Coal mine entry rating system: A case study

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Abstract

Coal mines are continuously seeking to determine the performance of entries with different ground control products and installation methods. There are many factors that impact how an entry will perform which include but are not limited to geology, overburden, bolting type and pattern, and mine design. At the National Institute for Occupational Safety and Health (NIOSH), research has been instituted to examine the relationship of the parts of a coal mine entry as a system and not as individual components. To study this relationship, the first step in this study was to create a numeric rating system that accurately reflects visual observations of the mine entry and is easy to implement. NIOSH researchers devised this rating system to improve upon previous ideas, offering increased flexibility which can be incorporated into an overall entry condition that offers different levels of confidence based on the user’s time devoted to the inspection. This new entry rating system was implemented at three different mines over varying periods of time to evaluate the ground response to the geology, bolt installation pattern, stress changes by mining, overburden, and time dependency.

Keywords
Coal; Geology; Rating system; Support

1. Introduction

Researchers at the National Institute for Occupational Safety and Health (NIOSH) have been researching methods to look at coal mine entries as a system that interacts as a whole versus observing at the roof, rib, and floor independently. To begin this research effort, a new entry
Engineers and geologists are always creating ways to bridge the gap in communication between qualitative and quantitative data when describing mine conditions through numbers and descriptions. Ultimately, numbers will allow a better analysis of entry conditions than using descriptions because numbers can be compared and analyzed and cannot be misinterpreted as can descriptions. The challenge of any rating system is how to address the gap in communication by developing a system that can be agreed upon to the satisfaction of both the geologists and engineers. To expand that challenge, the entry rating system should be useful to both research and industry while allowing virtually anyone with mining experience to implement it. This paper addresses a new mine entry rating system developed by the NIOSH at the Pittsburgh Mining Research Division (PMRD) that will attempt to satisfy all these issues and improve previous entry rating systems. This new system will be implemented in all future coal research at PMRD.

2. Previous geologic and rating systems

There is nothing new about the pursuit of creating an underground mapping and rating system. Many systems in the past have been created to describe the geology and entries in coal mines. There are too many previous systems to list and it would be outside the scope of this paper, but significant advances will be mentioned within the last 45 years.

The U.S. Bureau of Mines (USBM) created a report in 1975 that highlighted performing underground surveys to map geological features such as the orientation of coal cleat, clay veins, faults, sandstone channels, gas or water, and roof falls [1]. These features can have a significant impact on the performance of supports in entries and ultimately the entry itself. In addition, these features can be easily mapped by a trained geologist and can show the general direction of horizontal stress.

In 1986 an article was published that highlighted large-scale features just like the 1975 USBM report, but the article also brought attention to local geologic features such as rolls, bodies of different lithologies, and complex lithology that may cause local instability to mine entries [2]. These features follow broad regional trends that are formed by tectonic forces.

The Mine Safety and Health Administration (MSHA) published a paper on boundary element numerical modeling to evaluate rock mechanics problems in various mining situations [3]. To verify the accuracy of the model, actual correlations to underground conditions were compared using a pillar deterioration index (PDI), roof deterioration index (RDI), and floor deterioration index (FDI). The deterioration indices established a method to quantify mine entry conditions and compare them with numerical modeling. The PDI, RDI, and FDI from the MSHA paper can be seen in Fig. 1 and Table 1.

The USBM was researching in-mine mapping with regards to determining the principal horizontal stress direction. This method utilized mapping underground stress features by noting the direction and type of feature and where the feature occurred. Most of the
features mapped were roof potting, cutters, roof bolt offsets, and orientation of fractures and roof falls. The principal stress direction is always important to consider when performing underground mapping, and all stress features should be mapped when they are encountered. The mapping system also introduced a new stress damage rating for the roof while providing a mapping example (see Figs. 1 and 2).

The next step in entry rating systems came from the development of the LaModel program. In 1998, Heasley and Chekan published a paper on stress modeling for mine planning which introduced a rating system to calibrate LaModel for more accurate stress predictions [4]. The rating system only focused on pillar damage but was similar to Karabin and Evanto scale [3] because it was a relative scale based on observed damage; however, the rating scale consisted of only whole numbers and avoided providing any measurements or support recommendations [4].

Using the LaModel interface with AutoCAD software, Wang and Heasley [5] developed the stability mapping system in 2005. This created an integrated mapping system that can include complex geological structures and observed conditions. This new program allowed modeling that enabled forecasting of support design and optimization to be derived from the in-mine rib ratings.

Lawson et al. [6] published a paper addressing ground condition mapping with a new rating criterion that included measurements of sloughed or damaged material in the entry (see Fig. 3). The addition of having limits to ratings based on measurements allows less error between users if more than one person is performing the in-mine ratings. Also, the observed damage is better correlated to the models, which should provide better forecasting of models in unmined areas [6].

3. New rating system

Over the years geological and stress mapping systems have proven worthwhile and increased miner safety, health, and productivity. The results of the coal mine entry mapping system usually depended on the creator’s intent. Most systems were developed for the purpose of providing verification to modeling results while not focusing on changes due to local lithology. Geologic mapping systems have the opposite issue because they do not provide a numerical system to assist modeling efforts. The challenge is to develop a system that can address both issues and be user friendly so that objectiveness is taken out of the equation, which would allow multiple users to map an area and derive similar results. The purpose of the new rating system (see Fig. 4) is to provide numerical values associated with measurements for modeling and combine geological components to record and project lithological trends. The new method has provided value to both the research and industry communities. For research, the index values can be compared to modeled results and determine if the entry deformation values are reasonable. If the lithology and thicknesses are known, then the average bedding strengths can be calculated. In industry, the deterioration index can be compared to multiple readings over time and provide a relative time dependent entry support performance and highlight specific areas that may need additional support based on local or global stress increases due to mining. The ratings can also help mines
determine where to install additional support after initial development and just prior to longwall or pillar mining by highlighting where the most entry convergence has occurred. Historical data can be developed by comparing development mining versus post mining of first and second panel or section mining. By knowing this information, mine management can concentrate on specific areas to install the additional supports or change pillar designs, which enhances safety and productivity.

The rating system purposely does not include any wording regarding support recommendations because that should be a determination of the mine, and additional exploration such as roof scoping or corehole drilling could be required to make a sound recommendation. The measurements were altered to include smaller increments of movement, particularly to rib deformation. A stress rating of 1–6 was chosen much like the Mucho and Mark roof rating system [7], but the half ratings were not included. It was found that some modeling programs do not handle zero values properly when modeling, so zero values were omitted.

The values were designed to double with each incremental value to make it easier to remember the system and decrease the time needed to perform an entry rating survey. Floor and rib damage measurements can generally be performed much easier than roof damage measurements, which is why not all of the ratings for the roof contain measured intervals. During the testing of the rating system, it was discovered that descriptions of the damage when it is 5 or above is better because the difficulty of performing actual measurements was difficult and introduced an unnecessary risk to miners. Also, stress damage such as cutters can be measured, but if the entire roof sags as one, then the roof can be deceptive to determine the total amount of movement.

The descriptions and pictures with each rating are generalized but might not be typical of any particular mine. Some photographic examples in mine ratings can be seen in Figs. 5–7. The descriptions are designed to cover most coal mines in the U.S., and the end user of the rating system should take that into account. For example, mines with massive roof strata typically do not experience roof cutter due to the strength of the rock exceeding the stresses applied to it. In this case, the individual performing the rating should use other methods of measuring roof displacement, such as roof extensometers, to determine the amount of roof deformation.

4. Three tier method

After the beginning of the depression of coal prices in 2012, the numbers of geologists and engineers specializing in ground control was reduced industry wide. This creates a problem when conducting mapping programs like the one this paper will introduce as they can be time consuming to perform. To tackle that issue, three tiers of mapping were developed to satisfy employee availability and various specialties that could be available when the mapping is performed. The three tiers are: (1) intersection only, (2) intersections and straights, and (3) intersection, straights, and local stress and geological features. Each tier is designed to increase the density of data to provide a clearer picture of the entry
deformation of the survey area. The survey area is marked with a letter “P” for rib, “R” for roof, and “F” for floor, followed by a 1–6 rating depending on the damage observed.

The first tier of mapping focuses on intersections of the mapping area since they are a concentration of stress due to increased intersection spans. The end user only needs to travel from one intersection to the next recording the stress and time-related damage to the roof, ribs, and floor (as seen in Fig. 8). This mapping method allows the user to cover more ground in less time, but also will contain less detail. This tier covers the areas that are most likely to experience roof falls and floor heave due to greater distances between pillars. Damage to the ribs from equipment and stress are more likely to occur in the intersections due to pillar dimensions and development sequences.

The second tier of mapping contains damage ratings in the intersections from the first tier and introduces entry damage mapping in the straights between intersections (as seen in Fig. 9). This tier offers additional detail that could be possibly missed in the first tier but does take additional time to perform. The straights between the intersections are an average rating of the entire span and not specific to a small area.

The third tier of mapping contains additional local stress ratings and geological features. The benefit of including this tier into the mapping system is that it identifies local lithology changes and stress features that can cause deterioration of the mine entry that are separate from global stress effects (as seen in Fig. 10). The local features in this tier can provide indications of areas that could require supplemental support even before there is observable deterioration of the roof, rib, or floor by projecting the features into future development. This tier of mapping will most likely require an experienced geologist or engineer to perform but provides a significant addition of detail that enhances the knowledge of the effects of stress and time underground. Tier 3 mapping can be included to tier 1 or 2 depending on the end users’ needs and time constraints.

Additional geological information changes, such as but not limited to rib lithology measurements, in immediate roof lithology, slips, slicks, pot-outs, cutters, water, and rolls in the coal seam should be noted as described in a paper by Van Dyke et al. [8]. Performing this tier will help compare the stress and lithology features versus the entry rating that was assigned when assessing the difference in mapping between two different times. Stress and geological features can possibly rapidly degrade an entry faster than the surrounding entries. Adding the geological and stress component of the tier will capture that concept. Additional geotechnical information such as borescoping, geophysical logging, and corehole impetinations can enhance the third-tier mapping as well and should be included.

Tracking the geological features throughout a mine has both research and industry benefits. In industry, knowing what geological features are ahead of mining allows preparation of manpower and materials to be onsite and reduces the amount of delay. Also, better timing maps can be created since the mine management knows what features are in the reserves and can use previous entry mapping data to know what delays to expect.

The research community benefits from knowing the tier 3 geological features because local geology can have a significant impact on how an entry is expected to behave under
increasing stress or a directional change of stress. These factors can be an input into a model to provide more realistic results.

5. Time dependency

Stress and geologic features have a time-dependent effect on entry serviceability. Performing the entry rating system at regular intervals can reveal how these factors change the entry during and after mining. Understanding these changes can help with support performance and mine design. The entry rating mapping will provide the best results when done during development, when the longwall or retreat section is started, and after the longwall or retreat section is past the study area. This will provide entry performance data that can assist mine operators identify high-stress areas and if the installed support is adequate. If the mapping is in a long-term entry, such as the mains or bleeders, then yearly or biyearly mapping can provide insights into the long-term performance of supports. This concept was highlighted in a paper by Klemetti et al. [9] for when a gateroad section condition mapping was performed on a gateroad section upon development, when the longwall was at the study site, when the second panel longwall was 152 m inby the site, and when the second panel was at the site (as seen in Fig. 11). The entry rating system used in this paper was the first rendition of the system proposed in this paper. The ratings were later updated to reflect the new rating system.

Another case that used this system was a paper by Van Dyke et al. [10] that utilized the entry rating system in a longwall bleeder system that has been updated for this paper (as seen in Fig. 12). The results were also modeled and compared to the condition mapping, and the results were in agreement. The majority of additional stress damage caused by mining was focused in the foreman’s entry (the first bleeder entry) in the middle of the panel. Mine management can view these results and make decisions to increase rib and roof support density or types of supports used in the mid-bleeder area to counter the increased stress expected in future panels.

A recent study by Klemetti et al. [11] was performed utilizing the updated rating system presented in this paper at a longwall mine mainly focusing on the bleeder system in a 6-panel district that occurred over 5 to 6 years. The goal was to use the rating system to evaluate standing support performance and the long-term stability of the bleeder entries and to locate local areas of stress concentrations. The areas that concentrated stress damage were easily identified and determined that the mid-panel bleeder areas and the gateroads near the original longwall setup areas.

6. Case study

The entry stability rating system was tested on the first bleeder system of a 5-panel district for this paper. The bleeder system consisted of four entries with an average pillar size of 26 m × 50 m (85 ft × 164 ft) skin to skin and a 6.4-m (21-ft) wide entry. The bleeders were mined at a shallow NE33° to the panel to avoid a claystone-filled split within the coal seam from lifting into the roof, which has historically caused significant roof control problems. The area is also close to a thrust fault that is confined in the coal, causing a
linear thinning and thickening area which can impact the immediate roof and create more poor roof conditions. The average overburden thickness at the site was approximately 609 m (2000 ft), and a thick fire clay parting separated 0.3 m (the top foot) of coal and created higher-than-normal ribs in the area that were measured between 3.0 and 3.7 m (10 to 12 ft) high.

The three tier mapping method was used and took approximately 1 h to complete each time the area was mapped. The areas were mapped using the 1–6 rating with “P” for rib preceding the rating number, “R” for roof, and “F” for floor. There were no signs of floor heave during the entire mapping exercise, so all floor values are rated as a 1. The only significant stress or geological issues that could be mapped were zones of slicks and one kettle bottom, otherwise the initial roof ratings proved that there were no notable signs of deformation of the roof. The ribs did experience some areas of damage during the initial entry ratings. Some ribs received a 2 or 3 rating that was most likely from equipment coming into contact with the ribs causing equipment-related damage versus geological or stress damage (as seen in Fig. 13).

7. Discussion

Each case study showed continual damage due to increased stresses to the entries after mining occurred. The new case introduced in this paper should have seen less stress damage than the other cases, but the overburden averaged over 609 m (2000 ft). Damage to the ribs and roof generally increased throughout the bleeder entries. The largest areas of damage were observed near the gateroads on each side of the panel, which is a slightly different result when compared to the mid-bleeder entry damage that occurred in the second case history paper by Van Dyke et al. [10]. The first case history paper by Klemetti et al. [9] also displayed how stresses increase, but in a gateroad situation. As expected, damage to the entries increased as the first longwall passed and continued to increase as the second longwall approached the mapping area.

All three cases highlighted the increased damage to entries due to time and mining. The damage that occurred was in different areas based on mine design and geological factors. These areas are easy to identify with the entry rating mapping system introduced in this paper and can provide mine management identifiable areas to possibly change pillar or support designs. If this system is implemented at the critical times identified in this paper, when development occurs, prior to longwall extraction, post longwall extraction, and any other time which may pose an additional load to the area, there will be several opportunities to assess the current support systems and modify or add additional supports if necessary prior to the next change in loading or deterioration due to aging of the entries.

By performing these assessments and entry ratings, the mine management can also assess the potential for changing pillar or support designs in future mining areas to improve the utilization of the supports and maximize miner safety and health.
8. Conclusions

Through multiple case studies, entry condition mapping has proven to be a useful tool that can improve miners’ safety and health and increase production. The entry rating system including geological input satisfies the needs from both a research and industry prospective. The NIOSH PMRD Ground Control Branch has incorporated this rating system into all future research, and one mine that was studied in this paper has adopted the mapping technique and is using it to rate mains and gateroad entries.

The mapping effort can be time consuming and require specialized personnel to get the maximum benefits from it. The three-tier system allows for mines and researchers to compare the cost versus benefit and decide what is best for their individual situation. Including measurements into the mapping system allows more accurate accounts of what the rater saw during mapping versus previous rating systems that only included a description. This helps provide a better mental image of what the entry looks like to someone not involved in the actual rating.

The effectiveness of any rating system is to ensure that multiple rating sessions occur multiple times over a long enough period to develop trends. It is always best to at least map after initial development to achieve a baseline rating to compare future ratings. Second, map as a longwall or pillar section is mined and observe the difference from the baseline reading. Third, map the entries again after additional panels or sections are mined. If these mapping intervals are performed, then trends start to develop and can be projected into unmined areas.

In many cases including the case presented in this paper provide evidence to make a case to incorporate condition mapping into the daily operations of mines. This system will provide a standard for bridging the gap between quantitative and qualitative data. Quantitative data should always be the goal because it is more conclusive and can be easily compared to other situations such as computer models and from one section to the next in the mines. Knowing and having a recorded history on how entries react to the stresses and supports that are installed will help geologist and engineers better forecast conditions in reserves. Based on the recorded history better mine planning can occur, increasing miner safety, health, and productivity.

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Fig. 1.
Stress damage rating (after [7]).

| Roof rating | Profile | Description                                    |
|-------------|---------|------------------------------------------------|
| 1           |         | Stable                                         |
| 2           |         | Slight cutter, after mining (<0.6 m)           |
| 2.5         |         | Slight cutter, with mining (<0.6 m)            |
| 3           |         | Deep cutter, after mining (>0.6 m)             |
| 3.5         |         | Deep cutter, with mining (>0.6 m)              |
| 4           |         | Severe potting, 1/2 roof effected              |
| 5           |         | Severe potting, all roof effected              |
| 5.5         |         | Heavy roof, obvious deformation                 |
| 6           |         | Roof fall                                      |
Fig. 2.
Stress map with features and damage ratings (after [7]).
| Roof rating criteria | Rib rating criteria |
|---------------------|--------------------|
| **0** | 0 No sloughing. |
| 1 Tension cracks begin to form, most are parallel or sub-parallel to entries. Existing joints and newly formed tension cracks open slightly, with apertures smaller than 1.3 cm (0.5 in). Open joint apertures are much more common than tension cracks. Tight slicken sided discontinuities also justify this rating. These often occur as concentrations of radial and/or linear slicks, pre-bolting falls, and other local geological features. The roof does not sag and there is no observable yield on roof support. | 1 Ribs show minor sloughing, with sloughing extending an average of less than 0.5 m (1.5 ft) into the rib. Sloughing appears to be limited to the pilar skin. Large dislodged blocks are not observed or are infrequent. Rubblized zones are not observed. Rib/roof contacts are largely intact, although minor separation may occur. |
| 2 Tension cracks extend and are more common. Discontinuity apertures open to an average of 1.3 to 2.5 cm (0.5 to 1 in). Local distortion of roof support may be evident. | 2 Ribs show moderate sloughing, extending an average of less than 1 m (3 ft) into the ribs. Blocks of coal may begin to separate from the rib, but are not rubbed out and remain in place. These blocks may be slightly rotated, disturbing apparent clean orientation. The roof/rib interface is often separated on at least one side. |
| 3 Tension cracks and joint apertures open to an average of 2.5 cm (1 in) or greater. The roof is beginning to sag locally. Tension cracks are pervasive. Minor, local loss of roof material is apparent in the roof mesh. Bolt anchorage, however, is unaffected. Roof support may be yielding. | 3 Ribs show slightly more severe sloughing. Sloughing has extended into the rib for as much as as 1.5 m (5 ft), but generally less. Limited intervals of rubblized rib may be observed. Zones where significant amounts of coal have been shed from the ribs are generally less than 4.5 m (15 ft) wide. The roof/rib interface is often separated on at least one side. |
| 4 The mesh is visibly bagged with roof rock. Roof failure locally extends to and above the bolting horizon. Mesh and other support materials are locally damaged by dislodged roof rock. Roof support is yielding. Roof conditions are locally hazardous. | 4 Ribs show severe sloughing. Intervals of rubblized rib are extensive, and rubble locally spills out of rib mesh. Walkways are narrowed by accumulation of shed rib material. Depth of sloughing locally exceeds 1.5 m (5 ft). Mesh and/or rib bolts may be damaged by sloughing rib material. Rib/roof interfaces have separated. |
| 5 Roof failure is extensive, not merely local. Bolt anchorage and mesh are at least locally compromised, and have fallen along with broken roof rock. Roof conditions are hazardous through most of the entry. | 5 Ribs show severe sloughing. Accumulated rib material at the can line is significant, 0.5 m (1.5 ft) deep or more. Travel may be unsafe. |

**Fig. 3.**
Floor, roof, and rib stress rating criteria (after [6]).
Fig. 4.
New proposed entry rating system.

**Rib deterioration index**

1. Sloughage of 7.62 cm (3 in) or less. Damage is only skin of the pillar and rock dust is mostly intact in areas that are outby.

2. Wide spread skin damage 7.62 to 15.24 cm (3 to 6 in). Small cracks on floor.

3. Ribs are beyond slight skin damage and is observed from 15 to 30 cm (6 in to 1 ft) from the original rib line, larger blocks of sloughage appear on floor.

4. Obvious rib damage. Damage to pillars extends 0.3 to 0.6 m (1 to 2 ft) on average from the original pillar line.

5. Significant rib damage. Damage extends 0.6 to 1.2 m (2 to 4 ft) into the pillar from the original rib. Travel is very difficult due to sloughage covering most of the floor.

6. Severe rib sloughage. Rib damage extends beyond 1.2 m (4 ft). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.

**Roof deterioration index**

1. Original roof with bit marks mostly visible. Some flaking and scaling is limited to 2.54 cm (1 in) or less.

2. Flaking and scaling are limited to 2.54 to 7.62 cm (1 to 3 in). Minor closed cracks are possible and no sign of loading of supports is visible.

3. Flaking and scaling areas are seen between 7.62 to 30.00 cm (3 to 12 in). Small cutters are possible forming less than 0.6 m (2 ft). Some roof deformation observed and possible potting, open minor cracks. Bolt plate loading observed. Majority of roof beam is intact and cutters are greater than 0.6 m (2 ft) in depth. Standing support shows very little if any loading.

4. Standing supports are heavily loaded. Large pot-outs between bolts, bolts begin to fail. Majority of the original roofline is gone, multiple open cracks spanning the entry.

5. Roof fall above primary support.

**Floor deterioration index**

1. Floor has no signs of floor heave, sporadic cracks could be observed, no measurable heave.

2. Floor has consistent localized cracks. Floor heave is 15 cm (6 in) or less.

3. Widespread cracks, hollow floor. Floor heave measured between 0.15 to 0.30 m (6 in to 1 ft).

4. Continuous floor heave measured between 0.3 to 0.6 m (1 to 2 ft), damage to ribs can occur, travel is possible.

5. Significant displacement of 0.6 to 1.2 m (2 to 4 ft), damage to ribs will occur, pillars, cribs, and post can punch into floor, travel is difficult.

6. Severe floor displacement 1.2 m (4 ft) or more. Travel is extremely difficult or impossible. Significant damage to ribs, standing support will punch or roll.
Fig. 5.
Rib rating of 5 due to spalling of 0.9 m (3 ft).
Fig. 6.
Roof rating of 3 due to cracks and slicks greater than 7.62 cm (3 in).
Fig. 7.
Floor rating of 6 because floor heave is greater than 1.2 m (4 ft).
Fig. 8.
Tier 1 mapping of ribs and roof at intersections (all floor ratings were 1 and not displayed).
Fig. 9.
Tier 2 mapping including ratings of the straights and cross cuts (all floor ratings were 1 and not displayed).
Fig. 10.
Tier 3 mapping combining local geology and stress measurements. In this map, the slick zones affect the rating, but with time and mining they could increase in damage faster than the surrounding area.
Fig. 11.
Mapping of a longwall gateroad entry that was exposed to additional stresses and time due to longwall mining of the first and second panels (after [9]).
Fig. 12.
Entry rating of a longwall bleeder system before and after mining the panel (after [10]).
Fig. 13.
Bleeder entry damage after entry development, after the first panel was mined 30 m (100 ft), and after the first panel completion and 1463 m (4800 ft) were mined of the second panel.
Table 1

Pillar, roof, and floor deterioration indices (after [3]).

| Pillar deterioration index | Roof deterioration index | Floor deterioration index |
|----------------------------|--------------------------|---------------------------|
| 0: virtually no sloughing  | 0: virtually no deterioration | 0: virtually no deterioration |
| 1.0: corner sloughing      | 1.0: flaking or spalling  | 1.0: sporadic cracks      |
| 2.0: light perimeter sloughing | 2.0: cutter roof        | 2.0: consistent localized cracks |
| 2.5: onset of pillar stability concerns | 2.5: onset of roof stability concerns | 2.5: onset of floor stability concerns |
| 3.0: significant perimeter sloughing | 3.0: broken roof       | 3.0: widespread cracks & obvious heave |
| 3.5: supplemental support required | 3.5: supplemental support required | 3.5: travel impeded - grading required |
| 4.0: severe perimeter sloughing | 4.0: significant roof falls | 4.0: significant floor displacement |
| 5.0: complete pillar failure | 5.0: widespread & massive roof falls | 5.0: complete entry closure |