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DYNAMIC FAILURE CLASSIFICATION WITHIN THE CONTEXT OF REGIONAL GEOLOGY: A CASE STUDY FROM THE UINTA AND PICEANCE BASINS

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ABSTRACT

Dynamic failure may be defined as the violent ejection of coal or rock within a working area of an underground coal mine. Despite evolving mining techniques and practices, dynamic failures continue to occur. Between 1983 and 2013, American coal mines have experienced nearly 400 cases of reportable dynamic failure accidents, resulting in greater than 20 deaths and 155 lost-time accidents. The precise balance of risk factors and specific failure mechanism(s) may vary from case to case. Lack of consistent hazard prediction may come in part from an oversimplification of dynamic failure phenomena because there is not one type of dynamic failure, but rather several types—each having similar but distinct physical characteristics and driving causes. By clearly demarcating the differences between types of dynamic failure events and their associated characteristics and geologic settings, we can begin to more effectively identify patterns in specific risk factors that contribute to them. In response to this need, researchers at the National Institute for Occupational Safety and Health (NIOSH) developed a hierarchical classification decision tree based upon physical characteristics and potential event source(s), as identified through review of the available literature, historical dynamic failure reports, and Mine Safety and Health Administration (MSHA) accident and fatality reports. The classification hierarchy was applied to a database of 39 dynamic failure events from historical reports (pre-1983) and MSHA fatality reports occurring after 1983 in the Uinta and Piceance Basins. This region was chosen to apply the newly developed classification scheme as it accounts for 74% of reportable dynamic failure events occurring between 1983 and 2019.

Application of the dynamic failure classification hierarchy to the Uinta and Piceance Basins show several differences between events occurring in the two basins:

- Failures initiated by the massive collapse of strata are more prevalent in the Uinta Basin. Dynamic failure linked with the massive collapse of strata, such as bounces, air blasts, and shock bursts, may be the result of relatively rapid basin subsidence in conjunction with an inland depositional setting, resulting in thick competent units surrounding the coal.
- The loss of confinement failure mechanism is prevalent in both the Piceance and Uinta Basins, in association with coal/mudstone contacts at the roof and floor lithologies and may have its origins in frequent transgressive/regressive events associated with the retreat of the Western Cretaceous Seaway. However, the relative prevalence of mid-pillar bursting with no slip in the Uinta Basin may be the result of the frequency of coal/sandstone contacts, which may be a function of the basin's relatively distant position from the shoreline and preponderance of more inland depositional settings.
- Gas-driven failures in the Piceance Basin correlate to high vitrinite reflectance in the Colorado B seam and suggest that the primary risk in this area derives to a greater extent from thermal maturity of the seam itself than from strata-driven failures, as is the case in Uinta Basin failures.

These findings highlight the differences between regionally based risk factors in contrast to risk factors associated with the seam itself. In the Uinta Basin, risk is clearly related to stratigraphic features. In the Piceance Basin, however, risk was dominated by thermal maturity of the Colorado B seam, although other, more localized, stratigraphically influenced risk factors were not insignificant. These geologic dissimilarities resulted in observable differences in dominant modes of dynamic failure between these two regions and have implications toward the application of more targeted risk mitigation practices. Targeted risk mitigation practices can be enacted only once the sources and mechanisms of failure have been identified.

Keywords: coal, burst, bump, dynamic failure, Uinta, Piceance

INTRODUCTION

Dynamic failure may be defined as the abrupt, violent ejection of coal or rock within a working area of an underground coal mine (Peng, 2008). These events may occur with little or no warning. Despite evolving mining techniques and practices, dynamic failures continue to occur. Between 1983 and 2013, American coal mines have experienced nearly 400 cases of reportable dynamic failure accidents, resulting in greater than 20 deaths, 155 lost-time accidents, and an estimated 48,000 lost man hours. While these events are relatively rare in relation to other types of ground control accidents, they resulted in worker injury in greater than 50% of cases reported to the Mine Safety and Health Administration (MSHA) after the year 2000, and the fatality rate per capita for these events is more than ten times that associated with roof falls (MSHA, 2020).

Dynamic failure events occur when mining-induced stresses exceed the bearing capacity of the coal seam or surrounding strata, such that the rock mass fails abruptly and energetically. However, the precise balance of risk factors and specific failure mechanism(s) vary from case to case. Lack of consistent hazard prediction may come in part from an oversimplification of dynamic failure phenomena: There is not one type of dynamic failure, but rather several—each with similar but distinct physical characteristics and driving causes. Efforts to categorize dynamic failure events were documented as early as 1918, when Rice (1935) proposed that dynamic failure in coal mines falls into two primary categories—pressure bursts and shock bursts. Brauner (1994) additionally identified dynamic failure events in which internal gas pore pressure plays a significant contributing role in gas outbursts. More recently, Iannacchione and Tadolini (2016) proposed an expanded classification scheme that considers both the event source and the characteristics of its manifestation. Vardar et al. (2018) echoed these observations, referring to these event subtypes as direct and indirect, akin to Rice's pressure and shock bursts, respectively. As noted by Hebblewhite and Galvin (2014) and Vardar et al. (2018), however, there is no consistent terminology with which to refer to different types of dynamic failure. This makes clear and consistent communication between dynamic failure researchers more challenging and may contribute to slower progress toward comprehensive understanding of dynamic failure root causes.

As noted by Hebblewhite and Galvin (2014), all dynamic failure initiation events are predicated by the existence of four co-occurring variables in the coal-associated clastic rock system:

- The rock mass must be sufficiently stressed to produce failure.

- The system must be in some way unstable. Examples may include weak bedding contacts or the presence of soft mudstone layers that facilitate loss of confinement under load. Other examples might include proximity to faulting or floor or roof strata of some critical thickness, such that it is neither strong enough to withstand mining-induced loading nor weak enough to fail gradually, and instead failing suddenly and with great force.
- The rock mass must be able to store stress, which is then subsequently released in the form of kinetic energy, thus facilitating the expulsion of rock and coal into the working area. Factors that may contribute to this may include critically[1] sized pillars; competent, poorly cleated coals; or strong, thick roof and/or floor strata.
- There must be a triggering event or change in the ratio of load to capacity. Examples include the collapse of massive strata in the gob or changes in the localized stress regime.

The interaction of these variables in each case is unique and is likely to differ between events. By clearly demarcating the differences between types of dynamic failure events and their associated characteristics and geologic settings, we can begin to more effectively identify patterns in specific risk factors that contribute to these events.

Developing consistent terminology to describe unique event classifications is, then, an important first step in being able to discuss dynamic failure in a meaningful way. A preliminary classification system for dynamic failure events has been devised by the National Institute for Occupational Safety and Health (NIOSH), Spokane Mining Research Division (SMRD), in conjunction with the University of Utah Mining Engineering Department based on the characteristics of dynamic failure events described in the available literature and accidents reported to MSHA. The existing system represents a new classification scheme based upon the work of Whyatt (unpublished). The proposed classification system was developed through the systematic review of dozens of dynamic failure records and published cases and then establishing trends in event characteristics and apparent driving mechanisms. Physical characteristics considered include the source(s) of stressors, event location with respect to mining activities, volume of debris, violence of failure, primary source of damage (pillar, roof, or floor), mining method, and other information contained in accident narratives. This study applies this newly developed classification scheme to a sample set of dynamic failure accidents and seeks to evaluate classification patterns within the context of regional geology to better understand how geologic risk factors may influence the failure mechanisms. If geologically induced risk can be clearly identified, site-specific mitigation techniques may then be enacted, ultimately leading to a reduction in the number of reportable accidents.

METHODS

Development of a Classification Scheme

Development of the hierarchical classification decision tree (fig. 1) was based upon physical characteristics and potential event sources, as identified through review of the available literature, historical dynamic failure reports, and MSHA accident and fatality reports. Criteria considered for classification include the physical characteristics of the failure, proposed risk factors (by mine operators or MSHA officials, as indicated by published reports and accident narratives), geologic information, mining methods, and mine design.

The classification decision tree is subdivided into several tiers, based on event characteristics:
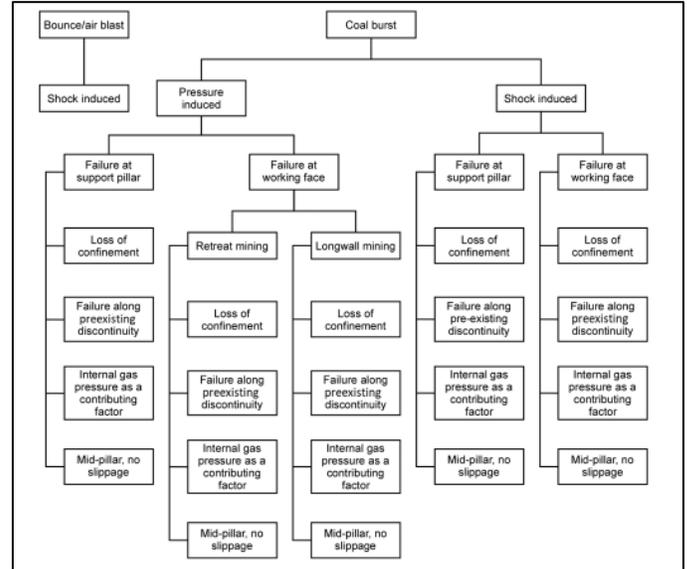

Figure 1. A hierarchical decision tree for dynamic failure classification developed by NIOSH in conjunction with the University of Utah Mining Engineering Department.

- Witnesses explicitly mention an air blast. There is no indication of bursting behavior, however, either at the working face or at any distance from it in conjunction with the bounce or air blast.
- Workers and/or equipment are thrown or displaced by ground movement.
- There is mention of the massive collapse of strata in the gob or poor caving. This criterion, however, is not diagnostic as it is also associated with other failure types and mechanisms.

Coal bursts can be identified by:

- Failure originating in the pillar or working face.
- Description of the accident as a "burst" or an "outburst."

Although less common in the United States, dynamic floor heave and dynamic roof failures can be identified by failure originating in the floor and roof, respectively. These failures can be distinguished from typical floor heave and roof failure by both the severity and violent nature of the failure. It is important to note that considerable rib damage is also often associated with these types of failure.

Second tier. The second-tier classification addresses the question of *why* the event has occurred. Pressure-induced failures result from an excess of localized stresses, which ultimately exceed the pillar's bearing capacity. These failures are typically located at or near the working face. They may also, however, be associated with areas of faulting or other geologically anomalous conditions; in these circumstances, they may occur at some limited distance from the working area. Shock-induced failures, by contrast, are the result of the propagation of shockwaves through the intact coal as the result of the collapse of strata at some point distal to failure. Shock-induced bursts are produced by the massive collapse of strata in the gob, similar to an air blast or bounce, and may include all characteristics of those failure types. However, a shock-induced burst also involves the ejection of rock or coal into the mine workings, and it is this criterion that distinguishes it from a bounce or air blast.

These designations are by nature qualitative in the absence of first-hand evidence, as they are determined solely by evaluating MSHA-reportable accident narratives and Reports of Investigation. This qualitative nature introduces an element of uncertainty into accident classifications. However, supporting evidence for a pressure-induced burst might include mention of highly stressed coal, rapid topographic changes, steep seam dips, critically sized pillars or panels, and geologically anomalous conditions, etc. Supporting evidence for shock-induced bursting behavior may include mention of poor gob

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[1] A critically sized pillar is defined as a pillar whose width-to-height ratio is such that it can neither function successfully as a yield pillar nor as an abutment pillar (DeMarco, 1994) and is conservatively estimated to be between 4–10 (Unlu, 2001).

caving and strong sandstone roof units or strong sandstones close to the immediate roof.

Third tier. The third-tier classification addresses the question of *where* failure has occurred. Specifically, this classification tier takes account where in the mine workings the dynamic failure event has occurred. This event characteristic is closely linked with the stress conditions active at the time of the event, local geology, and mining method[2]. These risk factors are very closely linked to second-tier classification through clarifying the stress-inducing factors active in the mining environment at the time of the dynamic failure event. Identifying mining method is an important component in developing risk assessment strategies. However, this study focuses primarily on classification within the context of geologically induced risk: accurate, comprehensive evaluation of mining-induced stressors in each case requires more comprehensive assessment of variables than is available through many accident narratives and is beyond the scope of this investigation.

Fourth tier. The fourth-tier classification addresses the specific mechanism or *how* the failure manifests in terms of damage characteristics. Mechanisms include loss of confinement, internal pore pressure, movement along preexisting discontinuities, and the mid-pillar expulsion of coal that does not involve slip along bedding planes or other discontinuities. Loss of confinement may be suggested by symptomatic criteria such as:

- Explicit mention of slip along bedding contacts or bedding plane faults,
- Slip at the roof/pillar or floor/pillar interface,
- Observation of red dust along failure planes, and
- The presence of weak overlying or underlying mudstone or shale units and seam splits.

Internal pore pressure as a contributing factor in dynamic failure occurrence may be suggested by:

- Very fine debris size,
- Release of significant volumes of methane,
- Association with subsequent ignitions or explosions, or
- Mention of preceding regular methane accumulations or "gassy" mine conditions.

Failure along preexisting discontinuities involves failure facilitated by the existence of faulting at the failure location. This may also include mention of features such as cleat swarms[3], which may indicate faulting that is not immediately visually apparent. Mid-pillar failures that do not involve failure along preexisting discontinuities or slip along bedding planes are determined by violence of failure, which is typically more pronounced than failure along weak or already extant planes, and process of elimination. The analysis of accident reports suggests that at this level failure commonly occurs through a hybrid mechanism, involving two or more classification categories. For example, an event may be classified as mid-pillar failure with no slippage while also exhibiting characteristics associated with influence by internal pore pressure.

Application of the Classification Scheme

Although reportable event narratives are relatively plentiful, accident reports for this study must include sufficient detail to apply the classification system. Most nonfatal MSHA-reportable events fail to meet this criterion. As such, the MSHA data used for this experimental application of the classification system are composed almost entirely of

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[2] Mining method is explicitly accounted for in coal bursts, dynamic floor heave events, and dynamic roof collapses, as the mining-induced stressors and associated risk factors differ between retreat and longwall mining.

[3] A cleat swarm is an area of cleating in which cleat density increases and often shows a distinct change in orientation relative to adjacent areas. Cleat swarms are often associated with unexposed faulting or localized changes in in-situ stresses and may also be referred to as "fracture swarms" (Flores, 2013).

information harvested from MSHA Fatality Reports and Reports of Investigation that predate 1983. Prior to the current litigious mining climate, accident reports included much greater detail. A database of 46 dynamic failure events was constructed from historical (pre-1983) and more recent (after 1983) MSHA Fatality Reports occurring in the Uinta and Piceance Basins. Twenty-three cases in this database come from the Uinta Basin, and 23 from the Piceance Basin. Approximately 44% of the database is composed of historical events, ranging from 1945 through 1982. The remaining 56% occurred after 1983 and are considered modern events and are mostly documented by Fatality Reports. Consequently, this experimental application of a classification system is weighted very heavily toward fatal events and represents the deaths of more than 40 miners as a result of dynamic failure. The authors of this paper acknowledge that mining practices represented by the ample set are not representative of modern mining methods and practices. As this study focuses on the interaction between inherent geologic risk and dynamic failure manifestation, this does not invalidate the findings of this study. However, of necessity, the mining method cannot be accounted for in a meaningful way through these investigations in the absence of a similarly detailed body of nonfatal, modern dynamic failure data.

STUDY AREA

The Uinta and Piceance Basin is located in the southwestern United States and covers portions of Utah and Colorado (fig. 2). It covers an estimated 64,000 km^2 [40,000 square miles] (Spencer, 1996) and hosts many of the coal deposits mined in the western United States (Hucka et al., 1997; Schultz et al., 2000). In fact, nearly all western U.S. underground coal mines currently in operation fall within the Uinta-Piceance Creek boundaries. Conjoined at the Douglas Creek Arch, the Uinta and Piceance Basins are two separate but related basins having unique physical boundaries, histories, and sedimentation patterns. This region was chosen to apply the newly developed classification system because it accounts for 74% of reportable dynamic failure events occurring from 1983 through 2019 (fig. 3). The bulk of underground coal mining in the United States occurring between 1983 and the present has occurred in the Appalachian Basin (U.S. Energy Information Administration Coal Data, no date). The high rate of dynamic failure occurrence in the Uinta-Piceance Basin, despite lower overall underground coal production than the Appalachian Basin, suggests some element of inherent risk. Clarifying the link between differences in dynamic failure mechanism and regional geology may begin to shed light on what the nature of this inherent risk may be.
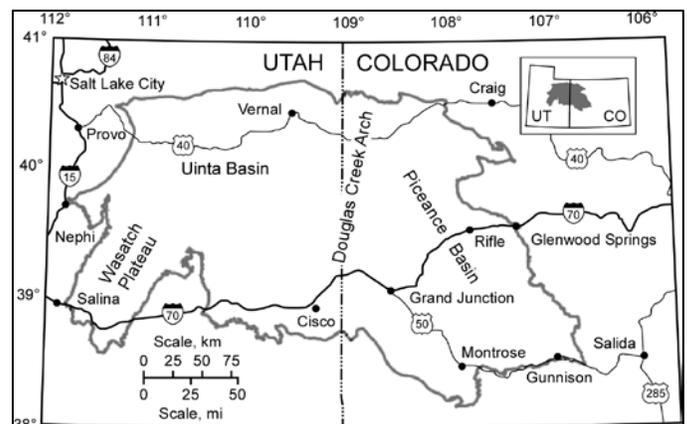
Figure 2. The physiographic boundaries of the Uinta and Piceance Basins, in which the dynamic failure classification system has been applied (modified after USGS, 2002).

Coal seams represented in the compiled MSHA accident reports include the Colorado B, C, and D seams in the Piceance Basin, and the Kenilworth, Castlegate, Blind Canyon, Hiawatha, Lower O'Connor, Rock Canyon, Sunnyside, and Aberdeen seams in the Uinta Basin. The relative distribution of accident cases from each seam are illustrated in Figures 5 and 6 and show that the vast majority of

considered accidents (91%) from the Piceance Basin occurred in the Colorado B seam. Accidents reported from the Uinta Basin, by contrast, are distributed relatively evenly among several seams, albeit with the Hiawatha and Lower Sunnyside seams exhibiting the greatest number of reportable dynamic failures. The discrepancies in relative distributions of reportable dynamic failure events between these two areas may be attributable to differential rates of production from the seams in each respective basin—perhaps the Colorado B seam has been mined much more heavily than other seams in the Piceance Basin, while mining in the Uinta Basin occurred in many seams more or less evenly. Unfortunately, production data by coal seam are not available through the U.S. Energy Administration prior to 1983, and production from 1945 through 1982 is difficult to accurately track, so this cannot be verified. An alternative explanation may also be that the Colorado B seam is particularly prone toward dynamic failure, suggesting seam-specific risk, whereas risk in the Uinta Basin may be more regional in nature.
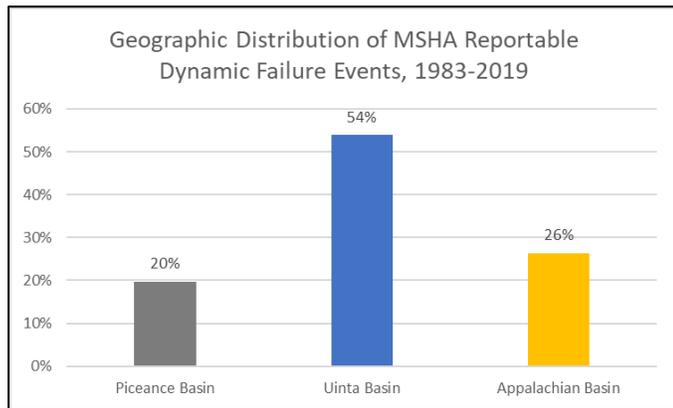

Figure 3. Seventy four percent of reportable dynamic failure accidents occurring within the United States in 1983–2019 occurred in the Uinta and Piceance Basins, despite consistently producing less coal from underground mines than the Appalachian Basin, suggesting some element of risk inherent to mines from this area (modified after Lawson, 2019).
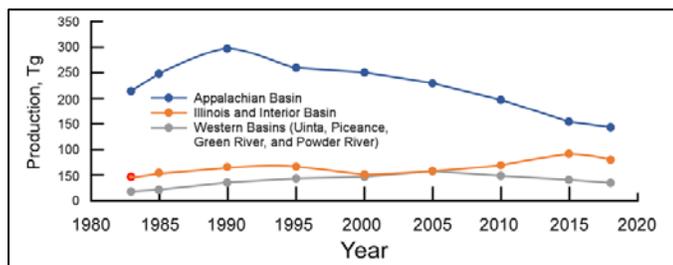

Figure 4. Underground coal production by basin from 1984 through 2018 shows that the Appalachian Basin has been the greatest producer of coal by underground mining in the United States. Data source: U.S. Energy Administration.
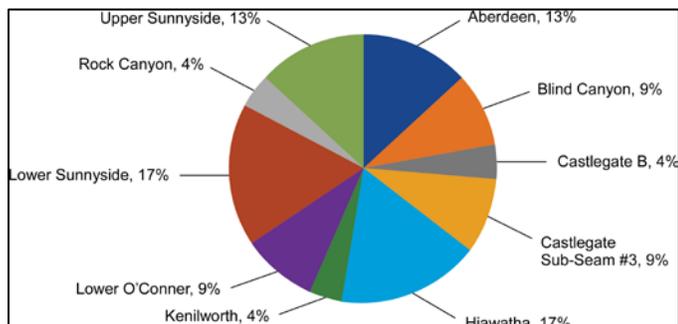

Figure 5. The distribution of dynamic failure accidents in the database by seam in the Uinta Basin.
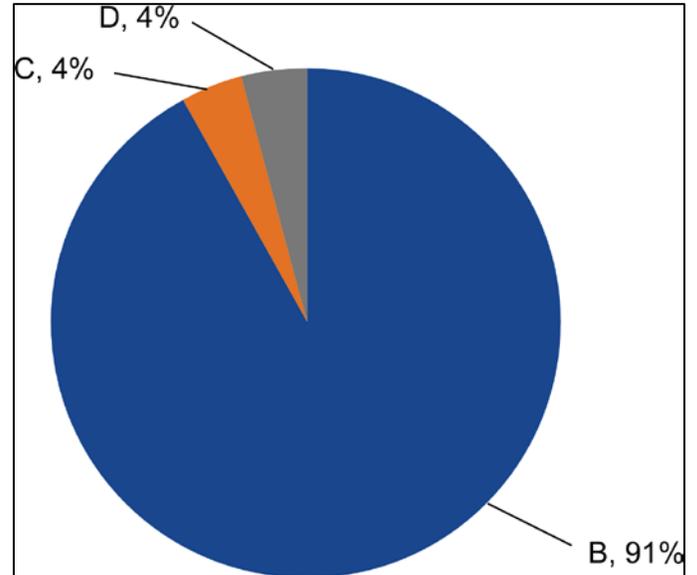

Figure 6. The distribution of dynamic failure accidents in the database by seam in the Piceance Basin.

RESULTS AND DISCUSSION: EVALUATION OF DYNAMIC FAILURE CLASSIFICATION WITHIN THE CONTEXT OF LOCAL GEOLOGY

Application of the dynamic failure classification hierarchy to the selected dataset shows several trends (Table 1, see APPENDIX).

When considering the dataset as a whole, most events are classified as coal bursts caused by excessive pressures at the working face. Eighty percent of events in the database can be classified as coal burst events (fig. 7). Dynamic floor heave events, involving the abrupt failure of floor strata which is then thrust upward into the working area of the mine, constitute 9% of events. Bounces constitute 7% of events. Dynamic roof-fall events, in which failure originates in the roof strata, but which differ from the more common roof-fall accidents in both energy and driving mechanisms, make up 2% of events in the database. Similarly, air blasts also constitute 2% of cases. Of these, strata failure is identified as the primary driving mechanism in 26% of cases. The remaining 74% are attributable to the buildup of excessive pressures in the pillar and/or working face (fig. 8). Eighty-four percent of events occurred at the working face, while only 16% occurred distal to the face (fig. 9).
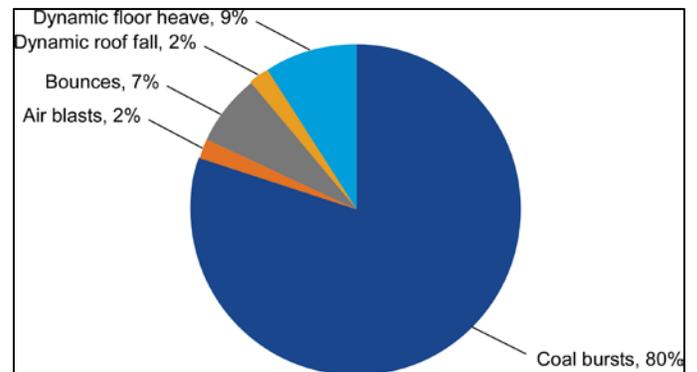

Figure 7. Event type classification of the events database as a whole, indicating that the dominant Tier 1 classification is coal burst.

These observations primarily reflect mining practices at the time of reporting, rather than geologically induced risk. As previously discussed, much of this dataset is derived from accident reports pre-dating 1983, prior to the widespread adoption of longwall mining in Western collieries. Moreover, much of this mining took place at excessive depths, ranging from approximately 460 m (1,500 ft) to 760

m (2,500 ft). Room-and-pillar mining at depths exceeding 300 m (1,000 feet) is acknowledged as a significant exacerbating factor in the occurrence of dynamic failure accidents (Iannacchione and Zelanko, 1995; Mark et al., 2003; MSHA, 2015). These practices are outdated and do not reflect modern mining in the Uinta and Piceance Basins.
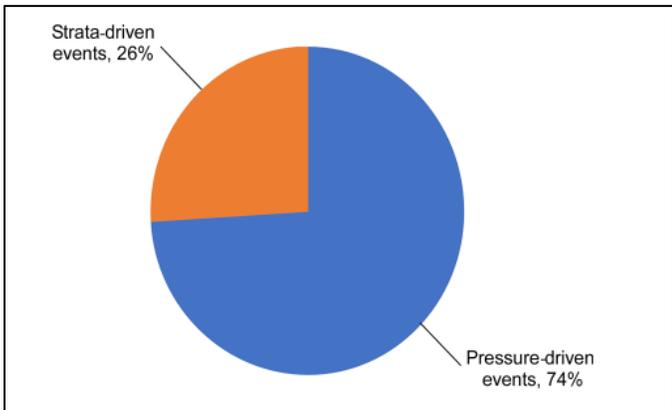

Figure 8. Categorization of driving mechanism in the events database as a whole, indicating that most events were induced by the buildup of excessive pressures in the rock mass.
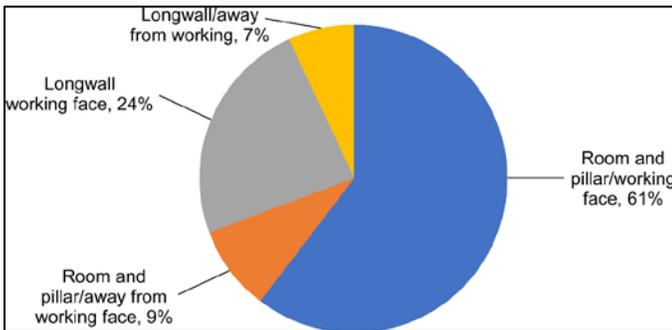

Figure 9. The types of mining represented in the database, and the location of failure relative to the working face.

However, with the understanding that pressure-induced coal bursts are likely to be less frequent in modern mining scenarios in the Uinta and Piceance Basins, the relative distribution of these event types and mechanisms can help to clarify differences in geologically induced risk factors between the two basins. This is particularly true with respect to Tier-2 classification (driving forces) and Tier-4 classification (specific failure mechanisms). We note, however, that events in the Piceance Basin come almost entirely from the Colorado B seam; as a result, it is possible that differences reflect disparities between depositional conditions between seams, rather than regionally associated risk. Nonetheless, several differences are apparent between events occurring in the two basins.

Failures driven by the massive collapse of strata, such as bounces, air blasts, and shock-induced coal bursts, are more frequent in the Uinta Basin (fig. 10). Thirty-five percent of failures in the Uinta Basin can be associated with the collapse of strata, whereas only 17% of events in the Piceance Basin are associated with strata collapse (fig. 11). This may suggest that thick competent strata are a more significant contributor to dynamic failure occurrence in the Uinta Basin than in the Piceance Basin. Pressure, however, is a significant contributor to failures in both regions.

Determining specific failure mechanisms from accident narratives carries a considerable element of qualitative analysis relative to other classification tiers, and, in many cases, could not be determined with confidence. Consequently, 30% of event mechanisms in the Piceance Basin and 17% of event mechanisms in the Uinta Basin could not be determined. The disparity in the number of cases wherein an event mechanism could not be determined stems from the preponderance of cases from the Dutch Creek mines in the Piceance Basin. Many

historical accident reports from this area contained text stating that dynamic failure occurrence was not understood (an unavoidable hazard of mining) and, accordingly, contained fewer diagnostic details.
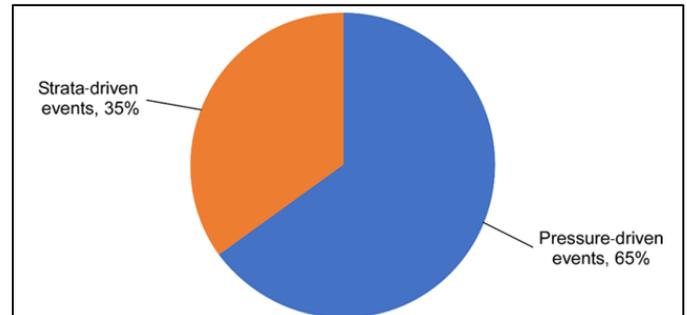

Figure 10. The distribution of driving force (strata-driven versus pressure-driven) in the Uinta Basin.
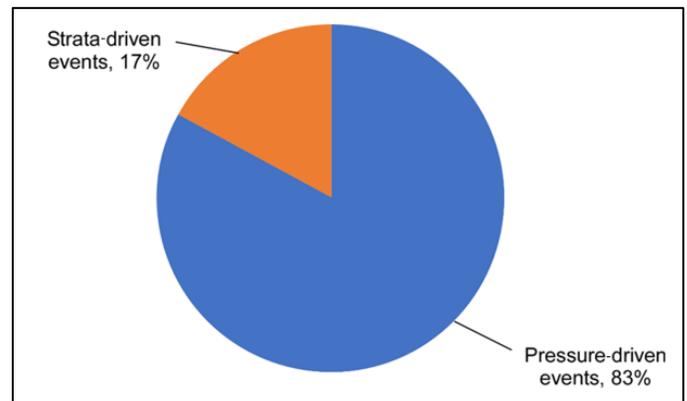

Figure 11. The distribution of driving force (strata-driven versus pressure-driven) in the Uinta Basin.

In the Piceance Basin, most dynamic failure events occurred as the result of a hybrid mechanism involving both significant internal gas pressures and loss of confinement at bedding plane contacts (fig. 12). Red dust at failure planes was identified as a common feature of failures, as was excessively gassy conditions that resulted in small dynamic failure events with "nearly every cut" (Elam et al., 1985). Loss of confinement alone with no clear-cut contribution from internal gas pressure was identified as a contributor in 1 out of the 23 Piceance Basin cases (4%). However, this does not preclude the contribution of internal gas pressure but rather indicates a lack of sufficient information with which to make this claim. Nine percent, or 2 out of 23 cases, were facilitated by failure of the floor strata. This is similar to more recent failure mechanisms observed in the Piceance Basin (Lawson et al., 2012; Tesarik et al., 2013) in the B and D seams in Delta and Gunnison Counties, Colorado.
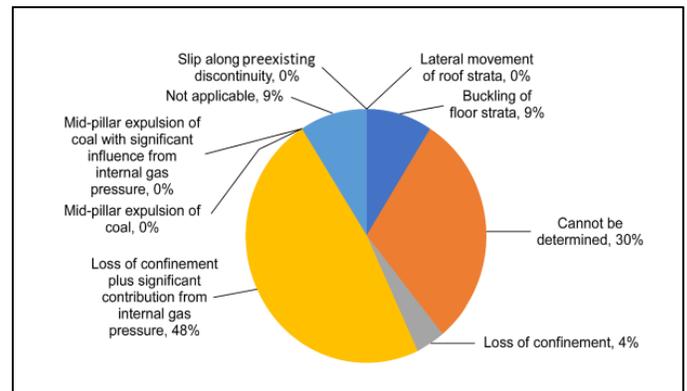

Figure 12. Specific failure mechanisms in the Piceance Basin (Tier 4).

The Uinta Basin, by contrast, shows a greater diversity in failure mechanisms (fig. 13). Loss of confinement was identified as a significant contributing factor in 26% of cases. Mid-pillar expulsion of coal having either no slip at coal/rock interfaces or excessive friction was identified as a significant contributor in 22% of cases. The determination between these two failure mechanisms was made using relative violence of failure, as indicated by the volume of ejected debris, and the type of surrounding lithology. As such, it is susceptible to evaluator bias. Lateral movement of roof strata and buckling of floor strata were both identified as significant facilitators of failure in 9% of cases. While failures in the Piceance Basin show similar frequencies of floor failures, failures originating in the roof rock was unique to the Uinta Basin. One case was identified as the result of a hybrid mechanism involving both internal gas pressure and loss of confinement. There is some uncertainty in this designation—other dynamic failure events in the Uinta Basin in this dataset were also associated with the liberation of significant amounts of methane. However, the source of this methane was identified as sandstone units in the floor, which may have acted as a reservoir for underlying gas-generating deposits. The source of methane generation remains obscure. Similar to the Piceance Basin, buckling of floor strata was identified as the dominant failure mechanism in 9% of cases. Slip along a preexisting discontinuity was identified as the failure mechanism in 1 out of 23 cases (4%) in the Uinta Basin. This case is the only pressure-induced failure not occurring at the working face.
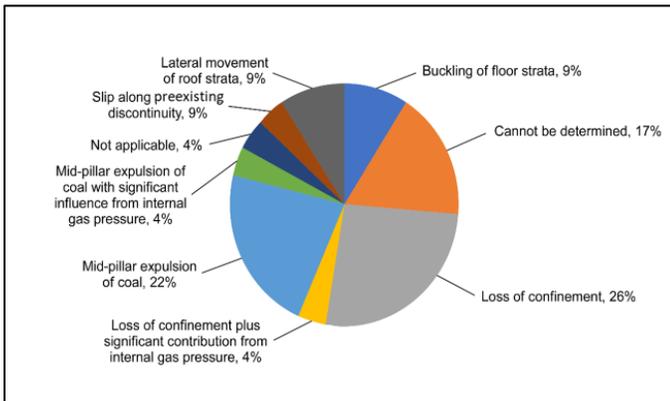

Figure 13. Specific failure mechanisms in the Uinta Basin (Tier 4).

Massive strata collapse-driven events versus pressure-driven events and differences in the frequencies of mid-pillar failure mechanism versus loss of confinement failure mechanism

Differences in first and second tier classification in the Piceance and Uinta Basins could be attributable to differences in the rates and environments of deposition between the two basins. Variable subsidence rates resulted in greater available accommodation space in the Uinta Basin and, subsequently, thicker accumulations of sediment (Osmond, 1964; USGS, 2002). Moreover, coals of the Uinta Basin are associated with coastal plain and deltaic facies of the Upper Cretaceous Mesaverde Group, with thick sandstone units overlying the coals (Osmond, 1964; Johnson and Roberts, 2002). Thick sandstone units are known risk factors for shock-induced failures and bounces (Rice, 1935; Whyatt, 2008; Whyatt and Varley, 2010).

The Piceance Basin, by contrast, subsided more slowly and, being closer to the Western Cretaceous Seaway shoreline at the time of economic coal deposition, was subject to more frequent transgressive/regressive episodes during early sedimentation, resulting in interlayered packages of coarse- and fine-grained sediments. This may account for the dominance of the loss of the confinement failure mechanism in the Piceance Basin, as this pattern of sedimentation may result in frequent coal-mudstone contacts. Lithologic data available through the Pennsylvania State Coal Sample Databank suggests that the immediate roof lithology for seams in the Piceance Basin used for this study was universally classified as shale or mudstone. Contacts in the Uinta Basin, by contrast, are divided between coal-shale/mudstone and coal-sandstone. Direct contact with sandstone is less likely to facilitate failure through the loss of

confinement mechanism owing to greater friction at the coal-rock[4] interface, and stresses are likely to build in the pillar, ultimately releasing as a mid-pillar burst.

Gas driven events in the Piceance Basin

Differences in thermal maturity of economic coal deposits in the Uinta and Piceance Basins correspond to observed differences in the relative prevalence of gas pressure as a contributing risk factor in dynamic failure events. Vitrinite reflectance values in the mined coal seams of the Uinta Basin range from as low as 0.30% to 0.70%, placing the rocks within the oil window and below. At greater depths, vitrinite reflectance may be significantly higher (USGS, 2002), which may contribute to methane seepage from floor units in some cases. However, no cases included in the test dataset were mined at these depths. In the coal seams represented in the event database, vitrinite reflectance ranged from 0.57% to 0.69%., as indicated by Pennsylvania State Coal Sample Databank records, well outside the gas-generating window. However, some cases do exist in the Uinta Basin in which gas is noted as a contributing factor regardless of the relatively low thermal maturity of these coal deposits. However, the reasons behind this phenomenon are not clear and may be due to the presence of microbial rather than thermogenic gas or may be a function of assumptions made by mine personnel at the time of the dynamic failure event or the qualitative nature of application of the classification hierarchy, or a combination of these factors. Ultimately, further research is required to identify causes behind these observations.

The coals of the Piceance Basin range in vitrinite reflectance from 0.58% to 1.59%. Only the Colorado B seam in the vicinity of Pitkin County, Colorado, occurs at the highest range of this spectrum, corresponding to the gas generation window, and, accordingly, all accidents in which gas pressure appears to have played a role come from this seam. The presence of gas in micropore structures of high-rank coal may have contributed to internal gas pressure in the Colorado B seam. This implies that the character of the seam itself is the most significant contributor to risk in this area; whereas, by contrast, events in the Uinta Basin are widespread and may be more influenced by stratigraphic risk factors.

SUMMARY AND PRACTICAL APPLICABILITY

Applying a dynamic failure classification scheme prototype to a database of events from the Uinta and Piceance Basins demonstrates differences in the character of event manifestation between the two areas. These differences are attributable to sedimentation and thermal histories of mined coals in these regions. Observations suggest that:

- Dynamic failure linked with the massive collapse of strata, such as bounces, air blasts and shock bursts, may be the result of relatively rapid basin subsidence in conjunction with an inland depositional setting, resulting in thick competent lithological units surrounding the coal.
- The loss of confinement failure mechanism is prevalent in both the Piceance and Uinta Basins in association with coal/mudstone contacts at the roof and/or floor and may have its origins in frequent transgressive/regressive events associated with the retreat of the Western Cretaceous Seaway. However, the relative prevalence of mid-pillar bursting with no slip in the Uinta Basin may be the result of the frequency of coal/sandstone contacts, which may be a function of the basin's relatively distant position from the shoreline and preponderance of more inland depositional settings.
- Gas-driven failures in the Piceance Basin correlate to high vitrinite reflectance in the Colorado B seam and suggest that the primary risk in this area derives to a greater extent from

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[4] The effect of coal/shale interfaces relative to and coal/silt- or sandstone interfaces in the mining environment is well documented. Dynamic failure potential has been clearly associated with seam interface friction, particularly in large pillars (Prassetyo, 2011; Rashed and Peng, 2015).

thermal maturity of the seam itself than strata-driven failures, as is the case in Uinta Basin failures.

The findings in this study are consistent with what might be expected in both regions. In the Uinta Basin, where strong lithology has long been indicated as a significant risk in dynamic failure occurrence, bounces, shock-induced bursts, and mid-pillar expulsion of coal are more frequent classifications. In the Piceance Basin, by contrast, these classification characteristics are less common and are superseded in prevalence by pressure-induced failures with slip at bedding contacts, often with gas as a contributing factor. Interestingly, these findings highlight the differences between regionally based risk factors in contrast to risk factors associated with the seam itself. In the Uinta Basin, risk is clearly dominated by stratigraphic features. In the Piceance Basin, however, risk was dominated by thermal maturity of the Colorado B seam, although other, more localized stratigraphically influenced risk factors were not insignificant. In terms of practical applications of these findings, the greatest benefit may stem from enhanced understanding of sources of dynamic failure risk and how these differ within the context of different geological settings. These geologic differences are relatively minor in this case, as the Uinta and Piceance Basins are genetically related and were, in fact, a single basin throughout much of their sedimentation histories (Osmond, 1964; Franczyk et al., 1992; Johnson and Nuccio, 1993; Johnson and Roberts, 2002). The most significant geologic differences in terms of dynamic failures in the Uinta and Piceance Basins appear to include differential rates of basinal subsidence, proximity to the Western Cretaceous Seaway during coal deposition, and differences in seam thermal maturity. These geologic differences are reflected in dominant modes of failure between these two regions and have implications toward the application of more targeted risk mitigation practices in these regions. Only by clearly identifying sources and mechanisms of dynamic failure risk can targeted risk mitigation be enacted.

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DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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APPENDIX

Table 1. Results of the application of the hierarchical classification scheme to the selected dataset.

Event identifier	State	Mine name	Seam	Tier 1 event type	Tier 2 event source	Tier 3 mining method/event location	Tier 4 event mechanism(s)
UT-1	Utah	Kenilworth	Kenilworth	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
UT-2	Utah	Spring Canyon	Castlegate B	Coal burst	Massive collapse	Room and pillar/working face	Mid-pillar expulsion of coal, internal gas pressure
UT-3	Utah	Bratzah #3	Castlegate Sub-Seam#3	Dynamic roof fall	Pressure	Room and pillar/working face	Lateral movement of roof strata
UT-4	Utah	Price River #3	Castlegate Sub-Seam #3	Coal burst	Pressure	Longwall/working face	Loss of confinement, methane at the time of event/ignition attributed to release through sandstone floor
UT-5	Utah	Deer Creek	Blind Canyon	Coal burst	Pressure	Room and pillar/working face	Loss of confinement
UT-6	Utah	Wilburg	Hiawatha	Dynamic floor heave	Pressure	Longwall/working face	Buckling of floor strata
UT-7	Utah	Trail Mountain #9	Hiawatha	Bounce, initiating simultaneous coal outburst and roof fall	Massive collapse	Room and pillar/working face	Lateral movement of roof strata and subsequent loss of confinement
UT-8	Utah	Belina #2	Lower O'Connor	Air blast	Massive collapse	Longwall/working face	Not applicable
UT-9	Utah	Soldier Canyon	Rock Canyon	Coal burst	Pressure	Room and pillar/working face	Loss of confinement
UT-10	Utah	Deer Creek	Blind Canyon	Coal burst	Massive collapse	Room and pillar/away from working face	Mid-pillar expulsion of coal
UT-11	Utah	Cottonwood	Hiawatha	Coal burst	Pressure	Room and pillar/working face	Cannot be determined
UT-12	Utah	Skyline #3	Lower O'Conner	Coal burst	Pressure	Longwall/away from working face	Slip along existing discontinuity
UT-13	Utah	Cottonwood	Hiawatha	Coal burst	Pressure	Longwall/working face	Cannot be determined
UT-14	Utah	Aberdeen	Aberdeen	Coal burst	Pressure	Longwall/working face	Mid-pillar expulsion of coal
UT-15	Utah	Aberdeen	Aberdeen	Coal burst	Pressure	Longwall/working face	Mid-pillar expulsion of coal
UT-16	Utah	Aberdeen	Aberdeen	Coal burst	Pressure	Longwall/working face	Mid-pillar expulsion of coal
UT-17	Utah	Sunnyside #1	Lower Sunnyside	Coal burst	Pressure	Room and pillar, location unclear	Cannot be determined
UT-18	Utah	Sunnyside #1	Lower Sunnyside	Coal burst	Massive collapse	Room and pillar/away from working face	Mid-pillar expulsion of coal, regional fault activity cited as a contributing initiating event
UT-19	Utah	Sunnyside #2	Upper Sunnyside	Coal burst	Pressure	Room and pillar/working face	Loss of confinement
UT-20	Utah	Sunnyside #2	Upper Sunnyside	Coal burst	Pressure	Room and pillar/working face	Cannot be determined
UT-21	Utah	Sunnyside #1	Lower Sunnyside	Coal burst	Pressure	Room and pillar/working face	Loss of confinement
UT-22	Utah	Sunnyside #1	Lower Sunnyside	Coal burst	Massive collapse	Longwall/working face	Loss of confinement
UT-23	Utah	Sunnyside #2	Upper Sunnyside	Dynamic floor heave	Massive collapse	Longwall/away from working face	Buckling of floor strata, roof fall and rib damage also accompany this event

Event identifier	State	Mine name	Seam	Tier 1 event type	Tier 2 event source	Tier 3 mining method/event location	Tier 4 event mechanism(s)
CO-1	Colorado	Dutch Creek #2	B	Coal burst	Pressure	Room and pillar/working face	Cannot be determined
CO-2	Colorado	Dutch Creek #1	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
CO-3	Colorado	L.S. Wood	B	Coal burst	Pressure	Room and pillar/working face	Cannot be determined
CO-4	Colorado	Somerset	B	Coal burst	Pressure	Room and pillar/working face	Cannot be determined
CO-5	Colorado	Somerset	C	Bounce	Massive collapse	Room and pillar/working face	Not applicable
CO-6	Colorado	L.S. Wood	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
CO-7	Colorado	Dutch Creek #2	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
CO-8	Colorado	Dutch Creek #1	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
CO-9	Colorado	L.S. Wood	B	Bounce	Massive collapse	Room and pillar/working face	Not applicable
CO-10	Colorado	Dutch Creek #1	B	Coal burst	Pressure	Room and pillar/working face	Cannot be determined
CO-11	Colorado	Dutch Creek #1	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
CO-12	Colorado	Dutch Creek #1	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
CO-13	Colorado	Dutch Creek #1	B	Coal burst	Pressure	Longwall/working face	Loss of confinement, internal gas pressure
CO-14	Colorado	Dutch Creek #1	B	Coal burst	Pressure	Longwall/working face	Loss of confinement, internal gas pressure
CO-15	Colorado	Dutch Creek #1	B	Coal burst	Pressure	Longwall/working face	Loss of confinement, internal gas pressure
CO-16	Colorado	Sanborn Creek	B	Dynamic floor heave	Pressure	Room and pillar/away from working face	Buckling of floor strata, internal gas pressure
CO-17	Colorado	Bowie #1	D	Coal burst	Pressure	Room and pillar/working face	Cannot be determined
CO-18	Colorado	L.S. Wood	B	Coal burst	Massive collapse	Room and pillar/away from working face	Cannot be determined
CO-19	Colorado	L.S. Wood	B	Dynamic floor heave	Pressure	Room and pillar/away from working face	Buckling of floor strata, significant methane liberated during the event
CO-20	Colorado	L.S. Wood	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
CO-21	Colorado	L.S. Wood	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement, internal gas pressure
CO-22	Colorado	L.S. Wood	B	Coal burst	Pressure	Room and pillar/working face	Cannot be determined
CO-23	Colorado	L.S. Wood	B	Coal burst	Pressure	Room and pillar/working face	Loss of confinement