AN EXAMINATION OF THE LOYALHANNA LIMESTONE'S STRUCTURAL FEATURES AND THEIR IMPACT ON MINING AND GROUND CONTROL PRACTICES

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ABSTRACT

A close look at the Loyalhanna Limestone of southwestern Pennsylvania reveals a complex structural environment. Most exposures of the Loyalhanna occur along Chestnut Ridge and Laurel Hill within the Allegheny Mountain Section of the Appalachian Plateaus Province. Because the Loyalhanna is rated as a super-pavement aggregate by the Pennsylvania Department of Transportation and because of its proximity to the population centers of southwestern Pennsylvania, the Loyalhanna has been extensively mined along these prominent anticlinal structures.

Geologic and engineering analyses were performed using gas well and core logs, outcrop examinations, underground observations, and mine maps. Strata exposures from both outcrops and quarries were used to construct geologic maps, stereonet, and rose diagram projections so that the Loyalhanna's structural environment could be understood better. Many of these structural conditions cause ground control problems at local quarries. These problems ranged from small-to-moderate sized rock falls associated with roof jointing to pillar failures associated with dipping discontinuities. Stresses ranged from tensional on structural domes where weathering dominates, to high levels of compression within structural saddles. A greater understanding of these characteristics is a prerequisite to develop engineering controls, such as improved mine layouts, pillar sizes, etc., that lessen miner exposure to these hazards.

INTRODUCTION

The Loyalhanna Limestone varies in composition from a quartzose limestone to a calcareous quartz arenite (1). It underlies 17,000 square miles of West Virginia, Maryland, Pennsylvania, and Ohio and averages 60 ft in thickness with a maximum thickness of 103 ft (1). Wells (2) has since expanded the aerial extent of the Loyalhanna to Sullivan Co. in the northwestern portion of Pennsylvania. While this limestone is found under an extensive area in four states and is a major source of crushed stone for southwestern Pennsylvania, it has a limited area accessible to mining. The Loyalhanna, which is typically greater than a thousand feet below the surface in the Pittsburgh Low Plateau Section of the Appalachian Plateaus Province, crops out at numerous sites along the crest of Chestnut Ridge, Laurel Hill, and Negro Mountain Anticlines in the Allegheny Mountain Section of the Appalachian Plateaus Province (figure 1). These outcrops have historically been the sites for commercial aggregate mining, especially those closest to the population centers in and around Pittsburgh, Pennsylvania. Currently nine quarries mine the Loyalhanna through underground and surface operations in Monongalia Co., West Virginia, and Fayette and Westmoreland Counties, Pennsylvania, (table 1) along the linear trace of Chestnut Ridge.

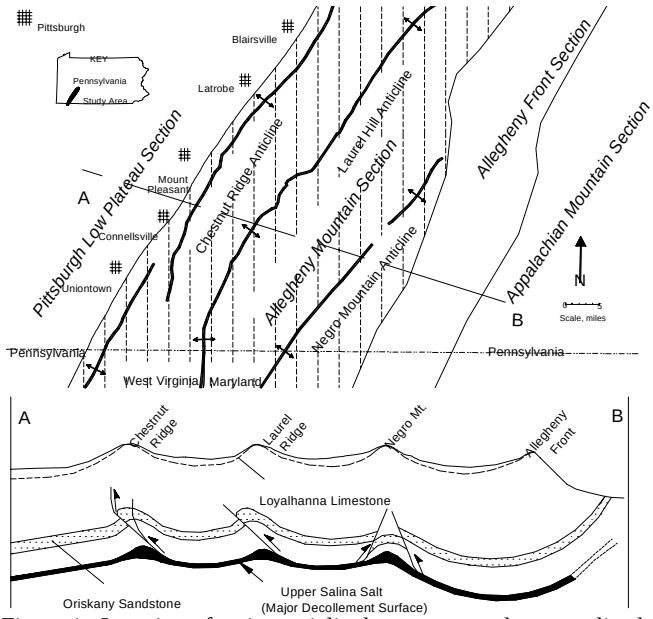

Figure 1. Location of major anticlinal structures and a generalized cross-section through the Allegheny Mountain Section of the Appalachian Plateaus Province.

The Chestnut Ridge Anticline is a fold with limbs dipping away from each other and, with erosion, exposes older geologic beds nearest its central core. As this fold was produced in conjunction with the formation of the Appalachian Mountains, the rocks fractured and broke to form joints and faults. Understanding the characteristics, such as orientation, dip, and spacing, of these structural features is necessary for mine design and development.

Table 1. Quarries, strip mines, and road cuts visited during study along Chestnut Ridge.

Letter	Name	County	Site Characteristic
A	Buckeye	Monongalia	Surface quarry
B	Laurel	Fayette	Surface quarry
C	Rt. 40	Fayette	Road outcrop
D	Coolsprings No. 1	Fayette	Surface and underground quarry
E	Coolsprings No. 2	Fayette	Surface and underground quarry
F	Springfield Pike	Fayette	Surface and underground quarry
G	Rich Hill	Fayette	Surface and underground quarry
H	Whitney	Westmoreland	Surface and underground quarry
I	Latrobe	Westmoreland	Underground quarry
J	Torrance	Westmoreland	Surface and Underground quarry
K	Bolivar	Westmoreland	Abandoned coal strip mine

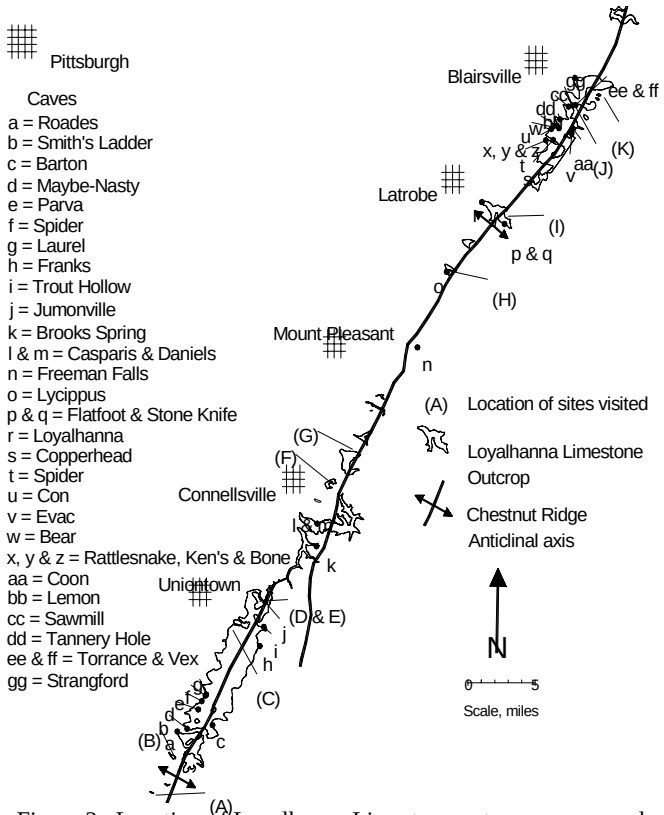

Figure 2. Location of Loyalhanna Limestone outcrop, caves, and sites visited during this study. Capital letters A, B, D, E, F, G, H, I, and J are quarries; C is a highway outcrop; and K is an abandoned coal strip mine.

These characteristics are also found in the 33 Loyalhanna caves along Chestnut Ridge (3). In general, these caves are comprised of a single passage extending several hundred yards although a few are made up of extensive interconnecting passages, such as Laurel Caverns and Bear Cave (Sites G and W, figure 2). Most of the caves are found within two structural highs or domes along Chestnut Ridge which are named after the gas fields they encompass, Summit and Griffin. In these areas the Loyalhanna has the greatest elevations and outcrop exposures, producing joints that are deeply weathered and, in many places, caves.

Mines along Chestnut Ridge have experienced roof and rib falls with some falls resulting in injuries to mine workers. One quarry with a workforce of approximately 30-miners experienced 7-injuries from ground falls over a 30-month period from March 1993, until September 1995 (table 2). A second mine had vehicles struck by falling rocks approximately a dozen times during a 12-month period. A third mine reported 9 roof falls to the Mine Safety and Health Administration (MSHA) during an 18-month period from April 1999, until November 2000 (4). Ground falls range in volume from boulder size rocks, falling from the roof or rib, to massive roof falls measuring 45 ft wide by 20 to 30 ft high and extending as far as 500 ft (figure 3). Many of the ground falls were, in part, due to the unique and complex structural environment of the Loyalhanna. The primary reason for initiating this National Institute for Occupational Safety and Health (NIOSH) study is to increase knowledge of the root causes of these hazards and promote the use of timely ground control measures so that miner safety can be improved.

Table 2 - Roof fall injury data for one quarry from March, 1993, to September, 1995.

Date	Injury	Job
March 3, 1993	1 fatal injury	Pumping
September 19, 1994	2 injured	Drilling
October 25, 1994	1 injured	Scaling
December 28, 1994	1 injured	Blasting
May 25, 1995	1 injured	Blasting
August 23, 1995	1 injured	Scaling

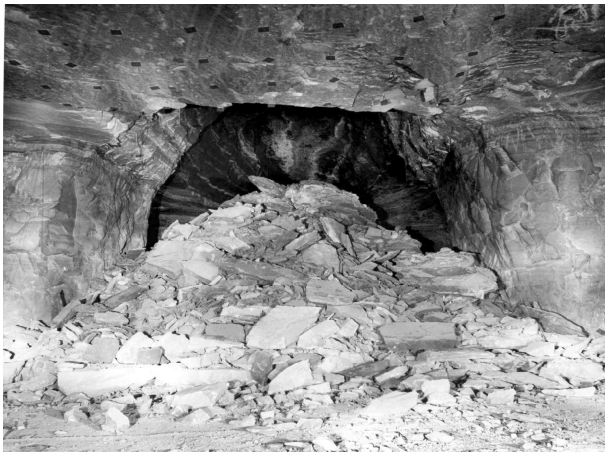

Figure 3. Massive roof fall measuring 45 ft wide by 20 to 30 ft high and extending for approximately 200 hundred feet.

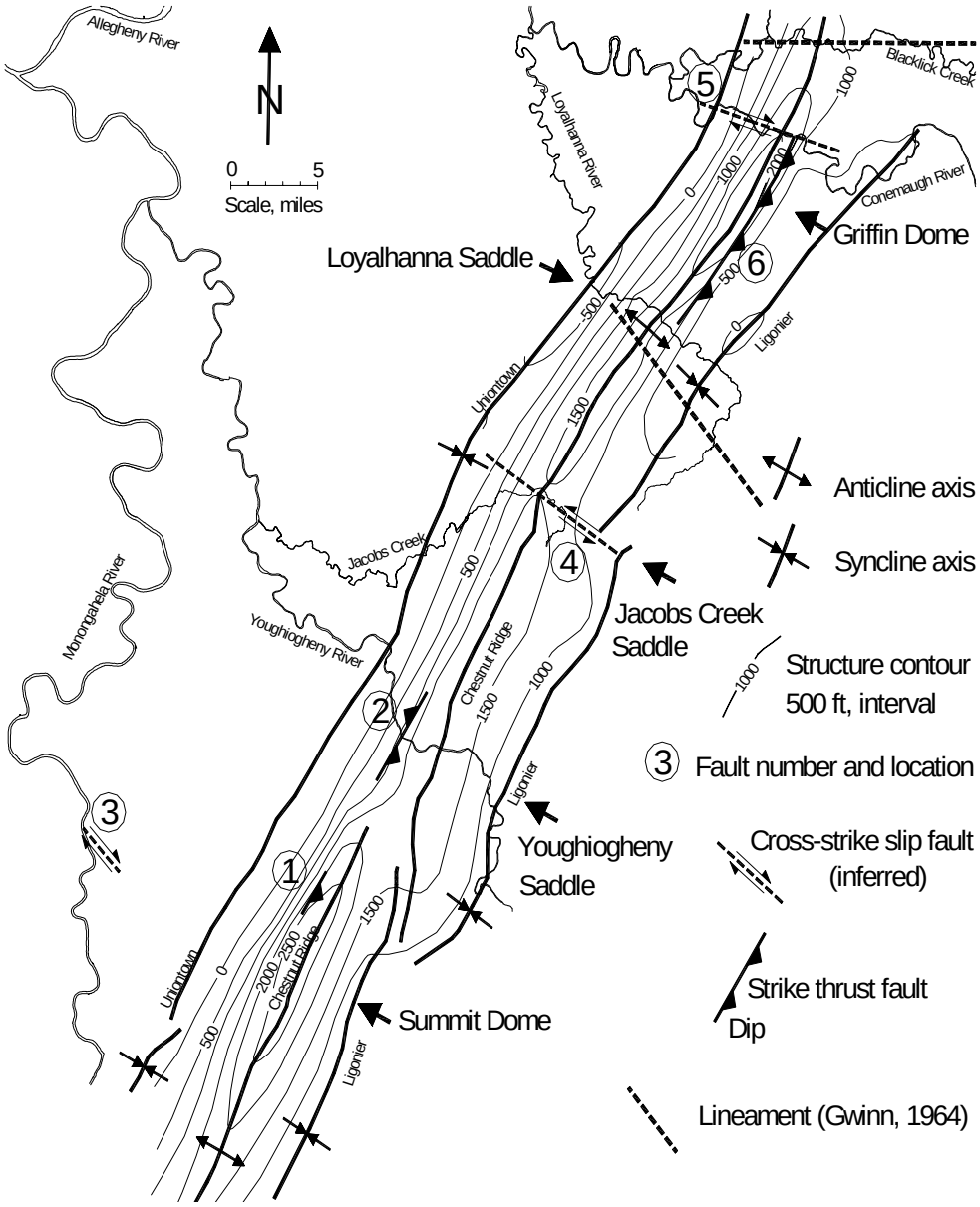

Figure 4. Structure contour map on the top of the Loyalhanna with major fold structures, surface faults, lineaments, and rivers and streams.

THE STRUCTURE OF THE CHESTNUT RIDGE ANTICLINE

Chestnut Ridge is a large anticlinal fold which was formed as part of the Appalachian Mountain system. This topographic feature is a subdued structure in comparison to the intensely folded and faulted strata in the Valley and Ridge Province some 30 miles to the east. However, upon closer inspection, significant structures exist in the form of steeply dipping strata, thrust and slip faults, lineaments, and a complex array of joints. All of these structures can present localized hazards to miners. This factor is important since Chestnut Ridge is southwestern Pennsylvania's major source of high-quality aggregate and miners will inevitably be exposed to these conditions as they do their work.

Major anticlinal folds within the Appalachian Plateaus Province of Pennsylvania are generally arcuate convex to the northwest and parallel to the arc of the Central Appalachians. Structural relief on anticlines decreases in step-like fashion northwestward in all parts of the plateau (5). Chestnut Ridge is the last anticline in the northwest portion of the Allegheny Mountain Section with significant structural relief. The shape and character of the Chestnut Ridge Anticline was analyzed in past geologic reports by McElroy (6), Hickok and Moyer (7), and Shaffner (8, 9). In this study, a structure contour map on the top of the Loyalhanna was prepared from oil and gas wells and limestone exploration drilling data (figure 4). The Loyalhanna was found to rise from depths between sea level and 1,000 ft along the Ligonier Syncline to heights between 1,500 and 2,700 ft along the crest of the Chestnut Ridge. Along the western flanks of Chestnut Ridge, the Loyalhanna rapidly drops into the Uniontown Syncline, where it can be found as much as 500 ft below sea level. The highest

areas form enclosed contour elevations called domes. The Summit Dome (figure 4) lies midway between the Cheat River Gorge to the southwest and the Youghiogheny River Gorge to the northeast. The Griffin Dome (figure 4) lies further to the northeast between the Loyalhanna and Blacklick Creeks.

The crest of the Chestnut Ridge Anticline experiences significant elevation reductions, dropping to approximately 1,500 ft along three prominent saddle structures. These three structural depressions or saddles along the anticlinal axis have rivers or streams coincident with them. The saddle northeast of the Summit Dome is coincident with the Youghiogheny River, northeast of it lies the Jacobs Creek Saddle, and further to the northeast lies the Loyalhanna Saddle. In one case, an inferred cross-strike slip fault (Fault No. 4) is coincident with the Jacobs Creek Saddle structure (9). In another case, the Loyalhanna Saddle structure coincides with a major lineament structure discussed by Gwinn (5). A lineament is "a mappable simple or composite linear feature of the earth's surface whose parts are aligned in a straight or gently curved relationship and presumably reflects a subsurface phenomenon" (10). The relationship between the saddle structures and other structural features will be discussed later in the paper.

DEEP-SEATED STRUCTURES AND DISCONTINUITIES AT THE SURFACE

With accelerated oil and gas exploration in the 1950's and 60's along Chestnut Ridge, unsuspected structures were discovered at depth. Repeated geologic sections were noted along with other evidence that suggested significant faulting near the base of the Devonian. Deeper wells below the Upper Silurian Salina Group found the geologic section to be regular with no evidence of complex structure (5). The Salina Salts act as the principal basal detachment horizon or decollement beneath much of the Appalachian Plateaus Province.

Apparently the Loyalhanna and surrounding strata in the Allegheny Mountain Section have moved some distance along the Salina detachment horizon (figure 1). In addition, the overlying Middle Devonian rocks are intensely faulted. The faults originate within the Salina and quickly rise into a series of branching splay thrust faults under the limbs of the anticline. The complicated nature of the stiffer rock units between the Salina and the Tully Limestone is shown in figure 5 where these units are either stacked in an imbricate fashion by ramping thrust faults (5) or flexurally bent by an overturned fold with imbricate faulting (11). Gwinn explained the stacking at depth as caused by shortening of the detached strata above the Salina Salt. This produced a depressed zone along the anticlinal crest which has helped to create Chestnut Ridge's broad fold at the surface. Shumaker indicates that the highly deformed Salina has thickened into a salt core under some parts of Chestnut Ridge. The overlying Middle Devonian rocks are overturned in relatively tight folds with large splay faults emanating from the base of the overturned limb.

Both Gwinn and Shumaker state that the strata above the Tully shows far less deformation than the rocks below this unit. Wiltschko and Chappel (12) suggested that most faults were absorbed by the Upper Devonian shales and did not extend above the Tully. While the displacements and frequency of faults are far less at the surface than at depth there is little doubt that many of the Middle Devonian faults have made it to the Loyalhanna. It is important that this connection be made so that the trends established at depth can be

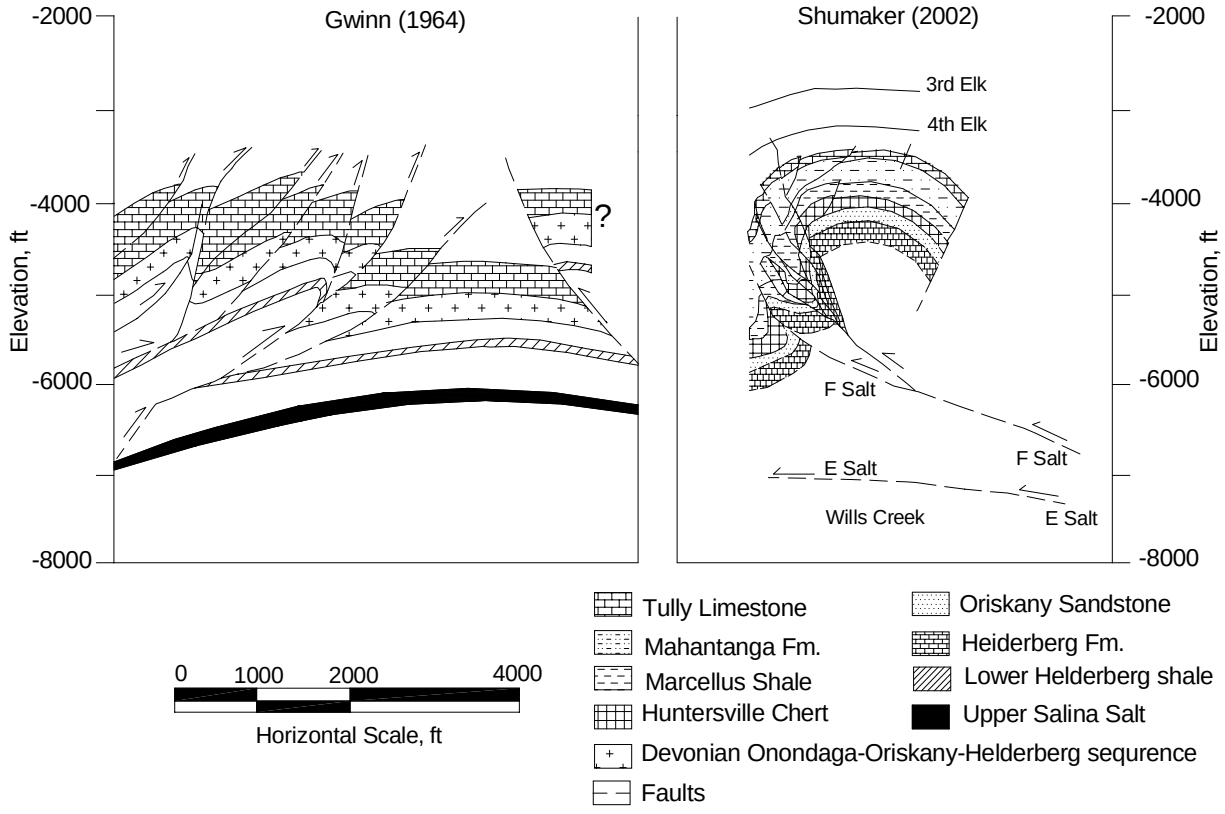

Figure 5. Complex structure under Chestnut Ridge at depths of -2,000 to -8,000 ft below sea level (5, 11).

looked for in the near surface rocks.

The intensity of movement at depth is not uniform along Chestnut Ridge as evidenced by differences in deformation patterns. Movements have been concentrated within lateral ramp zones that are bounded by cross-strike slip faults. Pohn (13) noted that sometimes these faults reach the surface and are observed as: 1) an abrupt change in wavelength or a termination of folds along strike, 2) a conspicuous change in frequency of mapped faults at the surface, and 3) long, straight river trends. The Conemaugh and Jacobs Creek slip faults, the Loyalhanna lineament, and the Youghiogheny saddle all have some of the features listed by Pohn (figure 4). To date, none of the quarries are actively mining within one of these structures, but several are mining in proximity and in time must decide if mining there is prudent. Thus the potential for exposing unstable strata associated with prominent discontinuities in these areas is very high.

EFFECT OF FOLDING ON MINING

The Chestnut Ridge Anticline provides access to the Loyalhanna but also limits the extent to which room-and-pillar mining can occur. Along the length of this anticline, the fold rises and falls in a fairly gentle fashion into domes and saddles. Here the strata typically dips from 1 to 5° and rarely exceeds 10°. The anticlinal crest is surprisingly broad so that many quarries have the opportunity to mine across these relatively flat areas for 0.5 to as much as 1.5 miles. Along the flanks of Chestnut Ridge, the strata quickly drop off into the adjacent synclines. This is especially true of the western flank, where the distance from anticline to syncline ranges from 4 to 6 miles with elevation changes of 1,800 to 2,800 ft. Several traverses were measured where strata dips ranged from 5 to 10°, with the steepest sections approaching 20°. On the eastern flank of the anticline the dips are slightly less severe, where the distance from anticline to syncline ranges from 4 to 5 miles with elevation changes of 900 to 2,100 ft. Here the average strata dips ranged from 3 to 6°. The degree of difficulty in mining with the room-and-pillar techniques grows significantly with dips exceeding 10°.

AFFECTS OF FAULTING ON MINING

Six major faults have been previously recognized within the study area as shown in figure 4. Three of the faults were reported by Hickok and Moyer (7) and three were reported by Shaffner (8, 9). Two were observed on the western flank of Chestnut Ridge (Fault No. 1 and No. 2), a third along the Monongahela River (Fault No. 3), a fourth and fifth inferred slip faults transecting Chestnut Ridge (Fault No. 4 and No. 5), and a sixth was observed along the eastern flank of Chestnut Ridge (Fault No. 6). These faults can be classified as either strike thrust faults or cross-strike slip faults. The strike thrust faults, in general, have bearings along the strike of the anticlinal structure and dip at a relatively low angle. The cross-strike slip faults (Faults No. 4 and No. 5) were never actually seen by Shaffner although he speculated that they must exist in order to explain the topographic and structural anomalies in this area. The inferred strike of these faults is perpendicular to the anticlinal structure with dips of approximately 90°. These trends are consistent with those expected in response to the formation of the Appalachian Mountain System. A summary of the characteristics of each fault shown on figure 4 follows:

1. The first fault is exposed along Rt. 40 (Site C, figure 2) where it climbs the western flank of Chestnut Ridge at an altitude of about 1,600 ft. It appears to be a thrust fault striking nearly parallel to the Chestnut Ridge Anticline (N 30° E) and the dipping about 30° SE.

2. The second fault is along the Western Maryland Railroad track in the Youghiogheny gorge about 0.7 mile south of the water pumping station across the river from South Connellsville. Here the fault itself was not seen, but the contact of the Greenbrier limestone with the overlying Mauch Chunk red shales has been moved down on the southeast side of a gully with respect to the same beds on the northwest side of the gully. According to Hickok and Moyer (7), a fault occurs here, but what its dip and strike are could not be determined. The displacement seems to be about 40 to 60 ft. The authors believe this to be a strike-thrust fault.

3. The third fault was found to parallel an adjacent kimberlite dike (14) which cuts the same strata and is recognized as a cross-strike slip fault. Its strike is N 45° W and the dip is nearly vertical. The horizontal displacement could not be determined but there was a 3.5 ft vertical displacement (7).

4. The fourth fault is inferred to occur along Jacobs Creek where the axis of the anticline has significant flexures, a local bulge in the structure, and a mild local reversal of the dip on the east limb of the anticline in the vicinity of the Pennsylvania Turnpike (9). A somewhat similar structural condition exists along adjacent portions of Laurel Hill Anticline, where a relatively milder flexure of the anticline axis is accompanied by a structural bulge on the east limb of the anticline. This inferred feature is considered a cross-strike slip fault.

5. The fifth fault is again inferred by Shaffner (9) on the basis of the difficulty in matching structure contour lines on opposite sides of the Conemaugh River. He estimated that this slip fault displaced strata by as much as 1,000 ft and probably influenced the course of the Conemaugh River in this area. This inferred feature is considered a cross-strike slip fault.

6. The sixth fault is exposed along the east flank of Chestnut Ridge, south of the Conemaugh River where the Connoquenessing (Pottsville) sandstone crops out, striking generally N 35° E and dipping from 40 and 85° southeast, and forming a conspicuous hogback running parallel to the ridge (8). This strike-thrust fault was also observed by Puglio and Iannacchione (15).

In addition to these known and inferred faults, numerous other faults were observed during visits to several quarries. Figure 6 shows the location, bearing, and dip of these faults in various formats. First, the location, strike, and dip of each fault are displayed in conjunction with the structure contour map on the Loyalhanna. Second, a stereonet projection is provided which locates the poles of the fault planes. Two important facts are revealed in the stereonet: (1) the faults align along a consistent orientation of N 40° E, and (2) the dips of these faults vary widely from approximately 60° to the northwest through 80° to the southeast. The consistent strike is further illustrated with the associated rose diagram. The strike of N 40° E, observed at all quarries with the exception of Site F (figure 6), aligns closely with the general bearing of Chestnut Ridge. While the dips vary widely, some consistencies can be observed. For example, all the faults from sites G, H, and K dip to the southeast, whereas the majority of the faults from site D dip to the northwest. Site F shows both northwest and southeast dipping faults.

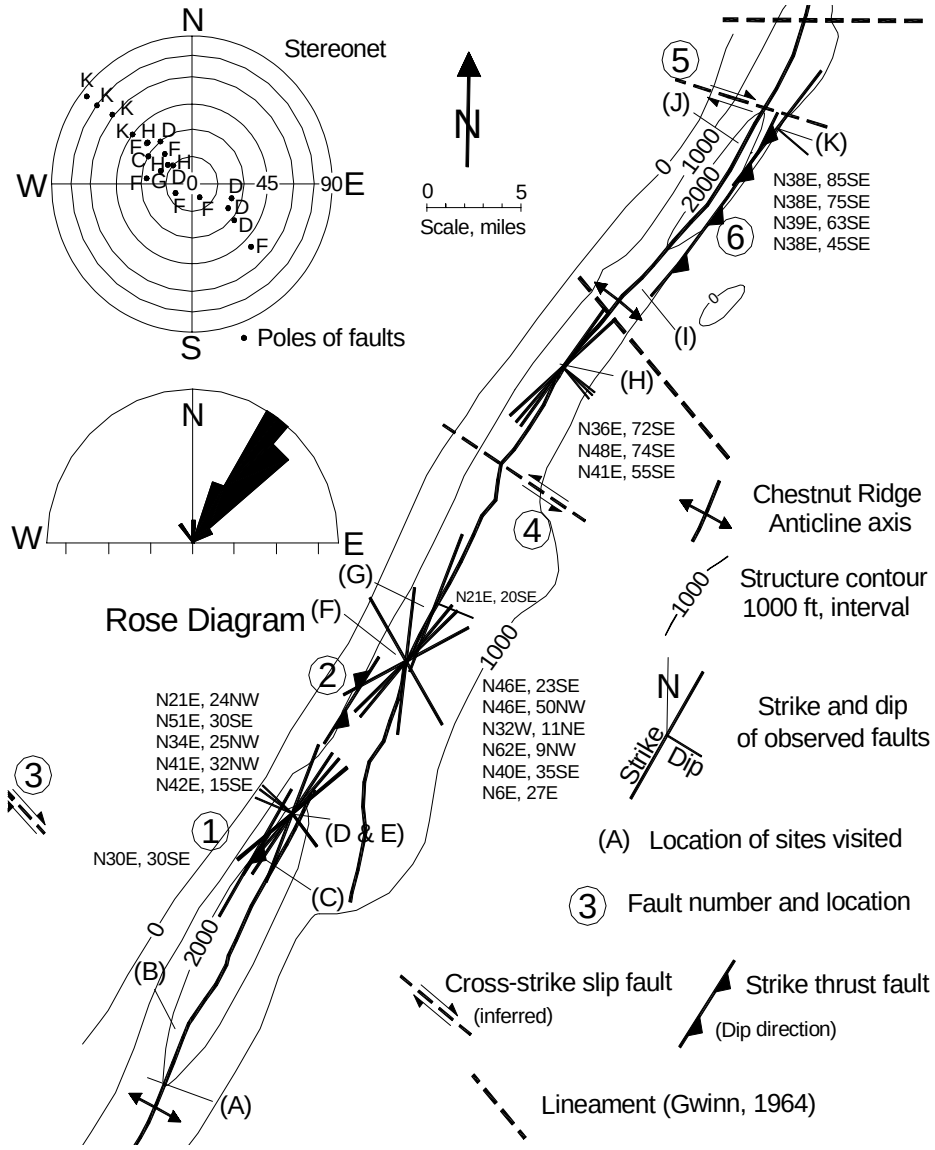

Figure 6. Location and strike and dip of faults observed during this study.

Most mines should expect to encounter strike faults with dips ranging from 10 to 60° either to the northwest or southeast. These strike faults are more likely to occur on the southeastern side of the Chestnut Ridge Anticline from the Loyalhanna Creek northward and on the northwestern side south of Loyalhanna Creek. It is also likely that Loyalhanna dips will increase significantly on the flank side of these faults. The immediate roof associated with typical low-angle thrust faults can be very unstable and in many locations has failed entirely (figure 7).

In addition to the strike thrust faults, significant deformation must have taken place along bedding in the less-stiff units above and below the Loyalhanna and along bedding planes and low-angle joints within the stiffer Loyalhanna. While the lateral deformations on these discontinuities may be slight, they can significantly weaken the roof strata, producing thinner roof beams which are not conducive to stable mine roofs in rooms averaging 45 ft wide.

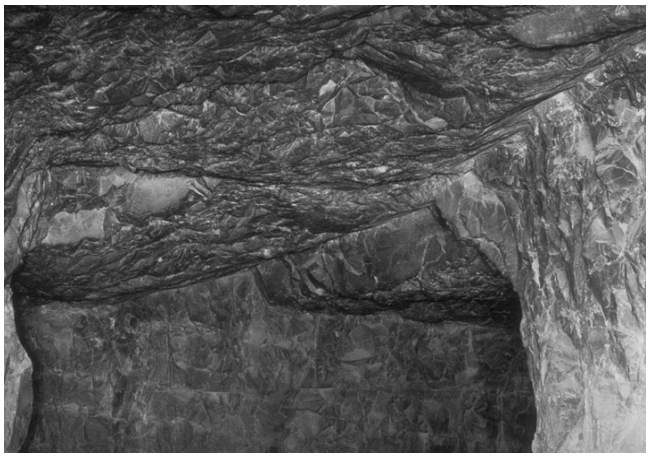

Figure 7. Unstable roof associated with typical low-angle thrust faults.

While faults in highwalls create significant planes of weakness, which can produce unstable strata, they seem to present a less formidable hazard to surface miners than underground miners. The exception to this is when the dip of a fault plane is directly into the excavation. In this case, large-scale highwall instabilities are possible if the hanging wall rock moves into the surface pit.

On the positive side, a consistent overall orientation of the strike thrust faults allows mine planners to easily project their trends into unmined areas. None of the quarries intercepted cross-strike slip faults. This is fortunate because cross-strike faults are thought to have considerable slip or displacement associated with them and may have an increased concentration of jointing. On the negative side, locally the strike thrust faults are very complicated, generally consisting of a number of related fault planes that can dip in different directions. Clearly, Chestnut Ridge has a relatively high degree of faulting for an area within the Appalachian Plateaus Province and presents a potential hazard for underground mining.

JOINTING IN THE LOYALHANNA

Jointing was observed throughout the study area and was found to have two distinct trends. A total of 371 joint bearings and dips were measured and plotted on a rose diagram shown in figure 8. These measurements were grouped into two clusters: 1) northwest quadrant data with a mean resultant direction of N 47°W of mostly vertical joints; and 2) northeast quadrant data with a mean resultant direction of N 48° E with varying dips. The N 47° W joint trend strikes across Chestnut Ridge and the N 48° E trend roughly parallel the strike of Chestnut Ridge. These trends are coincident with the orientation of local folding and faulting and are thought to be caused by the same processes.

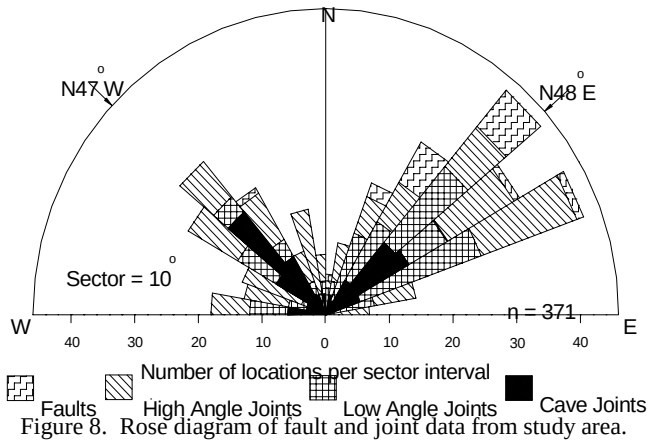

Figure 8. Rose diagram of fault and joint data from study area. 371 measurements were grouped into two clusters. Northwest quadrant data had a mean resultant direction of N 47° W (left arrow). Northeast quadrant data had a mean resultant direction of N 48° E (right arrow).

The joint bearings and dips become more significant when the measurements from individual sites within the study area are analyzed (figure 9). For example, at site D (figure 2) most of the joints are vertical with a modest concentration of joints dipping from 10 to 45° to the northwest and lesser concentration of joints dipping from 0 to 45° to the southwest. Site E and J are composed almost exclusively of vertical joints. Sites F and G are dominated by joints dipping from 0 to 90° to the northwest. Site H has a strong concentration of joints dipping from 0 to 45° to the southeast. Sites F and H have a significant number of joints dipping from 0 to 45° oriented over a wide range of bearings. The spacing of most joint sets ranges from a few feet to tens-of-feet. Displacements along vertical joints were not observed, however, lateral displacements along joints dipping from 0 to 45° were observed at Sites F and I.

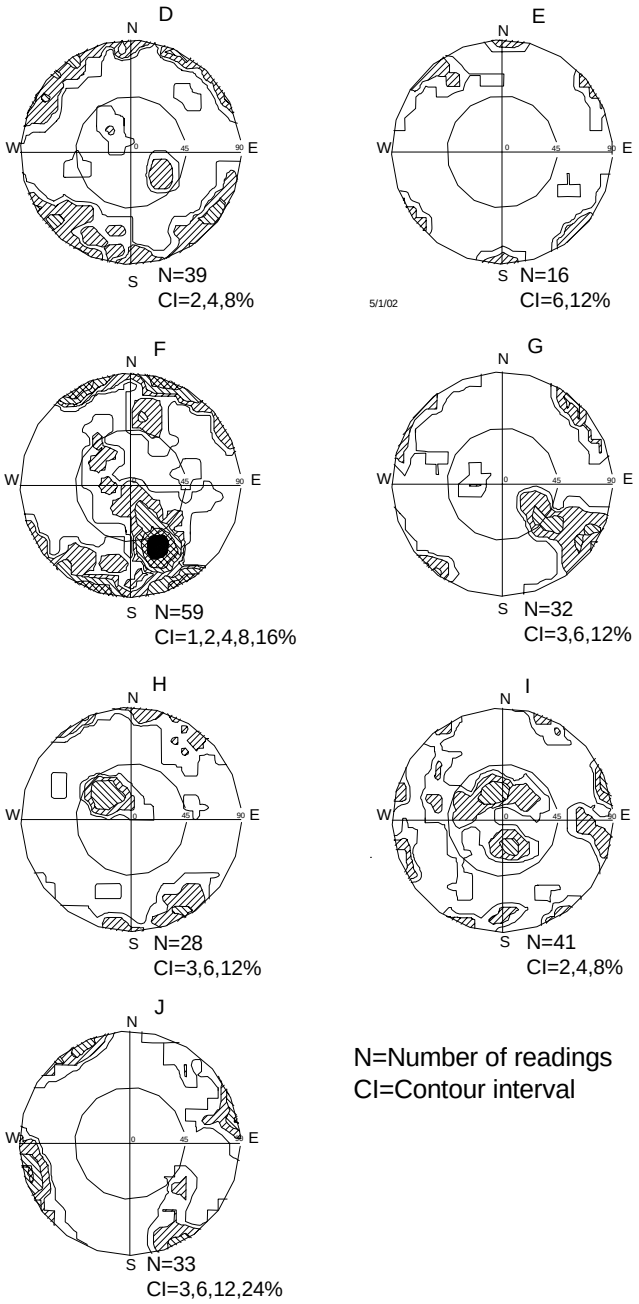

Figure 9. Stereonet projections for seven of the sites visited during this study.

It should be noted that the authors believe the dipping joints are structural in nature. They should not be confused with the strikes and dips of the very distinctive cross-bedding structures described by Adams (1) and Ahlbrandt (16). Adams (1) measured a N 72° E mean strike with a standard deviation of 76° for Loyalhanna cross-bedding. The mean dip was measured at 20° with a range of 5 to 40°. Cross-bedding can often provide a plane of weakness in roof and rib rocks

which can result in small-scale hazards. Structural discontinuities such as faults and joints are much more likely to produce significant ground fall hazards. The authors were careful to measure only joints as opposed to cross-beds during this study.

EFFECT OF DISCONTINUITIES ON GROUND CONTROL

Discontinuities in the form of faults, joints, and bedding planes have a significant impact on Loyalhanna ground control. They control immediate roof beam stability, roof line character, and pillar strength (17). Bedding plane structures within the Loyalhanna are sometime produced by the same processes that formed faults and joints. In general, these bedding planes lack persistence and have very shallow dips that produce roof beams of variable thicknesses. This becomes a ground control problem when the beds thin to less than one foot. At these thicknesses the magnitude of roof beam sag can reach critical levels. Additionally, these shallow dipping bedding planes make for poor roof lines because they lack persistence and inevitably lead the mining horizon too-close-to or too-far-away from the overlying shales in the Mauch Chunk Formation. Of course joints, especially those oriented parallel to the entries, further diminish beam strength.

Perhaps of even greater concern for miner safety is the effect that discontinuities have on the stability of Loyalhanna pillars. Important discontinuity properties which in some way affect pillar strength include: lengths, spacings, orientations, material properties, and dip. For example, the length of the discontinuity must be on the same scale as the pillar to impact its strength. For a single discontinuity, it will be of most concern if this structure passes entirely through the pillar. Sometimes the discontinuity spacing can be close enough so as to produce a strength reduction by allowing the edges of the pillar to progressively fail. The orientation of the discontinuity is important when the pillars are rectangular, in that strength will be most affected when the orientation of the discontinuity is aligned with the long axis of the pillar and the dips range from 40 to 90°. The material properties of the discontinuity can be used to assess the magnitude of strength reduction. The character of these discontinuities can range from sharp with a rough surface and no in-filling, to smooth or even polished, to in-filling by a residual fine-grained material with very low strength. Lastly, the dip of the discontinuity can dramatically affect pillar strength.

To illustrate some of these concepts, a model with very closely spaced joints, relatively low joint strength, and variable joint dip was presented by Iannacchione (18). The highest pillar strength occurred with a discontinuity dip of 0° and gradually decreased as discontinuity dip angle increased (figure 10). As the discontinuity dip angle increased above 60°, pillar strength began to increase again, although the original starting strength was never achieved. This result could be expected when near vertical joints are closely spaced, allowing buckling at the edges of the pillar and producing a strain-softening material behavior. Conversely, a near vertical through-going discontinuities with a dip approaching 90° could allow a pillar to regain almost of its strength (figure 10).

Of the total number of failed pillars observed by Iannacchione (18), approximately half were from mines in the Loyalhanna. These

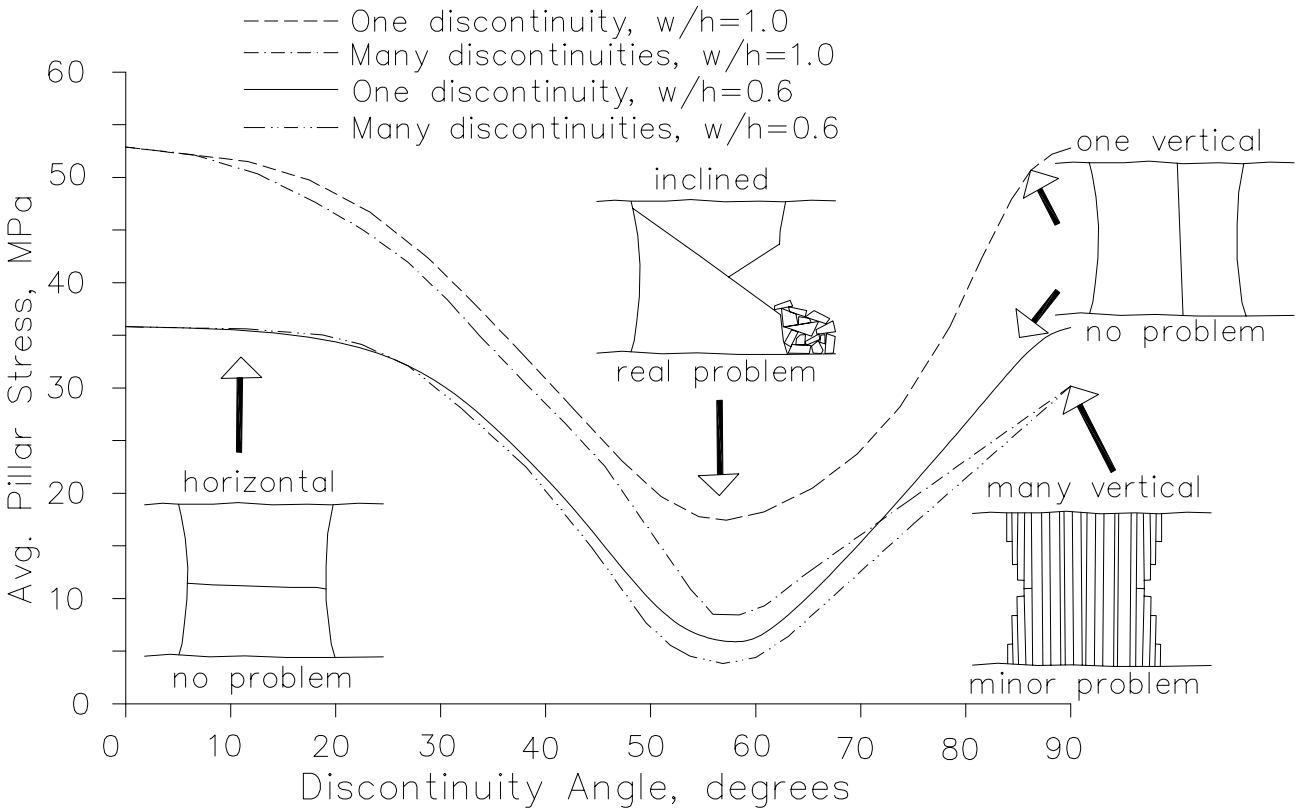

Figure 10. Changes in average vertical peak stress as the dips of discontinuities are varied from 0 to 90° for two different width-to-height ratio pillars.

pillars took on the appearance of the "real problem" pillars shown in figure 10. Because of the significant percentage of joints within the critical dip range of 30 to 75°, pillar stability is expected to be an important safety issue, especially when pillar width-to-height ratios fall below 1.0 (18, 19). Width-to-height ratios above one are more desirable because there is less chance for the discontinuity to pass entirely through the pillar.

THE EFFECT OF STRUCTURES ON STRESS LEVELS

The Loyalhanna generally has been observed to have excessive levels of horizontal stress because of its stiffness and position within the middle portion of the North America Plate (20). Stresses in this part of the Appalachian Plateaus Province are generally considered high, even for the less stiff coal-measure rocks in the Pennsylvanian strata above the Loyalhanna. It should be noted that current stresses are due to plate tectonics, not the ancient Appalachian Mountain building event. Horizontal stresses within the Loyalhanna have been measured from 2,200 to 8,000 psi with an orientation that clusters between the N 60° E and N 75° E (21). These excessive horizontal stresses were shown to be responsible for the mining induced seismicity and associated ground falls at one mine site.

It must be noted that high levels of horizontal stresses are not present at all Loyalhanna quarries. In fact, several quarries located within structural domes are thought to have very low compressive stresses within their immediate roof rock. These domes have brought the Loyalhanna to its highest elevations where it has been exposed to considerable weathering. Figure 2 shows that the most extensive areas of Loyalhanna outcrop occur within the Summit and Griffin Domes.

The Summit and Griffin Domes have extensive caves developed in the limestone. Caves occur when existing joints open as the confining stresses are relieved by erosion, uncovering the limestone. These unconfined joints are then widened as flowing water dissolves the limestone over extended periods of time. The residual fine-grained material that is left in place can be easily carried away by the small streams of flowing water. Under these conditions, whatever locked-in stresses that once existed are released. Quarries that clearly have low stress conditions (Site D and J, figure 2) are located within the Summit and Griffin Domes.

Despite the low stresses discussed above at two quarries, the level of horizontal stress is, in general, considered to be excessive. Mines with excessive levels of horizontal stresses (Sites F and I, figure 2) are located in saddle structures and are close to either an inferred cross-strike slip fault or a projected lineament that may form the boundary of a large ramp structure. At both of these mines a significant number of joints with low dip angles were observed. Additional research is required to fully understand the important structural factors that either diminish or concentrate stresses in this area.

SUMMARY AND CONCLUSIONS

Using data gathered from gas wells, core logs, mine visits, and geologic references, the geology of the Loyalhanna was investigated and its influence on mining was determined. The important structural characteristics of the limestone follow:

1. Underground mining has been concentrated along the crest of the Chestnut Ridge Anticline where dips range from 0 to 10°. These relatively flat crest zones range in width from 0.5 to 1.5 miles. The flanks of Chestnut Ridge have dips that range from 5 to 20° and are generally steeper with more overall relief to the northwest. Because mining becomes more difficult with increasing dips and corresponding overburdens rise quickly, future mining will continue to occur along the crest of Chestnut Ridge Anticline.

2. Two types of faults were recognized: strike thrust faults and cross-strike slip faults. The strike thrust faults parallel the trend of the Chestnut Ridge, whereas the cross-strike slip faults are perpendicular to the trend of Chestnut Ridge. Six faults have been noted in the literature. Several additional faults were observed as part of this study in six underground and surface mines.

3. Two general clusters of jointing were observed: vertical joints trending across the strike of Chestnut Ridge (N 47° W) and variable dipping joints roughly parallel to this same strike (N 48° E). These joints and the previously discussed faults have the potential to significantly reduce pillar strength. Whenever discontinuities dip more than 30° the potential for pillar failure increases. The most hazardous dips are from 45 to 70°.

4. Two major domes, Summit and Griffin, bring the Loyalhanna to elevations in excess of 2,500 ft. These domes have the highest amount of limestone exposed along outcrop and are sites where caves have developed. These areas have high concentrations of weathered, vertical joints. They are sites of relatively low concentrations of horizontal stress. The principal ground control concern in these areas should be with roof falls developing between blocks of rock outlined by weathered, vertical joints.

5. Three major saddles, Youghiogheny, Jacobs Creek, and Loyalhanna, are locations where significant elevation reductions occur along the crest of Chestnut Ridge. These structural depressions are coincident with major rivers and streams transecting Chestnut Ridge. The Jacobs Creek Saddle is also coincident with an inferred cross-strike slip fault. The Loyalhanna Saddle is coincident with the lineament identified by Gwinn (5). These areas have high concentrations of joints with low dip angles. They are sites of relatively high concentrations of horizontal stress. The principal ground control concern in these areas should be roof falls developing perpendicular to the major stress direction of N 60 to 70° E.

The shape and character of Chestnut Ridge Anticline has been influenced by the same tectonic forces that formed the Appalachian Mountains further to the east. These forces have created a complex structural setting that contains variably dipping strata, prominent joint structures, and significant fault trends. These structures have had considerable impact on mining in the area. Prominent discontinuities are evident in all of the underground mines and have been responsible for significant ground control issues. A case for relating ground control problems to the structural geologic environment of all these mines can be established. The future challenge is to apply this knowledge to proscribe operational remedies to mitigate the implied hazards to miners and facilities. Remember that over time, these hazards will become more prevalent as mining progresses into less accessible, higher stressed, and greater overburden areas.

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