Exploration of Petrographic, Elemental, and Material Properties of Dynamic Failure-Prone Coals

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ABSTRACT

The purpose of this study is to explore how the geochemical and petrographic components of coal may impact its physical properties, as well as how these components correlate with a history of reportable dynamic failure in coal mines. Dynamic failure events, also termed bumps, bounces, or bursts, are the explosive failures of rock in a mining environment. These events occur suddenly and often with no warning, resulting in worker injury up to and including fatality in greater than 60% of MSHA reportable cases. A database of variables was compiled using publicly available datasets, which included compositional geographic, strength, and Hardgrove Grindability Index (HGI) data (ACARP, 1998). Results indicate that bumping coals are less mature, lower in carbon, higher in oxygen, softer, and less well cleated than coals that do not bump. High liptinite content was found to correlate with higher average UCS values. However, no clear, direct correlation between UCS and dynamic failure status was observed. The findings of this study establish that differences exist between coals that have experienced reportable dynamic failure accidents versus those that have not. These differences are inherent to the coal itself, independent of mining-induced risk factors. Results further illuminate how compositional attributes of coal influence physical properties and begin to clarify potential links between geochemistry and dynamic failure status. Only through the better understanding of risk can more effective mitigating strategies be enacted.

INTRODUCTION

Dynamic failure events, also termed bumps, bounces, or bursts, are the sudden failures of rock in a mining or quarrying environment. Failure occurs when the rock's critical bearing capacity has been exceeded and the rock fails energetically through the outward expulsion of rubblized material (Peng, 2008). These events occur suddenly and often with no warning, resulting in worker injury up to and including fatality in greater than 60% of reported cases through the Mine Safety and Health Administration (MSHA). Much research has been devoted to the prevention of these events. The effects of overburden depth and stiffness, mine design, mining practices, and in situ stresses are well documented (Agapito and Goodrich, 2000; Brauner, 1994; Campoli and Kertis, 1987; Holland and Thomas, 1954; Iannacchione and Zelanko, 1995; Lawson et al., 2016b; Mark, 2016; Newman, 2002; Peng, 2008; Whyatt, 2008). Despite these significant advancements in coal mine ground control, however, events continue to occur. Proactive risk mitigation remains an important research area. This is particularly true in underground coal settings, where the rockmass is layered, lithologically diverse, and does not exhibit consistent material properties across deposits.

Many conditions have been associated with the occurrence of dynamic failure phenomena, including:

- thick, competent strata that can create a bridging effect, resulting in high abutment stresses (Rice, 1935; Holland and Thomas, 1954; Iannacchione and Zelanko, 1995; Agapito and Goodrich, 2000; Peng, 2008; Whyatt, 2008; Whyatt and Varley, 2010)
- overburden thicknesses greater than 500–700 ft. (Rice, 1935; Peng, 2008)
- a strong coal that is resistant to crushing (Rice, 1935; Peng, 2008) or that is "uncleated or poorly cleated, strong, sustains high stress and tends to fail suddenly" (Agapito and Goodrich, 2000)
- the presence of sandstone channels or rolls that can serve to concentrate stresses (Iannacchione and Zelanko, 1995; Agapito and Goodrich, 2000)
- fracturing of strong units above or below the coal seam (Whyatt and Varley, 2010)
- slip along pre-existing discontinuities (Peperakis, 1958; Whyatt and Varley, 2010)
- multiple seam mining interactions (Campoli, Kertis, and Goode, 1987; Iannacchione and Zelanko, 1995; Newman, 2002; Peng, 2008)
- mining sequences that can cause anomalously high stress concentrations (Campoli, Kertis, and Goode, 1987; Iannacchione and Zelanko, 1995)

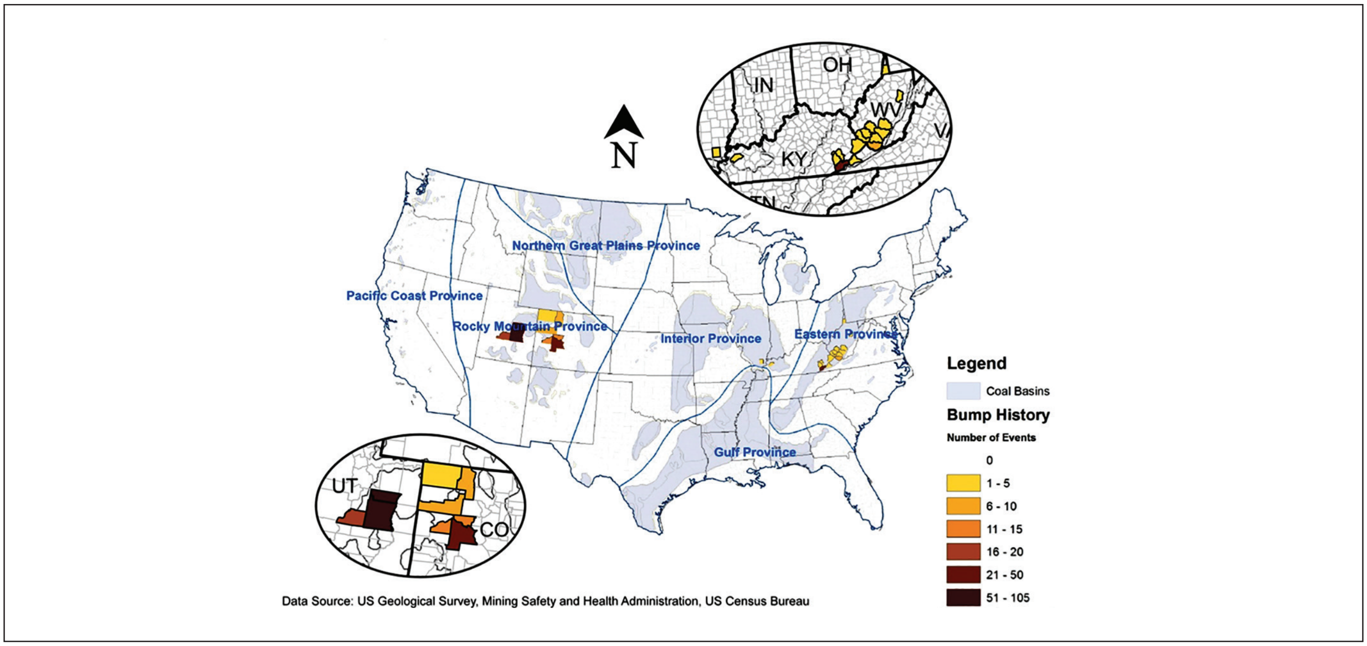

Figure 1. Reportable dynamic failure events occurring between 1983 and 2009. All reportable events occur within three basins—the Uinta, Piceance Creek, and Central Appalachian—despite the prevalence of widespread coal deposits (indicated in grey).

Peng (2008) states that, "a bump may occur even though one or more [generally accepted] geological conditions are not present." Rice (1935) suggested that a combination of factors, rather than one or two specific circumstances, is required to facilitate a bumping event. Identifying a set of conditions that will consistently produce bumping has proven elusive; conditions associated with dynamic failure might produce an event at one site but not another. It is more likely that dynamic failure occurrence is not produced by a single set of circumstances, but rather that they are facilitated by a critical nexus of innate bursting capacity and stress. To date, the majority of dynamic failure research has focused on identifying those factors that produce unfavorable stress conditions. Innate capacity of the coal to burst has been largely neglected as a research topic, with some researchers going so far as to suggest that coal properties play no role in dynamic failure risk (Mark, 2016).

However, history has clearly demonstrated that some coals bump more easily than others (Babcock and Bickel, 1984; Peperakis, 1958; Mark, 2018). A study of dynamic failures in the Sunnyside coal seam in the Uinta Basin, Utah, was carried out by Peperakis (1958) to identify the root causes of events occurring under low cover during development mining in virgin coal. Ultimately, it was concluded that the bumps were associated with regional faulting. However, this conclusion begs the obvious question: faulting is not an uncommon condition. Why has proximity to faults not consistently yielded similar events under similar conditions? More compellingly, Babcock and Bickel (1984) obliquely addressed this issue when they found that under laboratory conditions, some coals could be induced to exhibit bursting behavior more easily than others. In fact, out of 15 coal samples, 13 could be induced to burst with differing levels of difficulty. Of these 13, coals from the Uinta and Piceance Creek Basins of the Western United States could be induced to burst with the least difficulty.

Plotting the number of reportable dynamic failures by county on a map reveals that dynamic failure events are not geographically widespread. In fact, quite the opposite is the case; between 1983 and 2009, nearly all reported dynamic failure events occurred in bituminous coals within the Uinta basin, the Piceance Creek Basin, and the Central Appalachian Basin (Figure 1). Of these, the vast majority of events occurred in the Uinta and Piceance Basins (Figure 2), echoing the findings of Babcock and Bickel (1984) that these coals may be particularly prone to bursting behavior. It is important to note that during the time period from which the bulk of this data was collected that the majority of mining took place in the Appalachian Basin. It has not been until recent years that the Western American coal industry has begun to keep pace with Eastern coal mining with respect to economic sustainability. This suggests that:

1. Some sets of conditions exist within the Uinta, Piceance, and Central Appalachian Basins that do not exist outside of them, and that it is these conditions that facilitate dynamic failure events. Moreover, these factors are likely to be linked to some extent to the innate susceptibility of the rockmass to fail dynamically, as unfavorable stresses can and do accumulate across a broad swath of minable deposits without prompting similar events, and also that
2. Coal mines in the Uinta and Piceance Creek Basins appear to be at higher risk for dynamic failure events, as evidenced by high rates of reported occurrence, despite overall lower historical production rates relative to the Central Appalachian Basin.

Coal Composition as an Indicator of Material Properties

Significant success has been achieved in correlating the material properties of coals with their elemental and petrographic characteristics. Van Krevelen (1961) and Van Krevelen and

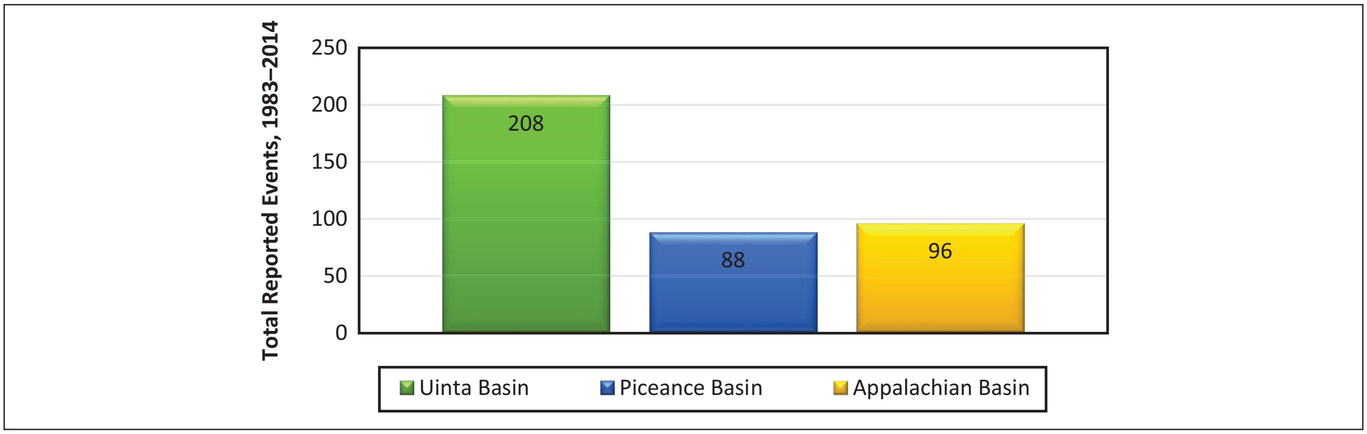

Figure 2. Geographic distribution of reported dynamic failure events by basin, 1983–2008 (MSHA).

Schuyer (1957) describe empirical relationships between the chemical composition of coal and acoustic properties, Hardgrove Grindability Index (HGI), thermal and electric conductivity, porosity, calorific value, and other attributes. Laubach et al. (1998) defined an empirical relationship between vitrinite reflectance—a common measure of kerogen maturity—and cleat density. Mathews et al. (2014) provides an overview of empirically determined relationships between both elemental and petrographic parameters of coal composition and many physical properties.

Given that compositional characteristics of coal correlate with many of its physical properties, it is reasonable to suggest that innate dynamic failure susceptibility may be assessed in the same way. This concept is not without precedent; Brauner (1994) makes the observation that bumps were not observed in coals with less than 12% volatile matter. This correlation between bumping and coal composition is supported by Osterwald, Dunrud, and Collins (1993), who stated that there is an apparent correlation between bumping and the presence of benzene in the coal matrix. More recently, research has suggested that coals that have a history of reportable dynamic failure phenomena also have high ratios of compositional volatile matter to organic sulfur (VM/S ratio) (Lawson, Weakley, and Miller, 2016a).

METHODS

This study examines correlations between coal properties, elemental and petrographic composition, and the presence or absence of dynamic failure history. The dataset used for this purpose represents the combination of several publicly available databases. These include coal records from the Penn State Coal Sample Databank, currently maintained by the Indiana Geological and Water Survey; accident reports available through the Mine Safety and Health administration (MSHA); and the Database of Unconfined Compressive Strength, or DUCS. Incorporation of DUCS data into this dataset represents an expansion of the original used by Lawson, Weakley, and Miller (2016a). Assignment of bump status was performed by Lawson, Weakley, and Miller (2016a) by first establishing seams mined in the MSHA database of reportable events, and then cross-referencing these seams with channel sample records available through the Penn State Coal Sample Databank, limited by the geographic controls of the event mine location. This is a binary true/false assignment of dynamic failure status, based on whether or not any evidence that a given seam had experienced reportable dynamic failure information could be found. It is important to note that dynamic failure status assignation does not take into account the number of events and has not been normalized to production rates. Moreover, it does not address mechanism or other known risk factors such as mining method, design, or overburden depth. Rather, it denotes only whether a seam has or has not experienced one or more reportable dynamic failure events at some point in its history after 1983. Incorporation of these data in future work will further clarify dynamic failure risk.

Variables Considered

Several variables were considered for bivariate analysis during this study. As physical properties of coal will ultimately be the outward expression of its molecular character (Van Krevelen, 1961), there is an inherent interrelatedness of many, if not all, of these variables. The purpose of approaching these data in this way, then, is to determine which compositional variables correlate most closely with both physical coal properties and dynamic failure history, with the understanding that there is an implicit connection across them. Only those variables exhibiting some correlation with dynamic failure history are presented here. These include:

1. Coal maturity
2. Petrographic composition, used here on a Moisture-Ash-Free (MAF) basis
3. Elemental composition
4. UCS,
5. HGI
6. Inferred cleat density**:** Many empirical relationships have been determined on a regional basis to approximate cleat spacing in coal. For the purposes of this paper, the relationship postulated by Laubach et al. (1998) is used to estimate average cleat spacings and is given by:

   Inferred cleat spacing, in inches = $(0.473 \times 10^{(0.398/V_{RO})}/2.54$,

   where V_{RO} is vitrinite reflectance.
7. Location and dynamic failure history, determined by referencing MSHA accident reports.

RESULTS AND DISCUSSION

Maturity

Plotting of the ratios of oxygen-to-carbon against hydrogen-to-carbon on a Van Krevelen diagram (Figure 3) shows clearly that the bulk of bumping seams cluster in the upper right-hand side of the graph. This is indicative of higher compositional concentrations of hydrogen and oxygen and overall lower maturity. High carbon content is associated with harder coals, but it also is associated with more well-developed cleating (Laubach et al., 1998). When these same data are plotted with the inclusion of the coal basin, it becomes apparent that, in general, coals from the Central Appalachian Basin are more mature than those in the Uinta and Piceance Basins. This is unsurprising given the relative ages of the coal deposits; Appalachian coals are generally Carboniferous in age versus Upper Cretaceous in age in the Uinta and Piceance Basins. However, dynamic failure-prone seams from the Appalachian Basin still follow the general trend of lower maturity exhibited by other dynamic failure-prone seams.

Several points deviate from this overall trend. These are highlighted in red in Figure 4. These come exclusively from the Pocahontas #3 coal seam in West Virginia and the Coal Basin B seam in Pitkin and Gunnison counties, Colorado. The Coal Basin B seam is the seam mined by the Dutch Creek Mine during the 1981 mine disaster that resulted in the death of 15 miners (Elam et al., 1981). This accident was classified as an ignition, rather than a dynamic failure. However, the initiating event was a dynamic failure that released methane gas, facilitating the subsequent ignition. There is evidence to suggest that dynamic failures in the northern B seam of Colorado are driven at least in part by internal gas pressures (NIOSH database, unpublished), suggesting that the primary failure mechanism observed in this area may diverge significantly from those observed in other American coal mines. While accident reports from the Pocahontas #3 seam do not suggest gas pressure as a significant contributing factor, it is possible that failure mechanism in these events may also represent unusual conditions in some other yet-to-be-established fashion.

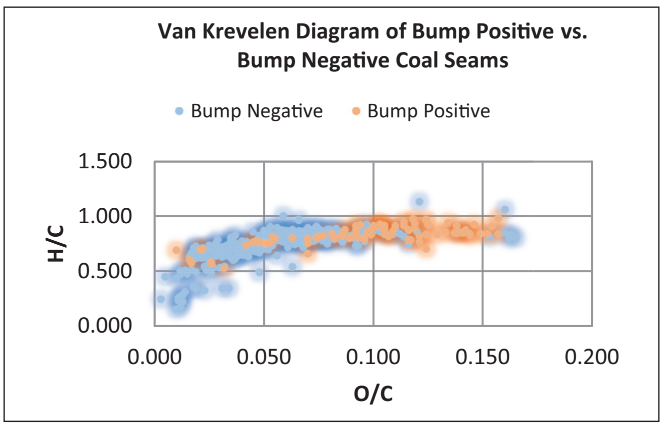

Figure 3. Van Krevelen diagram of bump-positive versus coals by bump-negative coals.

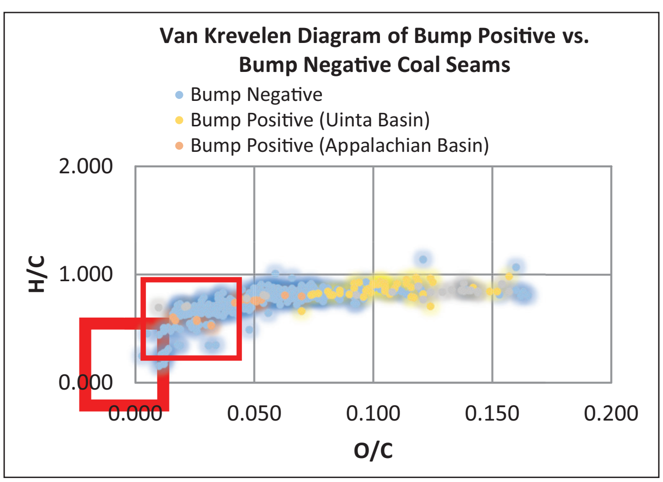

Figure 4. Van Krevelen diagram of bump-positive versus bump-negative by basin.

Petrographic Character

The ratio of vitrinite to the sum of liptinite and inertinite does not appear to bear any direct correlation with dynamic failure history (Figure 5). This ratio has been plotted against vitrinite reflectance to account for differences attributable to maturity. Bumping coals generally exhibit reflectance values of 1 or less. This finding only echoes the results of Van Krevelen diagrams indicating that bumping coals tend to be immature.

Figure 6 plots liptinite content against vitrinite reflectance. This plot shows that for both bumping and non-bumping sample sets, liptinite decreases with increasing vitrinite reflectance, reaching a value of zero for both groups at vitrinite reflectance values of about 1.4. Additionally, lower maturity coals in this sample set are, in general, moderately lower in liptinite than more mature coals, with vitrinite reflectance values from roughly 0.7 to 1.4. A possible explanation for this is that many of these "mid-range" coals were deposited during the Carboniferous period, prior to the evolution of angiosperms; the prominence of spore-producing flora could be responsible for overall higher liptinite composition during this time period. The abrupt decrease in liptinite content at vitrinite reflectance values of 1.4 suggests that liptinite does not survive the process of diagenesis as well as other maceral groups. However, no apparent direct correlation existed between dynamic failure status and liptinite content.

Elemental Composition

The ratios of nitrogen, hydrogen, oxygen, and carbon to sulfur were compared with respect to dynamic failure. Sulfur was chosen as a constant variable, as it is known to correlate very well with a history of dynamic failure, and it is the intent of this study to expand on this initial observation of Lawson, Weakley, and Miller (2016a). Moreover, plotting elemental data against vitrinite reflectance, as was done for maceral composition, reflects only regular changes in elemental composition during coal maturation.

Plotting carbon, hydrogen, and oxygen against sulfur content echoes the correlation between increasing maturity and decreasing dynamic failure susceptibility. Coals with a history of dynamic failure generally have lower carbon content and consistently lower sulfur content than their non-bumping counterparts. Interestingly, there appears to be a subgroup of the non-bumping samples whose carbon content overlaps the dominant range of

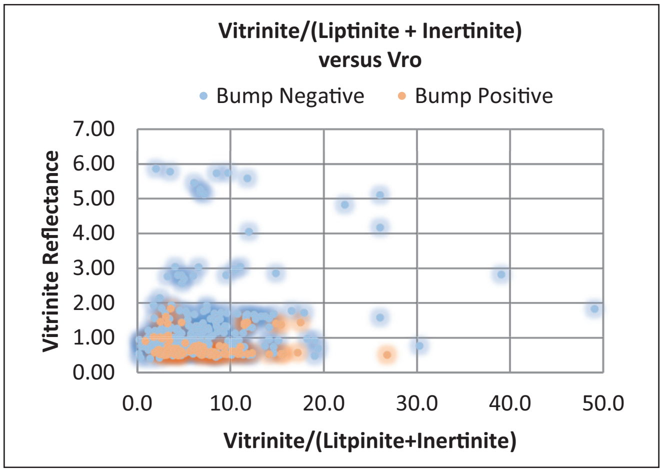

Figure 5. The ratio of vitrinite content to non-vitrinite macerals versus maturity as indicated by vitrinite reflectance.

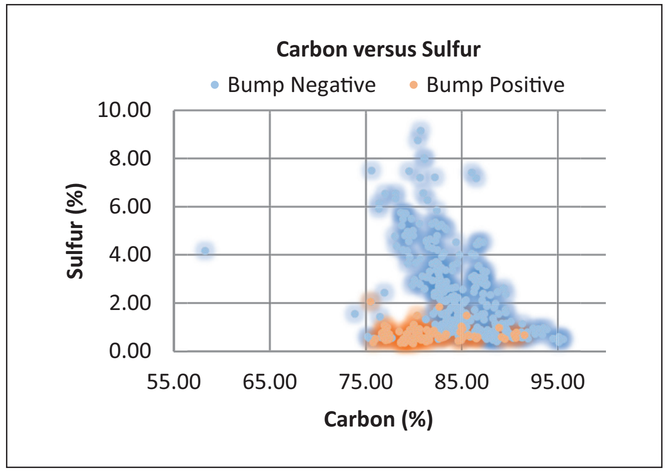

Figure 7. Sulfur versus carbon.

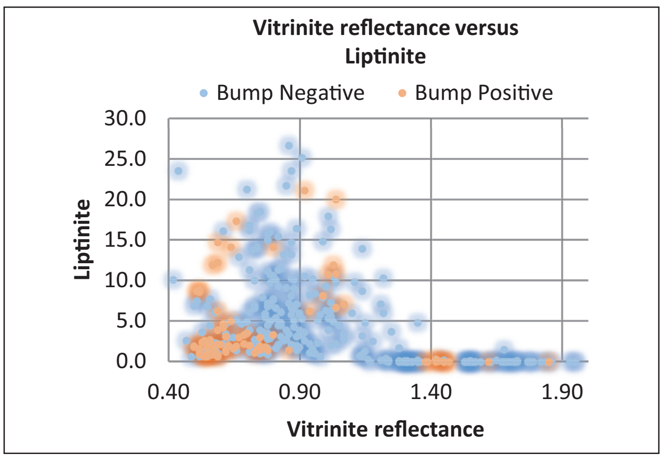

Figure 6. Liptinite versus vitrinite reflectance.

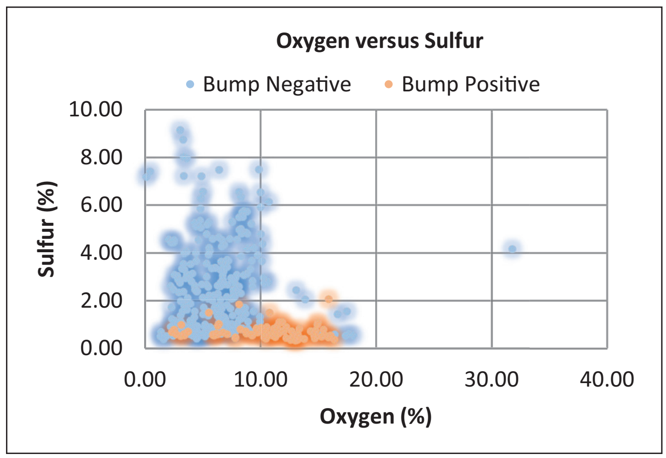

Figure 8. Sulfur versus oxygen.

bumping coals at approximately 75%–83% carbon (Figure 7). The defining differences between these two groups appears to be sulfur content, which is relatively high in the non-bumping sample set and decreases with increasing carbon content, corresponding to increasing maturity. This trend is not seen in the bumping samples; sulfur content begins low and remains low throughout their maturation process.

Plotting oxygen content against sulfur content indicates that, in general, bumping coals tend to have higher oxygen content than coals that have not bumped (Figure 8). While there is clearly overlap between the two groups, the majority of the bumping coal samples have oxygen contents of greater than 10%, while very few non-bumping samples have oxygen content above this value. Again, low sulfur content remains a constant attribute of bumping coals.

Hydrogen, by contrast, shows a large degree of overlap between the bumping and non-bumping groups, although the bumping samples have higher hydrogen content in general (Figure 9). This may be due to their lower maturity. However, no bumping samples within this dataset have hydrogen contents of less than approximately 4%, while some non-bumping samples fall below this limit.

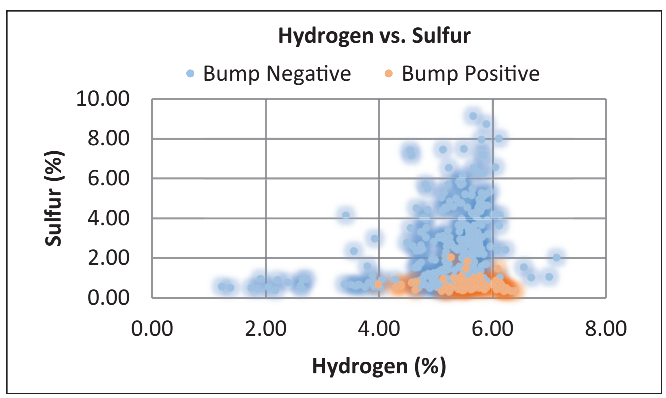

Figure 9. Sulfur versus hydrogen.

Carbon, oxygen, and hydrogen content are all functions of overall maturity, and these observations support the finding that dynamic failure history is closely linked to maturity. As coals that have bumped tend to be relatively immature, it is unsurprising that they are more relatively deficient in carbon, while having higher

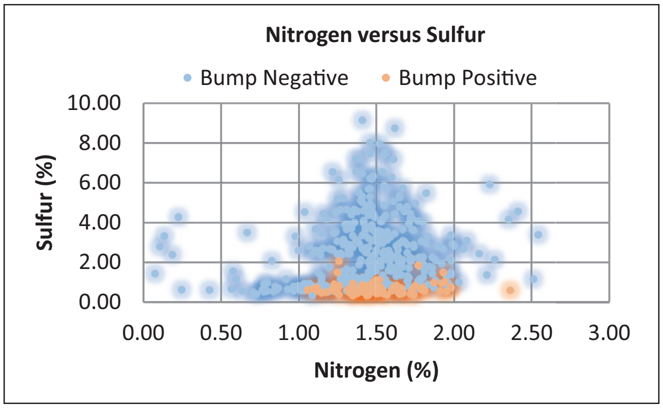

Figure 10. Sulfur versus nitrogen.

oxygen content. Disparities between the relative ratios of oxygen to hydrogen in bumping versus non-bumping sample sets of approximately 2:1 and 1:1, respectively, may be explained by changes in the slope of the line in Figures 3 and 4. The shallower slope of the portion of the curve furthest from the graph axis suggests that during the early stages of diagenesis demethanation occurs less rapidly than decarboxylation, increasing in relative rate with increasing maturity.

Nitrogen values tend to range from 1% to 2% for most coal records, regardless of dynamic failure status (Figure 10). Similarly to hydrogen, some bump-negative records fall below this range, likely corresponding to an increase in maturity.

Low sulfur content is consistently associated with coals with a history of dynamic failure in this sample set. The relative immaturity of bump-positive coal records in combination with consistently low sulfur composition suggests that the original depositional environment for these coals must be sulfur-lean. Sulfur is incorporated into coals during peat formation, and may be incorporated into organosulfur compounds, sulfide minerals, or sulfates (Chou, 2012; Novak, Wieder, and Schell, 1994).

There are two primary initial environmental sources of sulfur during peat formation: marine waters and parent plant material (Chou, 2012). Chou states that sulfur in sulfur-lean coals (<1% sulfur) likely derives wholly or nearly wholly from parent plant material, and that these coals likely formed in freshwater environments with limited influence from seawater. This suggests that coals prone toward dynamic failure were deposited in freshwater environments, and that this may be one unifying characteristic of bumping coals, regardless of geographic location.

Interestingly, marine-dominated stratigraphies rich in mudstone may also carry lower risk for unfavorable stress concentrations (Lawson et al., 2016b). Likewise, they are less likely to be associated with strong, competent strata capable of the bridging effects, noted by Rice (1935), Whyatt and Varley (2010), and others, to contribute to "shock bumps." This then raises the question of whether low sulfur content is associated with dynamic failure because it serves as a geochemical proxy for known stratigraphic risk factors, whether it increases the innate susceptibility of the coal for bursting behavior, or, as a more concerning possibility, both of these.

Unconfined Compressive Strength (UCS)

An abbreviated dataset of 64 Penn State records was correlated with DUCS values on the basis of seam and location. This is due to the limited number of samples within the DUCS dataset that were both (a) geometrically identical and also (b) had Penn State Coal Sample Databank counterparts. No direct correlation between UCS and a history of dynamic failure is observed in the available data (Figure 11). It may be notable, however, that the Blind Canyon and

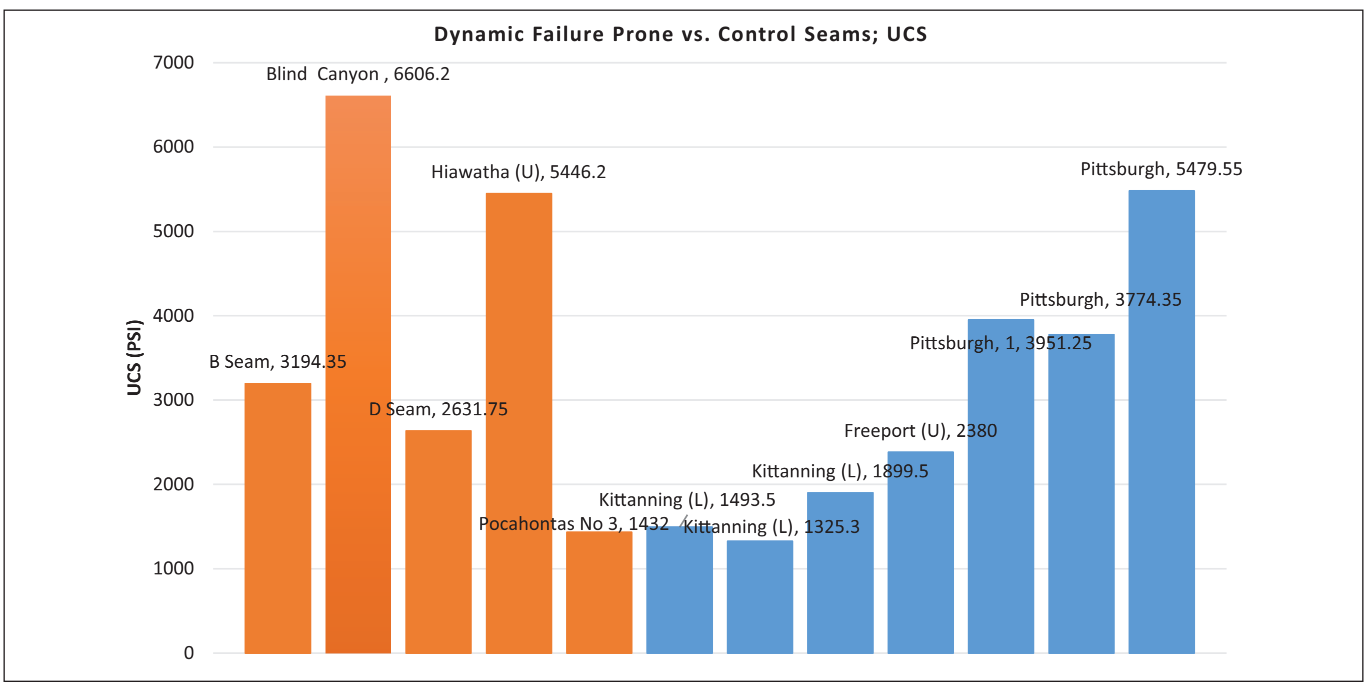

Figure 11. UCS of dynamic failure prone (orange) versus control seams (blue).

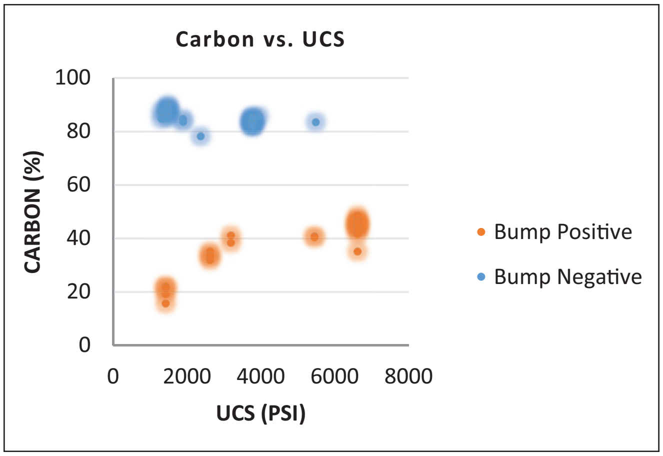

Figure 12. Carbon versus UCS.

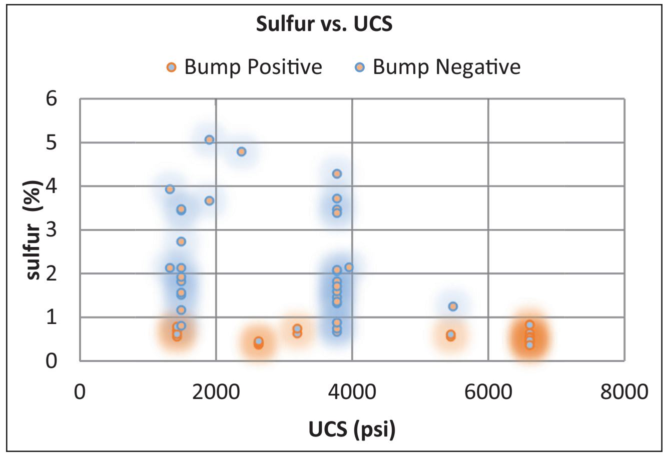

Figure 13. Sulfur versus UCS.

Upper Hiawatha seams of Utah exhibit the highest UCS values and that it is also these seams that have the highest rates of dynamic failure within this more limited dataset. Additionally, standard deviations in the DUCS range from 125 to 1,031 psi, a considerable range. In general, standard deviation was higher in the bumping sample set, perhaps due to less dense cleating, corresponding to lower maturity. More infrequent cleating on such a small scale may render testing results more sensitive to variability in cleat angle and number per sample. Each DUCS record represents the averaging of testing results of 7 to 20 individual specimens. The Pittsburgh No. 8 seam also shows relatively high UCS values, yet it has no history of dynamic failure.

A comparison of dynamic failure status with respect to compositional carbon versus UCS reveals that UCS values in the bumping sample set show a slight increase in carbon content relative to UCS (Figure 12). No such correlation, however, is observed in the non-bumping sample set.

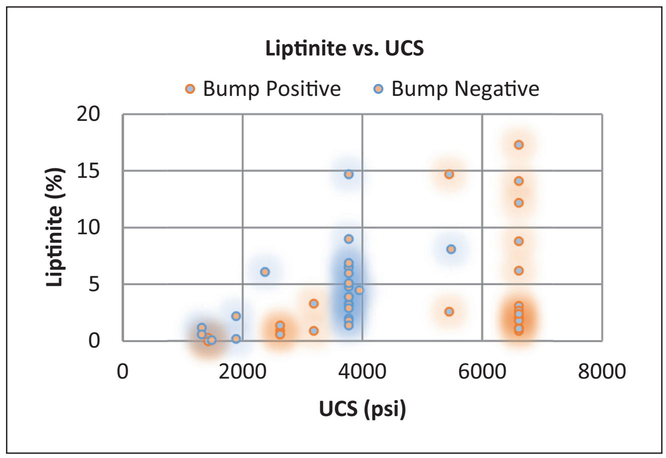

Figure 14. Liptinite versus UCS.

A comparison of compositional sulfur to UCS suggests that in the bump-negative sulfur set there may be a weak negative correlation between sulfur content and UCS (Figure 13). This supports the trend seen in bumping coals that average UCS increases with increasing carbon content, as sulfur would ultimately be expelled from the coal matrix during the condensation of carbon atoms. However, no such correlation exists in the bumping sample set; these coals had low initial sulfur values. In other words, low sulfur in bumping coals is not related to maturity, and hence greater condensation of carbon atoms, but rather result from initial depositional conditions.

There is also a correlation between liptinite content and UCS in both the bumping and non-bumping sample sets, with increasing liptinite content corresponding to increasing strength (Figure 14). However, as UCS does not appear to show any clear correlation with dynamic failure potential, it is questionable how meaningful this finding may be with respect to dynamic failure potential.

These results fail to provide sufficient evidence to conclude that UCS does or does not play a role in dynamic failure potential. Dynamic failure mechanisms are complex and distinct, compelled by many different risk factors. Within the appropriate context, UCS may yet show some relation to dynamic failure if other factors such as pillar design, cleat density and stresses are simultaneously taken into account. Incorporation of these risk factors, however, is beyond the scope of this simple study and may be the subject of future work. Furthermore, no data is available regarding potential localized disparities between individual DUCS specimens used to generate the published averages, such as changes in cleating or geochemical variability. Consequently, while DUCS provides a useful overview of differences in laboratory-measured UCS values, it may be too homogenized for use for this purpose.

HGI and Inferred Cleat Density

Figure 15 shows a clear correlation between increasing HGI and increasing carbon content. Bumping coals cluster near the lower spectrum of HGI values, corresponding to lower maturity and subsequently lower overall carbon content. This implies that, in general, coals with a history of dynamic failure are in fact softer than their non-bumping counterparts.

In both bumping and non-bumping coals, inferred cleat density decreases with decreasing carbon content; in other words, there are wider spaces between cleat apertures in coals with lower carbon content. Bumping coals cluster near the low-carbon, wide-cleat-

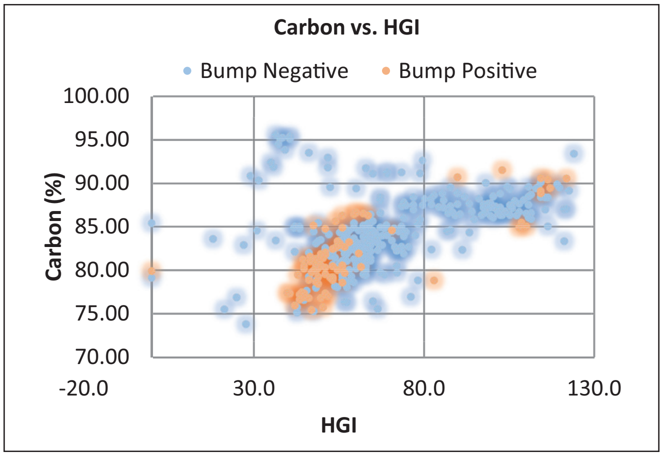

Figure 15. Carbon versus HGI.

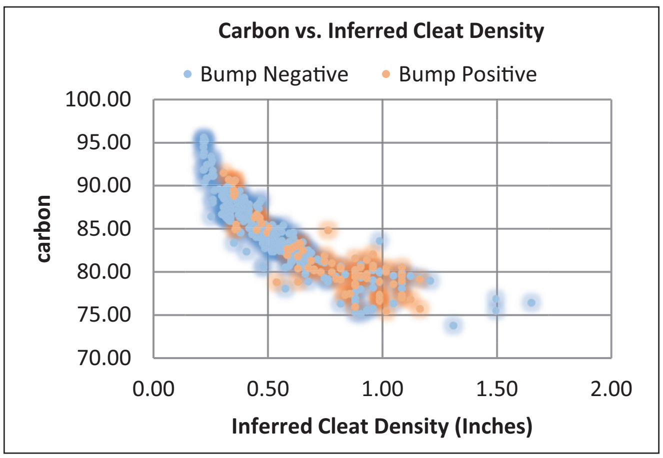

Figure 16. Carbon versus inferred cleat density.

spacing end of this curve (Figure 16). It is counterintuitive that a hard coal would be less prone toward dynamic failure, and it is likely that this attribute—an increase in cleating relative to carbon—may account for this apparent oddity. As maturity increases, carbon atoms become more condensed and HGI becomes higher, but simultaneously, the ubiquitousness of cleat also increases (Figure 17). These conclusions are reminiscent of the findings of Kim and Larson (2017), who suggest that cleating is a controlling variable in stress accumulation and dynamic failure occurrence.

Figure 18 shows the plot of sulfur against HGI and suggests a bimodal distribution of bump-positive seams with respect to these variables. While this is a somewhat ambiguous result, it may suggest that there are two clusters of bumping phenomena occurring in American coal deposits. This observation has been seen in other relationships in this study, such as in Figure 4 showing outlier data points corresponding to high maturity coals. Identifying the dynamic failure mechanism and the mechanism sub-type in these events is an important next step in clarifying their nature.

Figure 19 suggests that liptinite decreases with increasing HGI. Most coals with a history of dynamic failure have HGI values of 70 or less and contain liptinite in slightly higher concentrations to non-bumping coals of low maturity and lower concentrations in mid-range maturity coals (V_{RO}=0.7–1.4). In this case, it appears that HGI is the controlling variable and that this is a function of maturity.

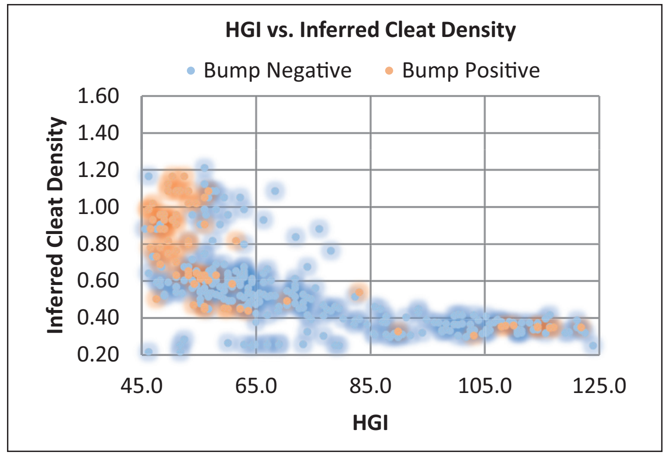

Figure 17. Inferred cleat density versus HGI.

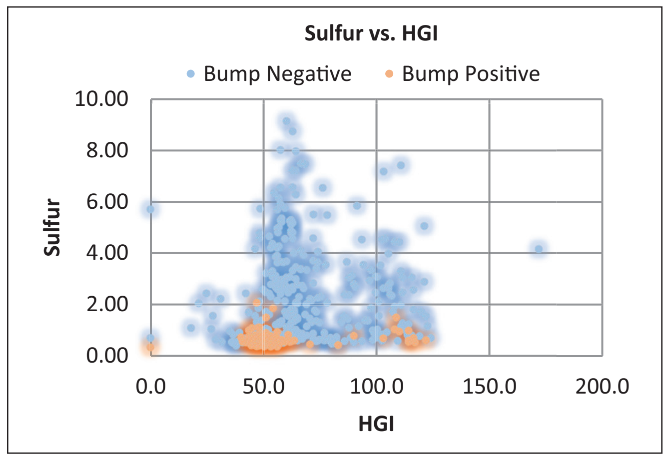

Figure 18. Sulfur versus HGI.

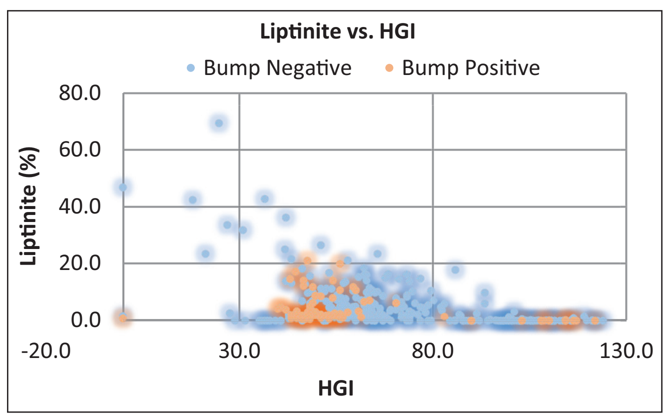

Figure 19. Liptinite versus HGI.

Table 1. Summary of bivariate statistics.

Dynamic Failure Status	Maturity	Sulfur Content	Carbon Content	Oxygen Content	Hydrogen Content	Liptinite	HGI	Inferred Cleat Density	UCS	Other Variables
Positive	Low	Low, <1%	Low, average range 75%–87%	High, >10%	Marginally higher, on average	Marginally higher, on average, in lower maturity coals, Lower or absent in mid-range maturity to mature coals	Softer, <60 on average	Wider, 0.6" +, on average	Ambiguous results, potentially suggesting higher values	No clear correlations
Negative	High	High, >1%	Higher, average range 75%–96%	Low, <10%	Marginally lower, on average	Higher, on average, in higher maturity coals below V_{ro}=1.4	Higher, >57 on average	Tighter, <0.7" on average	Ambiguous results	No clear correlations

SUMMARY

Results of bivariate statistics are summarized in Table 1 and indicate that bumping coals are generally less mature, lower in carbon, higher in oxygen, softer and less well cleated than coals that do not bump. They also show marginally higher average hydrogen. Liptinite content is marginally higher in low maturity bumping coals relative to non-bumping coals of similar maturity. High liptinite content was found to correlate with higher average UCS values. However, no clear, direct correlation between UCS and dynamic failure status was observed.

It is important to note that these results are generalities and relative; by no means do they represent firm limits beyond which dynamic failure-prone coals do or do not exist. Moreover, all samples in this study come from bituminous deposits and cannot be reasonably extrapolated to other coal ranks. Despite these limitations, however, these findings are useful as a relative tool in understanding how bumping coals may differ from those that have not bumped.

CONCLUSIONS

This study illustrates that differences exist in American bituminous coals that have experienced reportable dynamic failure events versus those that have not. In general, coals prone to dynamic failure are:

- Relatively immature, with overall carbon contents below 87% and average vitrinite reflectance values of less than 1.
- High in oxygen, relative to coals that have not bumped. This is likely a function of maturity. However, while bumping coals have moderately higher levels of hydrogen, this correlation is not well developed. This may be the effect of differential rates of demethanation and decarboxylation during earlier stages of diagenesis.
- Have relatively lower HGI values, and are less well cleated. Lower HGI likely results from lower carbon content: as carbon atoms condense, hardness increases. In other words, hardness increases with increasing maturity. However, as carbon content increases, so too do cleats become more tightly spaced and well-developed within the bituminous range, mitigating the effect of increasing hardness. This suggests that the degree of cleat development may be a controlling variable in the susceptibility of a given coal to dynamic failure phenomena.
- Consistently lower in sulfur, regardless of maturity. This suggests that coals that have experienced dynamic failure events may share similar depositional environments, which are likely freshwater, and isolated from marine flooding (i.e. more inland). This raises the question of whether sulfur is actually a proxy for stratigraphic risk factors, or whether sulfur content has some impact on innate coal susceptibility to bursting behavior. Dynamic failure status in this study was determined using records of in-mine events; in order to clarify this issue, coals must be tested under laboratory conditions, insulated from the effects of local stratigraphy.

Results further suggest that there may be two subsets of dynamic failure-prone coals. While the bulk of coals adhere to the general trends outlined above, a second, smaller group of records exists that are:

1. higher in maturity, with vitrinite reflectance values of greater than 1, but less than 2. These coals likewise have higher carbon content, and lower oxygen and hydrogen relative to other dynamic failure-prone coals;
2. harder and more well-cleated;
3. similarly to other dynamic failure prone coals, consistently low in sulfur.

Interestingly, these events come entirely from the B seam, in the vicinity of Pitkin County, Colorado, and from the Pocahontas #3 seam, in the vicinity of Wyoming County, West Virginia. More in-depth analysis of active risk factors associated with these events may help to clarify how or if these events differ from others used in this study, and indicate any similarities that they may share with each other.

The findings of this study help to define the differences between coals that have experienced reportable dynamic failure accidents with respect to compositional attributes and material properties versus those that have not. Only through the better understanding of risk can more effective mitigating strategies be enacted.

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, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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