HIGH STRESS MINING UNDER SHALLOW OVERBURDEN IN UNDERGROUND U.S. STONE MINES

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ABSTRACT:

The Chestnut Ridge Anticline is a prominent structure in southwestern Pennsylvania, USA. This structure has brought two economically valuable limestone formations to the surface, where they are easily accessible to room-and-pillar mining. Nine active crushed stone quarries, an underground research facility, and one industrial facility currently operate along the linear trend that represents the axis of the anticline. The National Institute for Occupational Safety and Health (NIOSH) has identified significant variation in levels of horizontal stress within relatively short distances at shallow overburdens along the anticline. At one quarry, the horizontal stress is high enough to shear strata with a modulus of approximately 77 Gpa. Conversely, zones of extension were observed in parts of another quarry, indicating very low horizontal stress conditions. This study found that high levels of horizontal stress are to be expected in this very stiff rock formation and that local geologic and topographic structures are capable of altering the magnitude and possibly the orientation of the horizontal stress field.

INTRODUCTION

While examples of ground control problems associated with mining at depth abound, high horizontal stresses at low overburdens also exist in some locations and can significantly impact local mine ground control. Factors responsible for these excessive levels of stress need to be understood and engineering controls must be developed and implemented in order to reduce the risk of falls of ground to miners. To evaluate these factors, a prominent stone mining district 90 km southeast of Pittsburgh, Pennsylvania, USA was selected. This mining district is within the Mid-North American Plate where high horizontal stresses have been recognized (Zoback, 1992) and measured in many of the area’s coal mines (Mark and Mucho, 1994; and Su and Hasenfus, 1995).

In 1995 during some routine reconnaissance, the authors noted shear failures at an underground stone mine similar to the cutter roof failure so common in local underground coal mines. These shear failures were particularly revealing to the authors since they occurred in limestone roof rock with compressive strengths ranging from 138 to 240 Mpa. This is almost an order of magnitude greater than the brittle shale roof involved in many of the region’s coal mine cutter roof falls. It was apparent that stresses at this site must be high to fail such strong roof rock; however, the reasons for these excessive levels of stress were not readily apparent. This paper concentrates on explaining what factors might cause high stress conditions in this area. Discussions of the most effective techniques for minimizing the impact of excessive horizontal stress on miner safety have been discussed in another publication (Iannacchione et al., 2001).

BACKGROUND

Most of this region's stone quarries occur in one of three geologic units. The youngest is the Vanport limestone, mainly mined north of Pittsburgh, Pennsylvania, and known for it's high concentration of calcium carbonate. The other two limestones, the Greenbrier and Loyalhanna, are older geologic units contained within Middle-Mississippian strata. These two units are relatively close to one another, separated by non-carbonate rocks ranging in thickness from 0.3 m to approximately 10 m. Because of their close stratigraphic proximity, they often crop out in adjacent locations. In Pennsylvania, the Loyalhanna has been mined more extensively because it is thicker and contains a relatively high concentration of quartz, making it an excellent aggregate for highway construction.

The Loyalhanna, typically well below the coal measure rocks that blanket much of this area, is brought close to the surface along prominent anticlinal structures. The largest of these structures, Chestnut Ridge, Laurel Hill, and Negro Mountain Anticlines, are located southeast of Pittsburgh in the Allegheny Mountain Section of the Appalachian Plateaus Province (Figure 1). These anticlines form topographic highs that extend for great distances, paralleling the trend of the Appalachian Mountains further to the southeast. Chestnut Ridge is the last major anticline in the northwest portion of the Allegheny Mountain Section with significant structural relief. The Loyalhanna rises to heights between 500 and 800 m along the crest of the Chestnut Ridge and falls to depths as low as 150 m below sea level along adjacent synclines. It crops out at many locations along the length of Chestnut Ridge, supplying numerous locations for quarries.

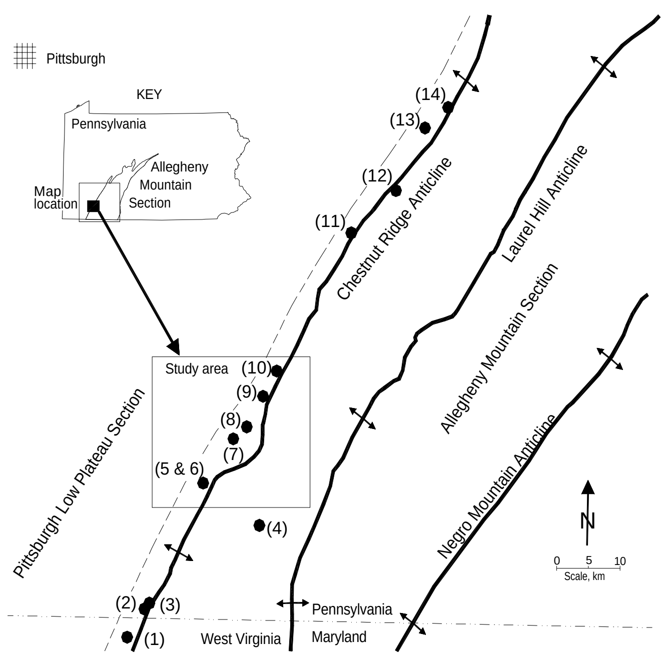

Figure 1 Three large anticlinal structures with more than 500 meters of elevation change occur within the Allegheny Mountain Section of the Appalachian Plateaus Province. Also shown are the locations of fourteen active and inactive quarries along Chestnut Ridge.

Nine active and three abandoned quarries are located in the Loyalhanna along Chestnut Ridge (Table 1). Two other sites are currently being used for research or industrial activities. It is remarkable that within this relatively high concentration of quarries, significant variations in stress and associated ground conditions exist. To help illustrate this variation, a portion of Chestnut Ridge centered around the Youghiogheny River Gorge was examined (Figure 1). This area possesses many of the diverse characteristics of quarries within this mining district. One of the quarries has excessive levels of horizontal stress while another has low levels of horizontal stress.

Table 1 Active and inactive quarries and other research and industrial sites within the Loyalhanna and Greenbrier Limestones along Chestnut Ridge.

No.	Name	County, State	Site Characteristic	Strata	Status
1	Buckeye	Monongalia, WV	Surface quarry	L[1] & G[2]	Active
2	Lake Lynn Laboratory	Fayette, PA	Experimental surface and underground quarry	L & G	Active
3	Laurel	Fayette, PA	Surface quarry	L & G	Active
4	Thompsons	Fayette, PA	Surface quarry	L	Inactive
5	Coolsprings No.1	Fayette, PA	Surface and underground quarry	L	Active
6	Coolsprings No.2	Fayette, PA	Surface and underground quarry	L	Active
7	Dynaclad	Fayette, PA	Industrial site surface and underground quarry	L	Active
8	Casparis	Fayette, PA	Surface and underground quarry	L	Inactive
9	Springfield Pike	Fayette, PA	Surface and underground quarry	L	Active
10	Rich Hill	Fayette, PA	Surface and underground quarry	L	Active
11	Whitney	Westmoreland, PA	Surface and underground quarry	L	Active
12	Latrobe	Westmoreland, PA	Underground quarry	L	Active
13	Gray=s	Westmoreland, PA	Surface quarry	L	Inactive
14	Torrance	Westmoreland, PA	Surface and Underground quarry	L	Active

[1]L = Loyalhanna Limestone
[2]G = Greenbrier Limestone

STRESS CONDITIONS WITHIN QUARRIES ALONG CHESTNUT RIDGE

In the past, Loyalhanna quarries were not expected to have stress-related problems because of their relatively shallow overburdens. An area containing 150 m of overburden with rooms and pillars 12 m wide should have average vertical pillar stresses of less 14 Mpa. Even with rooms 13.7 m and pillars 10.7 m wide, the average vertical pillar stress should be approximately 18 Mpa. If stress concentrations near the rib of the pillar double, these average values would reach 36 Mpa. Since the Loyalhanna's unconfined compressive strengths are 4 to 6 times greater than these peak stress conditions, it is unlikely that vertical stress, generated from the thickness of rocks above the mining horizon, will be a significant problem for this mining district.

If horizontal stresses were due solely to the Poisson effect, they would be even smaller that the vertical stresses. Such low stress concentrations could not possibly induce shear failures within the strong limestone roof rock, even in the thinnest of layers. However, this is not what is observed. Two quarries (9 and 12) have exhibited many of the characteristic signs of a mine with excessive horizontal stress conditions. At these quarries, extensive mapping of roof damage and roof falls confirms the presence of shear roof failure, a condition often found in Appalachian coal mines plagued with excessive horizontal stress ground control problems. Stress measurements at one quarry, using the hydraulic fracturing technique, found maximum principal stress values from 10 to 55 Mpa with the orientation of the principal stress direction from N 45° to 80° E (Iannacchione et al., 1998).

Within the northern Appalachian coal mines, it is common to find a maximum principal horizontal stress from 9 to 23 Mpa at overburdens of 120 to 240 m (Table 2). Both the Columbus (37.9 Mpa) and the Loyalhanna (47.7 Mpa) Limestones are outside the coalbed stress magnitudes; however, it can be shown that much of the difference is due to strata stiffness effects. If stress magnitudes are divided by the rock's Young's Modulus, strata strain can be calculated. The strains from the maximum stresses across the region vary from 461 to 736 microstrains. For the Loyalhanna, the strain from the 47.7 Mpa stress value with a Young's Modulus of 77.2 Gpa is just over 600 micro-strains. These results indicate that there is considerable uniformity in strains within the entire northern Appalachian region and the Loyalhanna seems to fit well into this regional pattern.

Table 2 Average stress measurements from mines in the northern Appalachian region.

Seam/formation	Maximum horizontal stress, Mpa	Minimum horizontal stress, Mpa	Maximum horizontal stress direction	Maximum horizontal strain, micro-strains	Depth, m
Lower Kittanning Coalbed	23.0	19.2	N 87° E	575	219
Lower Kittanning Coalbed	20.8	15.6	N 75° E	721	168
Pittsburgh Coalbed	9.1	7.1	N 32° E	736	122
Pittsburgh Coalbed	16.3	15.6	N 78° E	557	213
Pittsburgh Coalbed	21.2	15.0	N 70° E	461	244
Columbus Limestone	37.9	27.6	E-W	611	701
Loyalhanna Limestone	47.7	27.4	N 71° E	607	122

The similarity of northern Appalachian strain magnitudes and stress orientations clearly points to the influence of plate tectonics on regional horizontal stress conditions. Most measurements show that the maximum horizontal stress direction ranges from N 70° to N 80° E (Table 2). This direction correlates with the direction of movement for the North American plate as it is pushed from away from the Mid-Atlantic Ridge. The National Geodetic Survey computes the positions and velocities at numerous points around the world (Sella et al., 2002). These data have been used to determine the relative velocities of different tectonic plate motions (continental drift) and thereby map the movement of each plate. The North American Plate moves continuously away from the Mid-Atlantic Ridge at a rate of about 2.5 cm/yr. This knowledge is important since it helps us understand why some underground stone quarries can have such high horizontal stress conditions.

It should be noted that not all ground control problems are stress related. For example, at quarries 6, 10, and 11, the roof rock is generally stable with the exception of areas where increased concentrations of low-angled fractures cut the roof rock into a series of wedgeshaped structures. Quarries in this mining district seem to have a relatively high frequency of these kinds of roof rock conditions compared with other underground stone mines in the U.S. In general, the hazards they present can be controlled by appropriate scaling, bolting, or monitoring technique. Another ground control hazard that occurs at most Loyalhanna quarries is faulting. A series of faults extend across most mining properties at bearings of approximately N 38° E with dips of 15° to 32° in both the NW and SE directions (Iannacchione and Coyle, 2002).

GEOLOGIC AND TOPOGRAPHIC STRUCTURES AND THEIR INFLUENCE ON HORIZONTAL STRESS

Not all of the district's quarries have excessive levels of horizontal stress. There are locations within several quarries where the horizontal stresses are so low that the roof appears to be extending. Explaining how such dramatically different horizontal stress conditions exist so close to one another is more than just an academic exercise, in that techniques used to control the roof and rib for these two extreme stress conditions can be very different. The first step in identifying the controlling factors is to examine the specific geologic and topographic structures present along Chestnut Ridge. The study area centered around the Youghiogheny Gorge because quarries there exhibit a wide range of stress conditions and there is sufficient data available to perform a geologic and engineering analysis.

Chestnut Ridge is a large anticlinal structure with a broad flat crest and limbs that dip as much as 20° to the northwest and southeast (Figure 2). Along the crest of the anticline, the Loyalhanna experiences significant elevation changes. The highest elevations above sea level typically occur within domes, or elliptical areas along the crestline, where the rocks dip gently away in all directions. Quarries 5 and 6 are located along the northeastern end of the Summit Dome where the Loyalhanna rises some 700 m above sea level. Northeast from the Summit Dome the Loyalhanna falls along the crest of the Chestnut Ridge, entering the broad Youghiogheny Saddle. Structural saddles are low points along the crestline of a ridge. This saddle structure is coincident with the Youghiogheny River Gorge. To the northeast of this saddle structure, the Loyalhanna rises again to a minor unnamed dome.

The northeast portion of Summit Dome has three caves and a large strike-thrust fault (Figure 2) that parallels the axis of the Chestnut Ridge Anticline (Iannacchione and Coyle, 2002). The Youghiogheny Saddle has only one cave, located along the Youghiogheny Gorge. The gorge may have formed in conjunction with a large cross-strike slip fault at depth. There is no direct evidence for this fault; however, in this area the anticlinal axis is significantly distorted, and the dips of the associated strike-thrust faults rotate from northwest to southeast on either side of the gorge. The existence of a major cross-strike structural feature is supported by the projection of the Maryland-Pennsylvania Lineament through this area (Pohn, 1995). This structure may form the lateral boundary between major sheets of strata thrusted away from the Appalachian Mountains to the southeast.

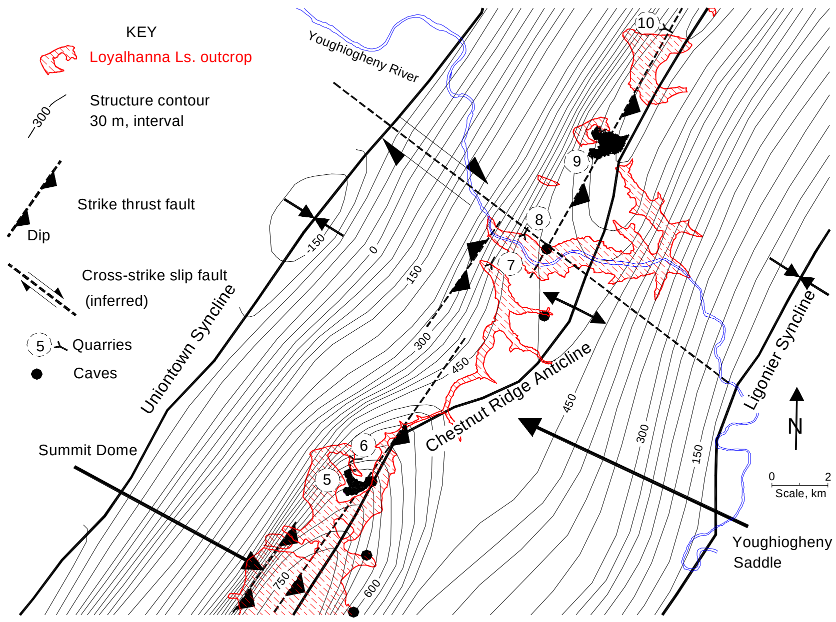

Figure 2 Chestnut Ridge's structural setting in the Youghiogheny Gorge area, showing the locations of quarries, caves, faults, and the Loyalhanna Limestone outcrop.

High Stress Conditions

Within the study area, Quarry No. 9 (Figure 2) is the one with excessive horizontal stress. It is located along the northeastern portion of the Youghiogheny Saddle. Horizontal stresses are great enough to cause sporadic roof shearing and, on occasion, have developed into massive directional roof falls. Roof instabilities typically begin with the development of compression zones consisting of low-angle shears oriented approximately N 30° W. Most roof falls are oval in shape with the long axis oriented in this same N 30° W direction. Most of these failure patterns support the existence of a pervasive horizontal stress field oriented approximately N 60° E (Location A, Figure 3).

At Quarry No. 9, the Loyalhanna outcrops in a relatively small area. During initial mine development, this quarry mined in a portion of the reserve that was surrounded by outcrop on three sides (Location B, Figure 3). Some portion of the original horizontal stress field was partially relieved through down-dip extension of the strata adjacent to the outcrop (see zone of extension, Figure 3). Here, no signs of excessive levels of horizontal stress were observed. The occurrence of shear failures and the associated directional roof falls only became a problem as the mine developed away from outcrop. Additionally, the character of joints from the quarry are unique, clustering around the N 65° E trend (Figure 4). Many of these joints have dips ranging from 25° to 70°. Weathered joints are rare, with some joints coated with a brown stain that implies surface water infiltration, but the vast majority of the joints show no signs of weathering. Faults are also found at this quarry and generally show signs of thrusting with minimal displacements (0 to 1 m).

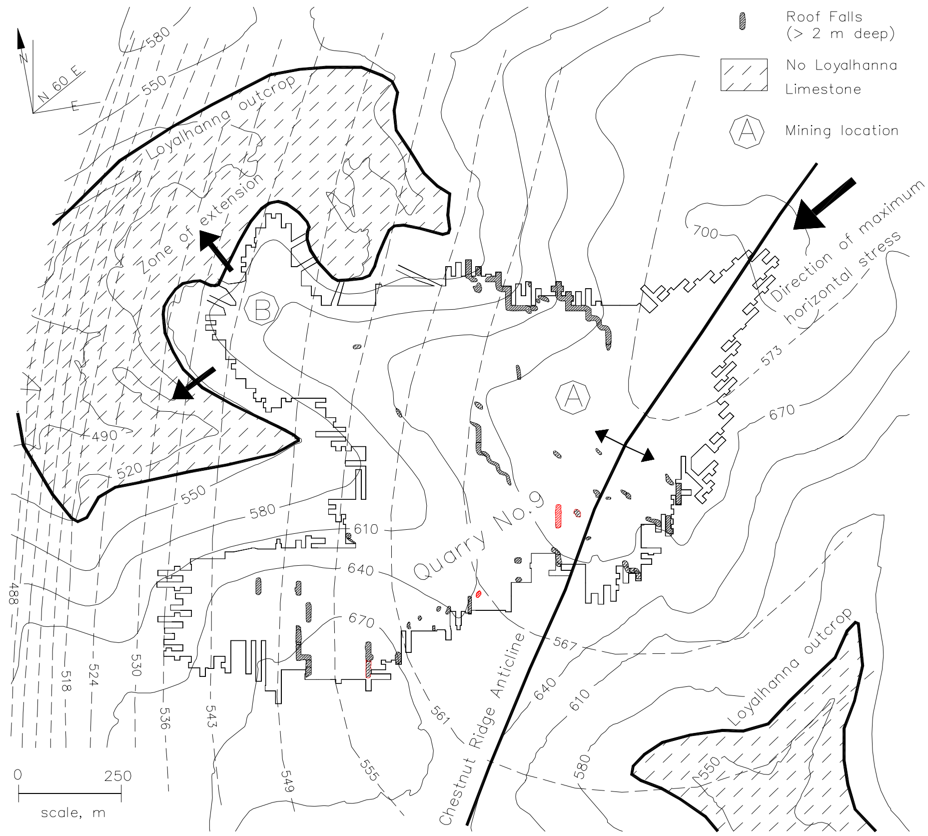

Figure 3 Structure contour elevations on the Loyalhanna Limestone, Loyalhanna outcrop, surface topographic contours, horizontal stress characteristics, and roof falls within and adjacent to quarry No. 9. Note: dashed lines are the Loyalhanna structure contour and solid lines are the topographic contours.

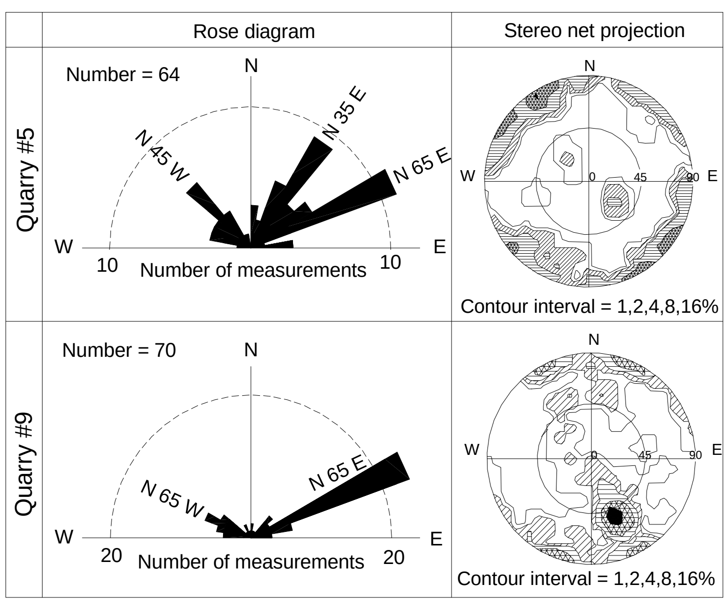

Figure 4 Rose diagrams and stereonet projections of strike and dip datum for joints and faults within quarries No. 5 and No. 9.

Low Stress Conditions

Some 9 km from this site a significantly different condition exist. At quarry No. 5, the entire underground mine is surrounded on three sides by outcrop (Figure 5). During initial mine development, rooms were driven up-dip from the portal within a narrow strip of strata approximately 300 m wide. The first significant ground control problem occurred when mining encountered the regional strike-thrust fault (Location C, Figure 5). Once the mine advanced through this area, conditions improved until mining progressed under the nose of an oval-shaped knob at the top of Chestnut Ridge (Location D, Figure 5), where significant ground control problems were encountered. In this area, the Loyalhanna gradually slopes towards the northwest. Here the N 35° E and N 65° E joint sets trend approximately parallel to both the knob and the anticlinal crest. Many of these joints are weathered with some of the them containing a residual fine-grained material. This material infilling was sometimes removed, probably by erosion, and voids several feet in diameter were observed. The joints in this area are sub-parallel with the mine's headings and cross-cuts. The spacing of these joints is such that one to three joints were encountered during normal development of a room. On one visit to the mine, the authors observed several massive roof falls outlined by these weathered joint structures. Because of the extensive weathering and the occurrence of voids, pre-existing horizontal stress could have dissipated as these large blocks nearest the outcrop separated from the confined, intake rock mass under the influence of gravity (see zone of extension, Figure 5).

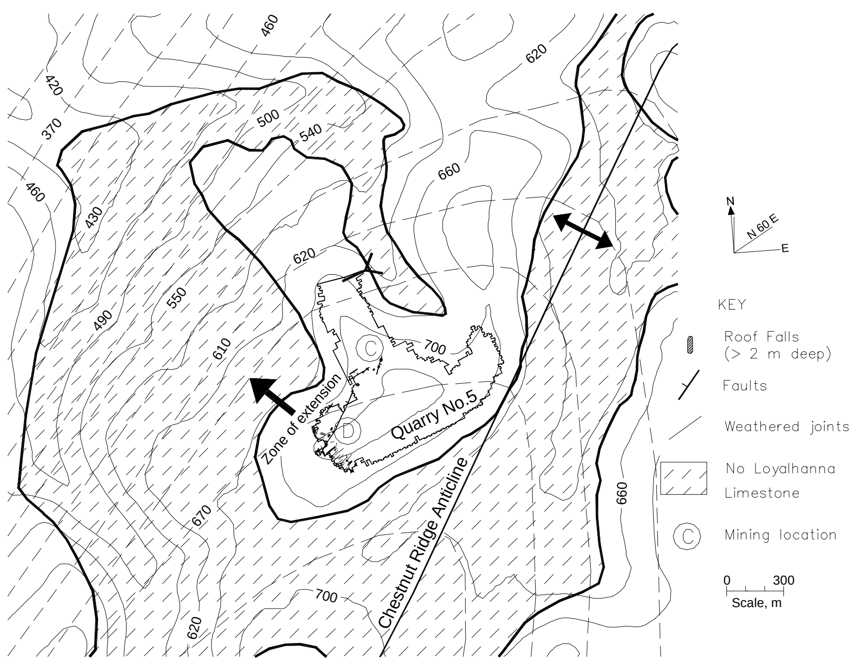

Figure 5 Structural contour elevations on the Loyalhanna Limestone, Loyalhanna outcrop, surface topographic contours, roof falls, weathered joints, and faults within and adjacent to quarry No. 5. Solid lines are topographic contours and dashed lines are Loyalhanna contour elevations.

DISCUSSION

The quarry with the excessive horizontal stress conditions is located on the margins of the Loyalhanna Saddle structure. With the exception of the outcrops that developed along the Youghiogheny Gorge, this structural feature produced fewer outcrop exposures than the adjacent saddle structure. Additionally, the jointing within this area included of more dipping joints and fewer weathered joints than the average quarry within this district. Here it would seem the regional stress field has been unaffected by surface topography.

There is also some evidence that this area is adjacent to a large cross-strike structure that extends from the Appalachian Mountains to the southeast through the Youghiogheny Gorge. Perhaps the distortion of the anticlinal crestline, the rotation of the strike-thrust fault dips, and the shape of the associated saddle structure are influenced by the inferred cross-strike slip fault. This kind of geologic structure could locally add additional strain to the substantial amount already present within the northern Appalachian region. In addition, the shape of the saddle structure may act to promote strata confinement, since the Loyalhanna dips both towards and away from its center.

Reductions in horizontal stress due to geologic and topographic structures were observed and documented at both quarries No. 5 and No. 9. Within a dome structure, strata dip away from the center in all directions. Domes are characterized by large concentrations of caves and weathered joints. All of these conditions could act locally to lower horizontal stress.

Certain topographic structural shapes can isolate strata, producing unconfined rock outliers. In the absence of confinement, water can readily attack the rock mass, dissolving limestone along its most vulnerable features–the rock joints. These joints isolate blocks of strata that, under the right conditions, can move away from the outcrop. The extension of blocks away from the solid, confined rock mass is influenced by the structural dip of the strata and the presence of a bedding plane that allows the rock to glide down-dip.

At quarry No. 5, joints are strongly weathered, producing a fracture trace that contains clay infilling ranging from a thin film to several feet in width. The degree of joint weathering increases toward the outcrop and is especially prevalent along the nose of the outlier (surrounded on three sides by outcrop). In this area the strata dip to the northwest, promoting the movement of large blocks down-dip. The extension of the strata has a detrimental effect on strata stability. Joint orientation and spacing are such that large blocks of strata can occur within these large rooms that are unsupported by pillars. Horizontal forces, applied perpendicular to the joint surface, keep these blocks in place. The lower the stress, the less rock load the joint can support. Thus, when horizontal stress is reduced by strata extension, there is an increased risk of roof failure.

SUMMARY AND CONCLUSIONS

It has been established that levels of horizontal stress high enough to produce shear failures within the very stiff Loyalhanna limestone exist and are probably caused by strains within the middle of the North American Plate. Where these excessive stress conditions exist, free from the influences of significant geologic and topographic structures, they appear to fit the regional strain pattern. It has also been established that excessive horizontal stresses are not necessarily a condition found within all underground quarries of southwestern Pennsylvania. A detailed geologic and topographic examination was made of two relatively closely spaced quarries with very different stress conditions to help examine factors that may be responsible for these diverse conditions.

Geologic and topographic structures can act to alter horizontal stress conditions. Geologic structures evaluated in this study were associated with the changing shape of Chestnut Ridge Anticline. The crestline of this anticline is composed of domes and saddles. Domes are enclosed structural contour elevation areas where the Loyalhanna dips rapidly away from the center of the dome. Domes are characterized by increases in caves and weathered joints. These geologic structures could be acting as stress reduction zones.

Saddles are structural depressions along the Chestnut Ridge Anticline where the Loyalhanna strata dip both towards and away from its center. Saddles are characterized by a decrease in caves and weathered joints and an increase in cross-strike structural features. These structures do not reduce the stress and leave the regional stress regime intact.

Topographic structures evaluated in this study were those shapes that produced laterally discontinuous Loyalhanna strata. These topographic structures were knobs and ridges where the Loyalhanna outcrops on several sides. In general, the closer the mining front comes to an outcrop, the greater the potential for stress reduction. If the outcrop partially surrounds the mining zone, then this zone becomes an outlier of the strata. If mining takes place in an outlier area and the dip of the strata is towards the outcrop, then there is an increased risk for strata extension. In some of these mining environments, the stress magnitudes are low enough to allow blocks of unsupported roof, outlined by weathered joints, to fail and produce large roof falls. These topographic structures reduce the stress, altering the regional stress regime.

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