the outby workings were stress relieved, and this was most probably a contributing factor in the noticeable reduction of outby roof falls.

Another topic which warrants discussion in this paper is panel width. Obviously, the more narrow the panel, the faster it can be both developed and stress relieved. This has led Sargent Hollow Mine Operators to opt for single development pillar extraction using MRS's. As indicated earlier, Sargent Hollow began extracting two production pillars to induce higher caving in order to enhance the stress shadowing effect. The logic being that the stresses would flow above the caved zone and over the adjacent workings. However, this required that the panel be widened and stress damage could have occurred in the number 8 entry. It is important to remember that the stress shadowing effect is limited in extent. The horizontal stress levels in the immediate roof will return to their "pre-relieved values" at some point beyond the failed ground. Where dealing with high horizontal stresses, one should examine the problem as a three dimensional issue, and realize that there is a risk of stress damage occurring in the outside entries of wider panels. As for Sargent Hollow's experiences with dual production pillar extraction, the unfavorable panel orientation coupled with channel margin roof geology did not provide reasonable mining conditions to evaluate the plan's effectiveness. If these problems were mitigated, the dual pillar extraction method may warrant further consideration.

One final matter which was debated is how many crosscuts the pillared out workings should lag behind the working faces. Clearly, the faces would be stress relieved sooner if pillaring were conducted one crosscut outby instead of two. The major concern however was, that a pillar line fall may override the breakers into the face area. This actually occurred, without incident, on two occasions at Sargent Hollow. Both of the incidents occurred after 1 Right Panel had been reoriented (figure 8, Area B). On one of these occasions, mine personnel allowed the roof to fall for additional stress relief because the heading was going to be discontinued.

CONCLUSIONS

1. Roof control problems associated with high horizontal stress were significantly reduced after initiating the single production pillar advance and relieve plan at Sargent Hollow Mine. Underground experiences indicated that timely panel advance and systematic pillar extraction were critical to the plan's success. Single development pillar extraction using MRS's proved to be the most effective method of keeping the section on cycle. However, this is not to say that equally effective, or even more effective, results might be achieved utilizing the dual pillar extraction method given the proper circumstances.

2. Prior to instituting an advance and relieve plan, mine personnel should stress map underground workings adjacent to the planned mining area to determine the maximum horizontal stress direction. This information is critical when determining both the panel orientation and the correct pillar plan.

3. Where dealing with high horizontal stresses, one should examine the problem as a three dimensional issue, and consider restricting panel width to minimize the possibility of stress damage occurring in the outside entries. It is important to note that the stress shadowing effect is limited in extent. The horizontal stress levels in the immediate roof will return to their "pre-relieved values" at some point beyond the failed ground. Also, narrower panels can be developed and stress relieved more rapidly which minimizes stress concentrations.

4. The face areas will be stressed relieved more quickly the closer the pillared out workings are to the faces. However, gob falls can override the breakers into the face area. Where conducting optimum directional mining with respect to the maximum horizontal stressfield under favorable geologic condition, additional study and experience is warranted to resolve whether the pillared out workings should lag one or two crosscuts outby of the faces.

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