# A Case Study of Potential Geologic Factors Affecting the Occurrence of Massive Ground Collapses at an Underground Limestone Mine in Southwestern Pennsylvania

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## ABSTRACT

Five massive ground collapses have occurred in underground limestone mines in the United States between 2015 to 2021, with two of the collapses occurring at a single mine. Preliminary investigations have been focused on pillar geometry. The effect of the variable strength and thickness of the overlying strata have yet to be analyzed. The strength and thickness of the overlying strata are potentially influenced by the structural features and the stratigraphic characteristics of the strata above the areas where massive collapses are occurring. This paper reviews some of these features and characteristics observed in a mine in southwestern Pennsylvania, where a more recent massive ground collapse has occurred. This operation is one of many mining the Loyalhanna Limestone using underground room-and-pillar methods. The conditions observed at this site help better understand how geologic structure contributes to the massive ground collapses at other current and future mining operations.

## INTRODUCTION

Five well-documented massive ground collapses occurred in underground stone mines in the U.S. from 2015 to 2021, with two occurring in Loyalhanna Limestone mines in southwestern Pennsylvania. An important geomechanical issue centers on developing a better understanding as to how mining and geologic factors might contribute to these types of failures. A massive ground collapse, as defined in this study, consists of broken strata partially filling multiple entries and rendering them unsafe to enter. These collapses can occur over short periods of time, inducing dangerous wind blasts, or over months of intermittent growth. These collapse zones can include multiple pillars that have, in part, failed and are no longer capable of supporting the overburden. It is difficult to know what came first—the failure of the overlying strata or of the enveloped pillars. Massive roof failures occur when the layers comprising the roof rock are not sufficiently strong to prevent unstable conditions. Massive pillar failures can initiate with the failure of a single pillar that triggers cascading pillar failures over a wide area and ultimately leads to roof failures as well. If the collapse is rapid, the overburden falling into the void created by mining can produce an air blast capable of destroying ventilation controls and creating projectiles. Miners working in areas of unstable ground are at risk of serious falls of roof and rib injuries. In the most severe cases, escapeways can be blocked and a subsidence basin could occur on the surface. These massive ground collapses occur unexpectedly, and they represent a high-consequences health and safety hazard with the potential to produce serious injuries to underground mine workers as well as those on the surface near the portals and above the collapse.

## BACKGROUND

The case study examined in this report is an underground operation mining the Loyalhanna Limestone along Chestnut Ridge in Pennsylvania (Figure 1). This mine experienced a massive ground collapse in October of 2020 in an area of the mine where benching was occurring at the time. The primary cause of the massive ground collapse has not yet been determined but is possibly related to pillars with inadequate width-to-height (W/H) ratios. Several pillars surrounding the collapse area were measured and found to have W/H less than 0.8. Past research suggests W/H ratios of less than 0.8 are at a high risk of instability (Esterhuizen and Murphy, 2018). The influences of the structure and stratigraphy surrounding this mine have not been analyzed. Information collected during this study will help to better understand possible geologic factors that lead to the massive ground collapse at this site.

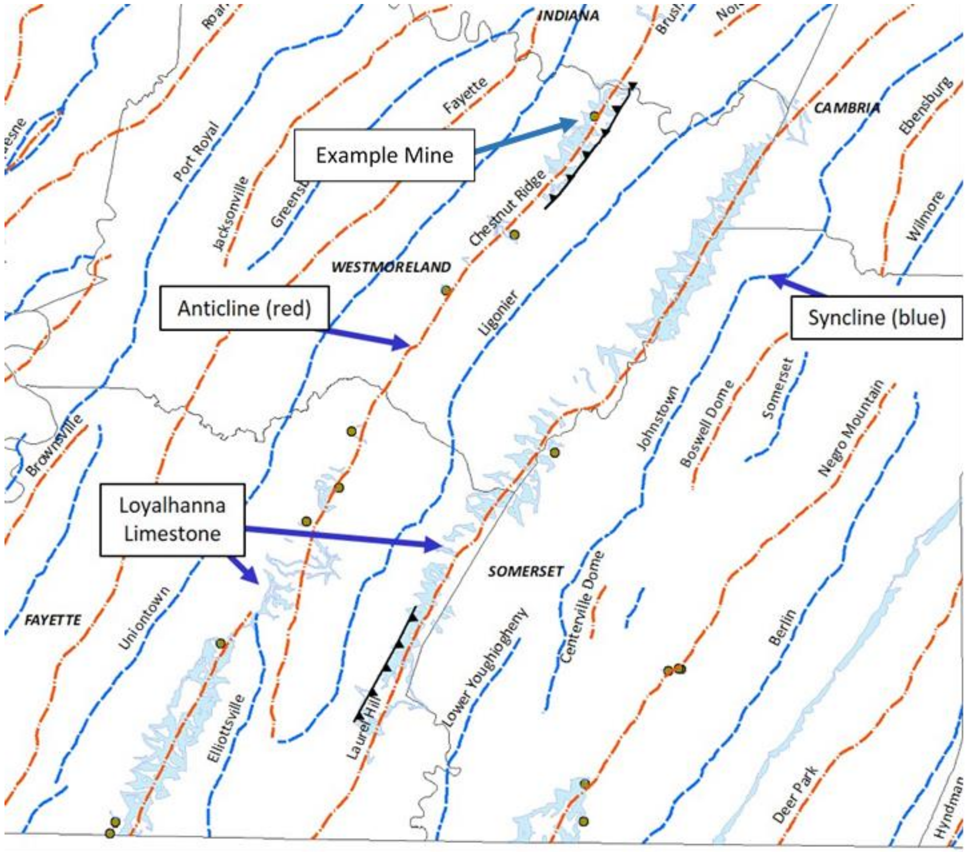


**Figure 1.** Location of underground limestone mines (dots) within the Loyalhanna Limestone (light blue zones) in relation to major structural features within Fayette, Somerset, and Westmoreland Counties of southwestern Pennsylvania.

### Structural Features Associated with the October 2020 Massive Ground Collapse

The National Institute for Occupational Safety and Health (NIOSH) was requested to perform a LiDAR scan of the area surrounding the October 2020 massive ground collapse (Figure 2). The details of this scan are presented here to show the shape and location of the collapse area and to discuss the structural features observed within the stable pillars and rooms around its perimeter.

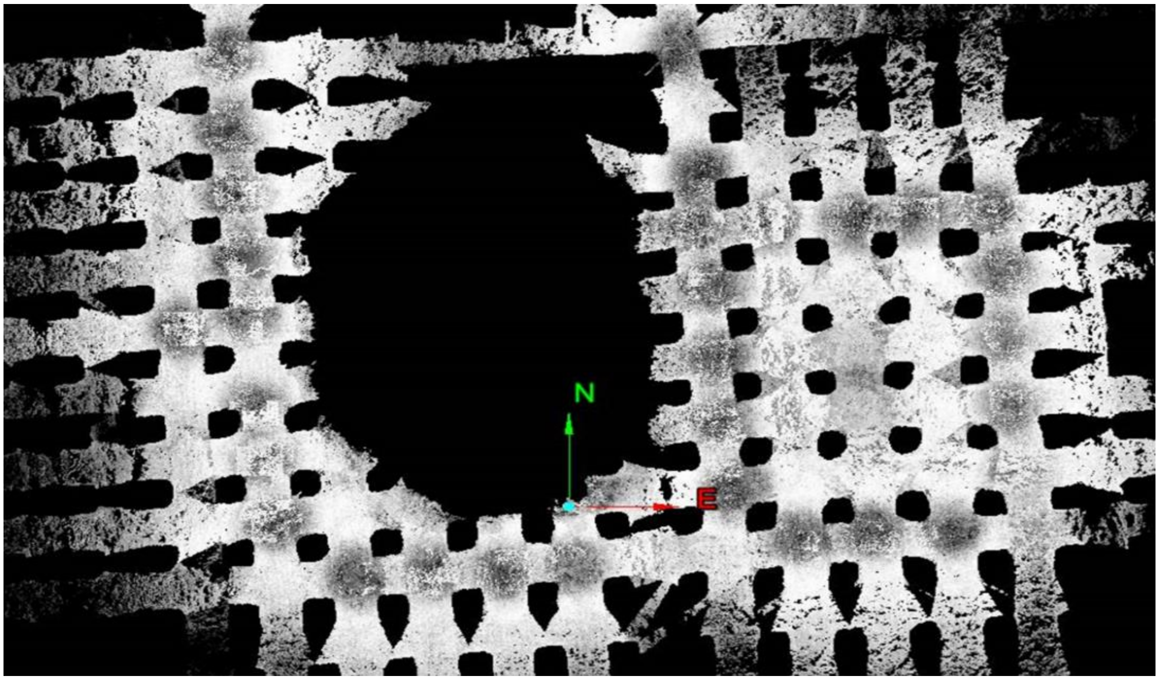


**Figure 2.** Collapse area as determined from NIOSH LiDAR scans in December of 2020. Typical entries are 40-ft wide.

The structural elevations and the overburden on the top of the Loyalhanna Limestone in the study area are shown in Figure 3. The mine overburden ranges from less than 250-ft to, in some places, less than 100-ft near the outcrop. Overburden in the area of mine collapse ranges between 140 and 180-ft. The mine site is located along the axis of the Chestnut Ridge anticline. In this area, the Loyalhanna Limestone structure contours form a dome, resulting in the strata dipping up to 9 degrees away from the center of the mine in all directions. Structural domes along the Chestnut Ridge anticline are known to have higher concentrations of caves and weathered joints than along its limbs and can represent areas of low horizontal stress (Iannacchione, 2002). At this mine, Loyalhanna Limestone crops out on three of its sides. In these areas, strata extension resulting from a lack of confinement is more likely.

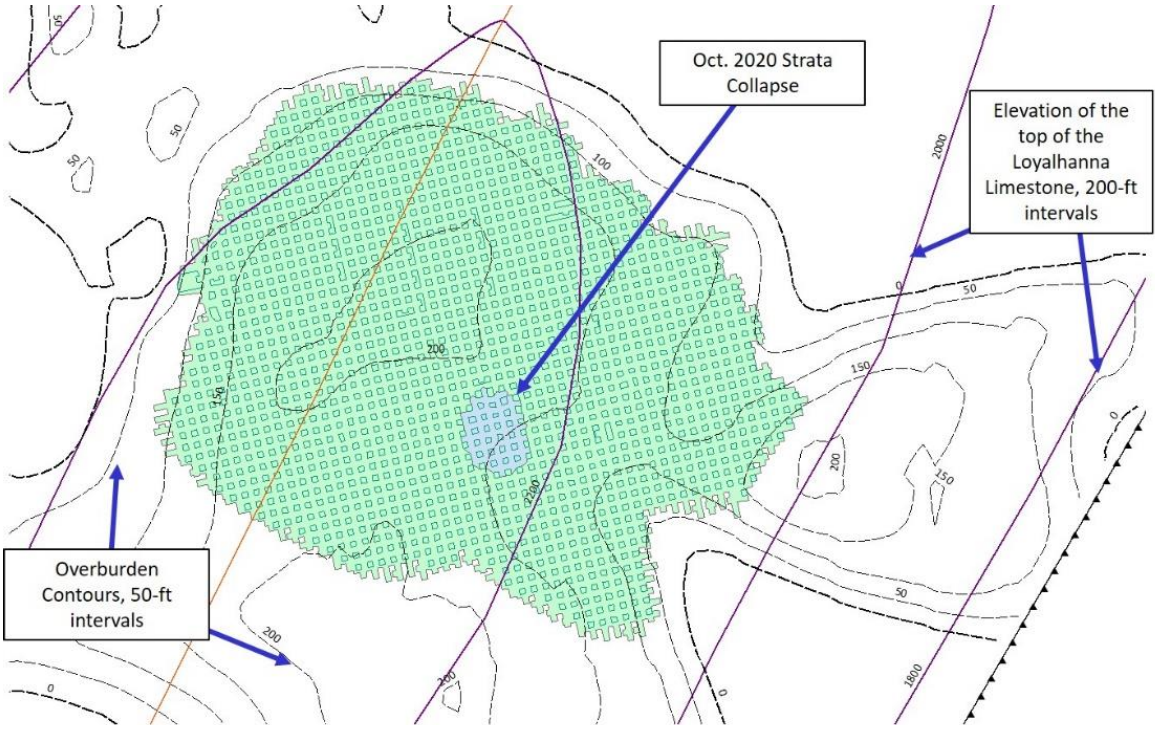


**Figure 3.** Map showing the outline of the underground mine, the October 2020 collapse, as well as the structural elevation and overburden contours on the top of the Loyalhanna Limestone.

When strata extension occurs, groundwater can more easily degrade the rock and dissolve the limestone along existing rock joints (large structural fractures or breaks in the strata). The weathered joints then have the potential to isolate blocks of strata that could be subject to gravity driven movement under low confinement (Iannacchione et al., 2002). Dissolution of the limestone along rock joints was observed near the collapse area (Figure 4).

**Figure 4.** One example of a weathered joint with a cavity in one of the pillars adjacent to the collapse area.

Four of these weathered joints with cavities were recorded during scanning around the outer edges of the collapse area. These joints may have contained residual fine-grained material that has since been removed by weathering. The 3D static LiDAR scans of this area were used to locate and measure the length of these structural features. One of the largest of these weathered joints is shown in Figure 5. The LiDAR scanner was able to pick up points within the cavity at a depth into the pillar of 6.7 m (22 ft). The formation and orientation of these joints is comparable with those observed in other mines along the Chestnut Ridge anticline (Iannacchione and Coyle, 2002). Iron staining was present on a particular joint set near the collapse area (Figure 6), which indicates some water movement along the joints.

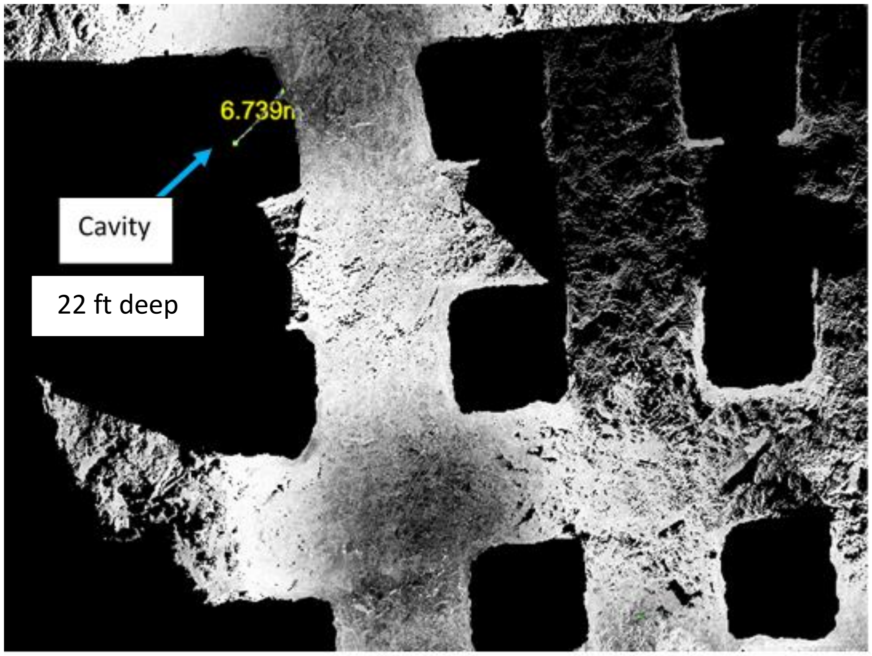


**Figure 5.** 3D LiDAR scan of a cavity along a weathered joint in a pillar at the edge of the October 2020 collapse.


**Figure 6.** Iron stained joint in a pillar on the edge of the collapse area.

Another structural feature found along the flanks of the Chestnut Ridge anticline in this area is the Bolivar Fault (Figure 7). This fault extends along the eastern flank of Chestnut Ridge and is visible at the surface approximately 600 m (~2,000 ft) from the edge of the mine and approximately 1,040 m (~3,400 ft) from the collapse area. The displacement and direction of movement of the fault is unknown, but the section affected by faulting ranges is at least 152 m (500 ft) from the Middle Mississippian Loyalhanna Limestone to the Upper Freeport coal group (Puglio and Iannacchione, 1979). On the northwest side of the fault zone the section has low dips of 8 to 9 degrees (Figure 7), while on the southeast side the dips were measured by Shaffner (1958) to be upwards of 70 degrees (Figure 7).

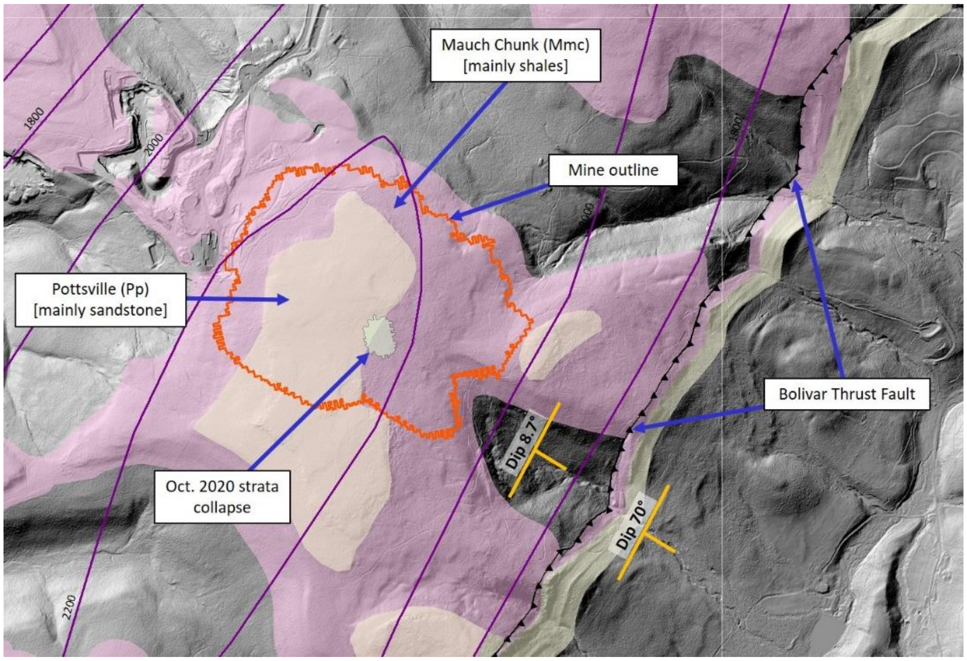


**Figure 7.** Hillshade map showing the enhanced location and characteristics of the Bolivar Fault.

Recognition of the scale of the Bolivar Fault is evidenced from the flatiron structures associated with the Pottsville Sandstone found on its southeast limbs (Figure 7). The Bolivar Fault is thought to extend to the northeast, possibly passing through the Conemaugh River Gorge. A fault of this size is likely to be associated with a potential transverse fault that may have helped to form the Conemaugh River Gorge in this area (Puglio and Iannacchione, 1979). Mapping the flatiron structures associated with the Pottsville Sandstone with the aid of the hillshade feature within a GIS (Geographic Information System) database indicates the Bolivar Fault extends at least 15 km (9.3 miles) to the southwest from the Conemaugh River Gorge. Lastly, drill holes near the Bolivar Fault indicate voids within the Loyalhanna Limestone. This study could not determine if this structural feature influenced this massive ground collapse, but its presence merits further consideration.

### Stratigraphic Features Associated with the October 2020 Massive Ground Collapse

The Loyalhanna Limestone is Mississippian in age, outcropping along Chestnut, Laurel Hill, and Negro Mountain anticlines in western Pennsylvania. Directly above the Loyalhanna Limestone lies first the Mauch Chunk Formation, capped by the Pottsville Formation which is Pennsylvanian in age (Shaulis, 1993). The Mauch Chunk Formation is characterized by simple monotonous sequencing of almost entirely nonmarine, fine to medium-grained red shales (Edmunds, 1993). The Loyalhanna Limestone overlies the Pocono Formation. Edmunds (1993) indicated that the Loyalhanna/Pocono boundary represents a probable unconformity. At the time the Loyalhanna was deposited, it appears that the slow transgressive encroachment of the sea reached this flat erosional surface and created a marine depositional environment for the Loyalhanna to develop (Edmunds, 1993).

The Loyalhanna Limestone has been mined extensively as an aggregate for highway construction. Brezinski (1984) showed that the Loyalhanna Limestone ranges in thickness within Fayette, Somerset, and Westmoreland Counties of Pennsylvania from approximately 11 to 19 m (~36 to 62 ft). The overburden above the Loyalhanna Limestone near the case study mine consists of the Mauch Chunk Formation and, in some areas, the sandstones and shales of the Pottsville Formation (Figure 8). Examination of multiple drill logs within the study area found that the Mauch Chunk is comprised mostly of red, green, and gray shales with occasional layers of thin limestones and locally thick sandstone layers.

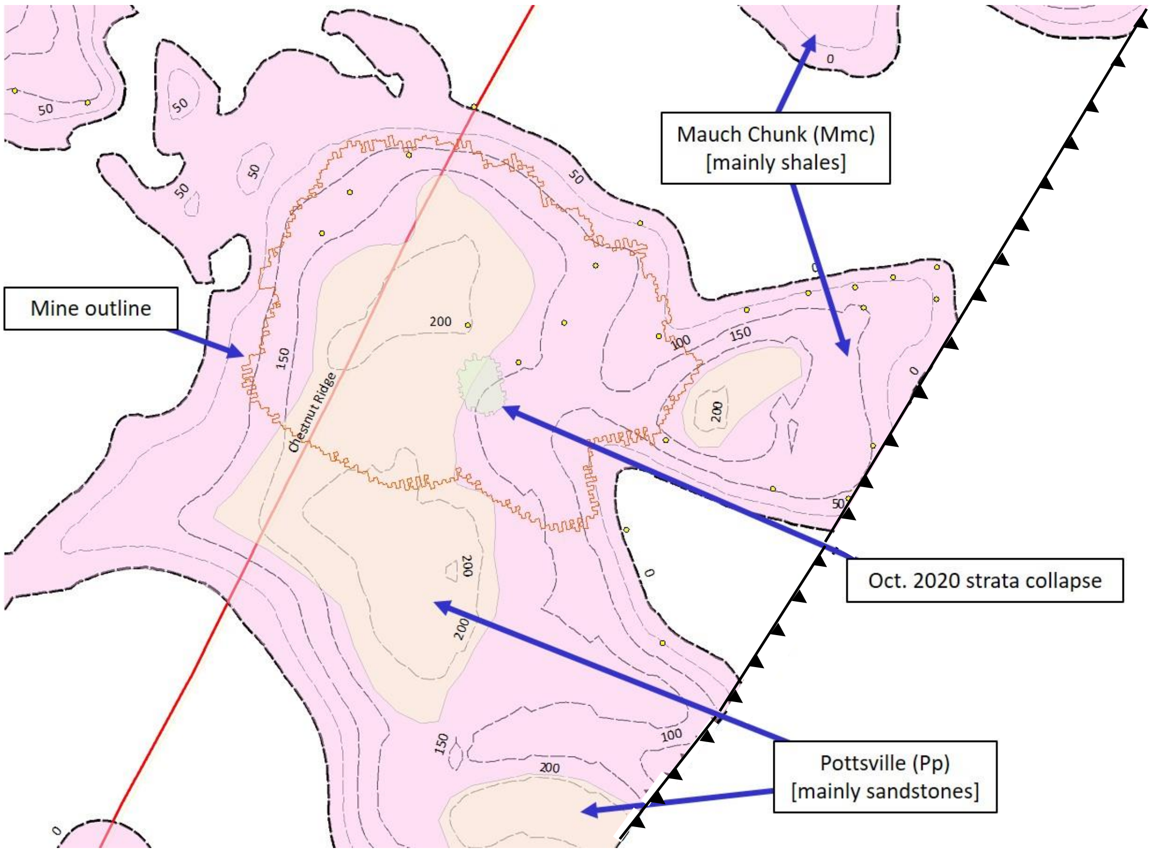


**Figure 8.** Location of the Mauch Chunk and Pottsville Formations above the top of the Loyalhanna Limestone within the study area. Also shown are the outline for the underground mine, the October 2020 collapse area, and the Bolivar Fault discussed in Figure 7.

A cross-section from drillhole logs in the area was constructed across the mine and near the October 2020 collapse area (Figure 9a). In this area, the strata above the collapse area was comprised of approximately 47 m (~155 ft) of the red, green, brown, and gray shales of the Mauch Chunk Formation (Figure 9b). Some drillhole logs to the northwest of the mine showed a sandstone in the lower portions of the Mauch Chunk while others to the southwest showed a sandstone in the upper portions of the Mauch Chunk (Figure 9c). A small portion of the overburden above the northwest portion of the collapse area (Figure 8) contains strata of the lower portion of the Pottsville Formation. Traces of a resistant member, potentially the Connoquenessing Sandstone, are found when examining the hillshading map of this area (Figure 7). The examination of the stratigraphic features above the collapse area indicates that the structurally weak shale and claystone members of the Mauch Chunk Formation are dominant, potentially contributing to this massive ground collapse.

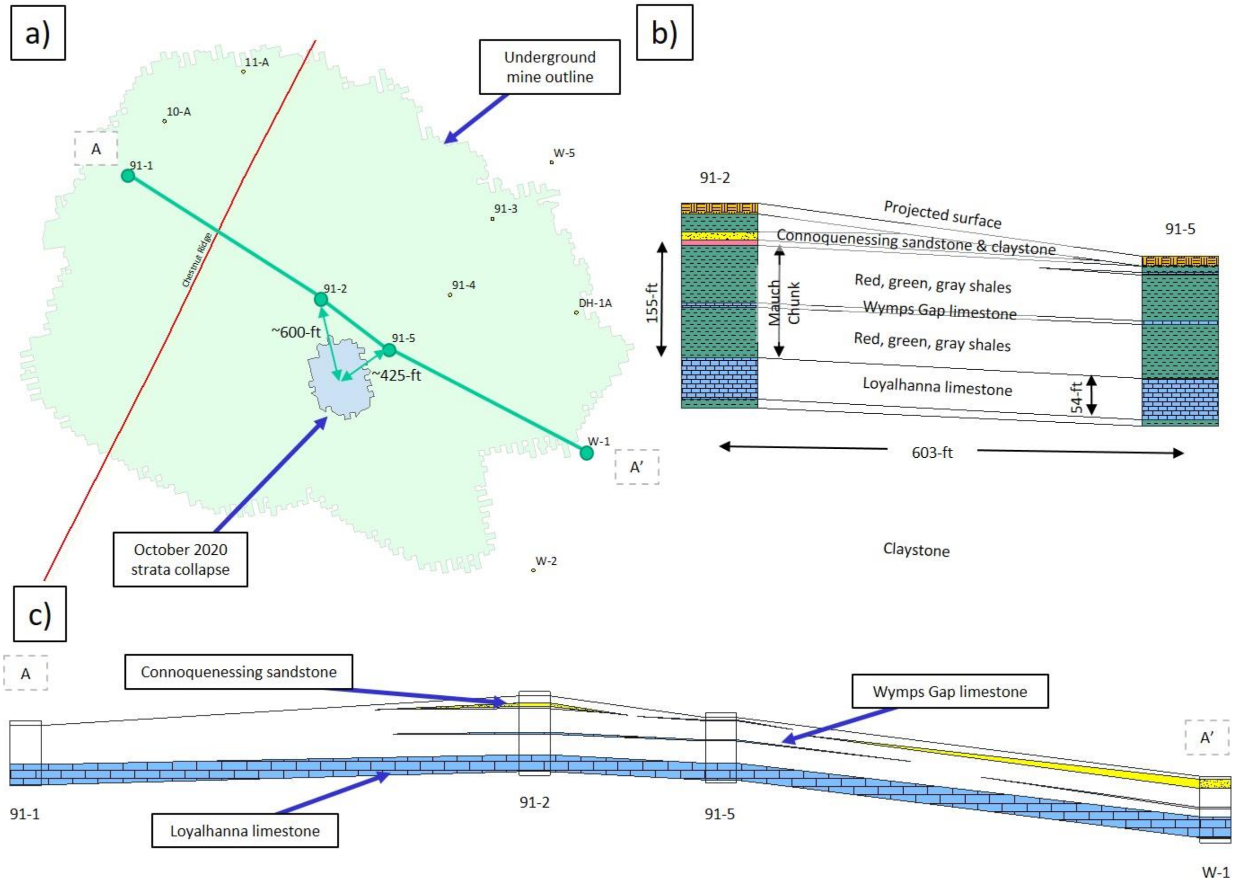


**Figure 9.** Cross-section near the October 2022 collapse showing the overlying strata is comprised almost exclusively of shales. a) Study mine outline showing the location of drillholes, the October 2020 ground collapse, and the strata cross-section from A to A'; b) detailed stratigraphic sections of the two drillholes closest to the ground collapse areas; and c) strata cross-section across one portion of the mine from A to A'.

## SUMMARY

This mine is located on a dome structure along the axis of the Chestnut Ridge anticline allowing the strata to dip gently away from the center of the mine. The dome structure has allowed for the Loyalhanna Limestone unit to crop out on three sides of the mine. Both of these factors indicate that low horizontal stress exists within the study area and a general lack of confinement on the overlying strata could allow for extension to occur. The overburden directly above the collapsed area is dominated with weak shales of the Mauch Chunk Formation. The lack of sufficient confinement to the Mauch Chunk strata above the underground mine may have allowed for a gravity-driven glide down-dip under the vertical pressures of the overburden. Differential movement along bedding planes between the rock layers and along the joints can reduce the overall stability of the overburden and allow water from surface runoff to infiltrate at a higher rate. The existence of opened weathered joints near the collapse area are suggestive of this occurrence.

Geologic factors that may have contributed to the occurrence of the October 2020 massive ground collapse include:

- The Loyalhanna Limestone crops out directly adjacent to three sections of the underground mine, and in all three sections the strata dips towards the outcrop. These conditions increase the potential for strata extension within the strata of the underground mine

- The presence of the weak Mauch Chunk shale in the immediate overburden above the collapse area and the lack of any other massive unit such as limestones or sandstones in the 47 m (155 ft) of strata above the Loyalhanna Limestone

It is possible that the Bolivar Fault zone and associated transverse fault systems could also have led to instability; however, there is not enough information at this time to suggest this influenced the collapse. There is evidence that groundwater has impacted the characteristics of the joints near the collapse area. The influence of groundwater movement on this collapse also needs to be investigated further.

This research effort is aimed at developing a better understanding of the geologic factors influencing this particular collapse. This analysis and accompanying statements made from the study area are meant to assist in determining leading causes in other massive ground collapse cases so that appropriate health and safety interventions can be made to prevent this hazard from occurring at future underground limestone mines.

## DISCLAIMER



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