The influence of intra-seam coal character variation on outburst risk potential

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THE INFLUENCE OF INTRA-SEAM COAL CHARACTER VARIATION ON OUTBURST RISK POTENTIAL.

Patrick Booth¹, Jan Nemcik¹, Ting Ren¹

ABSTRACT: Effective quantification and management of risk associated with sudden gas release during mining (outburst) is reliant on coal and gas properties measurement bases being representative of the local geological and operational conditions. Contemporary gas emission calculation techniques often inappropriately generalise, or neglect, known site-specific extraction geometry, geological conditions, or heterogeneity and anisotropy within the working seam.

Over 5000 coal core gas sample results, obtained from two Southern Sydney Basin Bulli Seam underground coal mines, plus coal samples collected from multiple locations at one studied mine, have been analysed in various geospatial and mining process-based context. Analysis has focused on the alignment of spatiotemporal relationships between; in-situ coal and gas reservoir character, stress regimes influenced by stratigraphic features and geological structure, and gas emission response to mining extraction processes.

Sampling and experimental processes have been developed to facilitate the alignment of experimentally determined coal and gas characteristic properties and their response to applied stress, with datasets typically collected as part of mine gas and outburst risk management practice. Results demonstrate the high degree of intra-seam variability and anisotropy possible in Bulli Seam coal within relatively small lateral and vertical extents.

Generalised relationships between increased applied confining stress and reduced gas permeability were found to be consistent with the literature. However, in specific cores featuring bright horizontal bands, bedding plies, or other visible cleat fractures, the permeability response to increased stress load was found to vary up to two orders of magnitude greater than those cores without such features. Furthermore, gas emission data from the assembled coal gas core results database, combined with density-based CT analysis and other characterisation of spatially referenced coal samples, confirmed laterally extensive uniform floor-to-roof intra-seam coal character and gas emission response patterns. These patterns, consistent with geochronological deposition sequence, may be used to reduce the apparent variability in observed gas emission behaviour.

Results demonstrate the criticality of retaining both spatial and intra-seam context in the measurement of gas sorption capacity, content and emission behaviour. Measurement should therefore be undertaken at a resolution appropriate to the local in-situ conditions and degree of intra-seam vertical heterogeneity. This additional context may facilitate ongoing spatiotemporal alignment of observed gas emission response and hence improvement to outburst risk management processes as higher resolution information becomes available with mining advance.

INTRODUCTION

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Emission predictions are essential for the quantification and management of risk associated with sudden gas release during mining (outbursts), and accumulation of noxious or combustible gases within the mining environment. Unexplained variation in gas and coal character rightly requires conservative mining practices to manage such risks (Balusu, et al, 2010). In many cases, risks are identified later in the mining cycle where remedial action is typically more expensive and is more likely to incur production delay or loss.

The improved resolution and definition in the prediction of site-specific transient gas emission character, in terms of source location, quantity, composition, flow path and timing is acknowledged by several authors as critical for maintaining current production rates. (Karacan, et al, 2011; Packham, et al, 2011; Wang, et al, 2011). Extensive gas and coal datasets of various forms are typically collected as part of best-practice in mine gas and outburst risk management. However, these datasets may range in spatial resolution, timeliness and quality, resulting in commensurate ranges in calculation outputs for gas emission volumes and rates used in the assessment of risk.

The Southern Sydney coalfields have not been immune to gas explosions and outbursts with fatal consequences. Multiple fatalities occurred in gas explosions at Old Bulli Colliery, Mt Kembla Colliery and Appin Colliery resulting in the loss of over 200 lives. Documented gas outbursts have also occurred at almost all mines operating in the Bulli Seam within the region, resulting in the loss of 12 lives (Harvey, 2001). The Collieries that are the subject of this research, have recorded over 150 and 250 outburst events respectively, with each mine also experiencing outbursts on the longwall face (Walsh, 1997; Hyslop, 2017).

Following the last fatal Bulli seam outburst at West Cliff Colliery in 1994, a directive was issued to all Bulli seam coal mine operators, under the powers of the Coal Mines Regulation Act 1982 Section 63, prescribing Threshold Limit Values (TLV) to manage outburst risk and prevent future coal and gas outbursts (NSW DMR, 1995). Original TLVs ranging from 6 to 9 m$^3$/t represent the maximum allowable gas content, relative to seam gas composition, considered safe for mine operations via normal mining, outburst mining procedures, or remote mining only. Pre-drainage of coal seam gas, to reduce initial gas content below 6 m$^3$/t, has been clearly demonstrated to reduce the likelihood of such hazardous occurrences. Furthermore, in jurisdictions where TLV legislation has been enacted and enforced, pre-drainage of coal seam gas to below the TLV has eliminated fatalities due to outburst.

Delay to development advance for reduction of gas content and outburst risk may be tolerable in the overall economics of specific mines. However, more frequent delays to development and subsequent longwall production, given increasing depths of mine workings and higher seam gas contents with lower in-situ permeability is unlikely to be sustainable (Mitchell, 2014).

RELEVANT GAS AND COAL FUNDAMENTALS

Coal seam gas generation and transportation behaviour is dependent on fundamental physical and chemical characteristics, and changes in both magnitude and form of energy sources available within the specific mining environment being considered (Booth, et al, 2016). Physical and chemical properties of gas molecules and their constituent atoms have a profound effect on gas behaviour during adsorption, desorption, diffusion, and bulk flow. Molecular-scale modelling has provided detailed simulation of the physical adsorption processes between typical species of coal seam gas and coal (Mosher et al, 2013).

Although many models for adsorption and desorption principles are described in the literature, the most common are the Langmuir single layer model, the BET multi-layer model, and the Dubinin pore-filling model presented schematically in Figure. In either model, the critical parameters are the accessible surface area available for the sorption process to occur, which is a function of the coal adsorbent structure, and the physical properties of the fluid adsorbate.
Rates of gas adsorption and desorption may be estimated experimentally as part of isotherm determination, however the controlled (i.e. crushed) particle sizing typically used in such experiments may not be representative of in-situ conditions, and this additional context may prove critical in true assessment of outburst risk.

Saghafi (2009) suggested the gas concentration (content) rate of change (\( \frac{\partial c}{\partial t} \)) with respect to time (\( \frac{\partial t}{\partial t} \)) can be expressed as shown in Equation (1), where \( (\nabla) \) is the divergence operator, \( \psi \) is the viscous gas flow, and \( s \) is the rate of gas desorption or adsorption dependent on the diffusivity of the coal.

\[
\frac{\partial c}{\partial t} = (\nabla) \cdot \psi + s
\]  

(1)

The diffusive length becomes the key determining factor in practical estimation or calculation of both the amount and rate of diffusive gas flow, as it becomes more probable that molecules will be subject to much larger external energy forces (e.g. pressure gradients) in shorter timeframes. Gas diffusivity applied in coal represents the ease of gas migration from micropores and into macropores and cleat or fracture systems. Depending on the gas type and pore geometry, diffusive flows are typically dominated by the surface diffusion where the gas species is strongly adsorptive such as with CO2 (Saghafi, 2007).

When considered with respect to time (\( t \)), diffusive flow volume from coal \( Q \), as a proportion of total volume \( Q_m \), has been reported by researchers to be simply represented by Equation (2), where \( a \) is one-half of the average cleat spacing (Gunther, 1965; Airey, 1968; Saghafi, 2007). Moreover, by rearranging Equation (2) to allow comparison and fitting of experimental data, a single parameter \( \tau \), representing a time constant as shown in Equation (3) may be used to replace a measured value of the diffusion coefficient \( D \). Therefore, as the length (\( a \)) becomes increasingly smaller, while maintaining all other parameters constant, the rate of diffusive gas flow increases.

\[
\frac{Q}{Q_m} = \frac{6}{\sqrt{\pi}} \frac{\sqrt{Dt}}{a^2}
\]  

(2)
\[ \tau = \frac{a^2}{D} \]  

(3)

The relative effect of the key variables of diffusive length \( a \) and diffusion coefficient \( D \) on the proportional amount of initial gas available at the boundary with respect to time is illustrated in Figure . For example, with a diffusion co-efficient of \( 1 \times 10^{-8} \text{ m}^2/\text{s} \), a reduction in sample diffusive length from 5mm to 1mm would result in four-fold increase in the amount of gas diffused within 10 seconds. However, for a diffusion co-efficient of \( 1 \times 10^{-10} \text{ m}^2/\text{s} \), only 10% of gas is diffused from the 1mm sample within 10 seconds initially, and less than 5% of gas is diffused for samples of 5mm diffusive length or greater over a period of up to 120 seconds.

Figure 2: Comparison of gas diffusion rates over time with diffusion co-efficient and length

Darcy’s Law describes bulk free gas flow under the influence of a pressure differential. It may be applied to either single-phase gas or two-phase gas-liquid flow. The timing \( (\delta t) \) of pressure differential \( (\delta p) \) is significant in the application to transient gas emission behaviour from coal, as the combination of time and magnitude of pressure differential will largely determine the gas emission flow rate. The level of gas emission risk exposure throughout the mining interaction processes is thus directly proportional to flow rate, and the larger the pressure differential in the shorter timeframe would generally increase the level of potential risk.

Conservation of mass and energy dictates that the gas reservoir response to a change in boundary conditions will be to re-establish equilibrium by transitioning from higher to lower energy states. Transition timing is dependent upon both initial quantity of gas available for free flow to points of lower energy, and the magnitude of the differential. The flow quantity over time may be described by an exponential decay function of the form shown in Equation (4), where \( Q(t) \) is flow at time \( t \), \( Q_0 \) is the initial flow, and \( \tau \) is a constant reflecting the rate of flow decay. Various parameters, which are discussed in detail following, affect the time constant \( \tau \).
The exponential decay function may also be applied in terms of pressure equalisation over time, between two volumes at different commencing pressures.

\[ Q(t) = Q_0 e^{-\frac{t}{\tau}} \quad (4) \]

For application of the exponential decay function to the mining environment, assumptions related to the boundary conditions include:

a) Mining interactions are being undertaken from locations initially containing air, at or near atmospheric pressure.

b) Initial gas reservoir conditions (pre-mining interaction) are typically at a much higher pressure than atmospheric pressure, which is typically in the order of 100 kPa.

c) A pressure differential between two points in space still requires a pathway for any amount of free gas to flow. The number and effective resistance of each pathway to flow may change dynamically as a complex function of changing stress conditions.

d) Additional gas sourced from coal matrix desorption and diffusion processes may contribute to Darcian flow throughout the period of equilibrium transition.

e) In-situ initial gas reservoir pressures may, or may not, equal the pressure indicated by a traditional calculation of hydrostatic pressure using depth of cover as a basis.

For calculation of gas emissions and assessment of potential risk, the combination of gas available to be desorbed and diffused within short timeframes, plus already existing free gas must be considered. Gas emission may be limited by either diffusion processes, or the pressure gradient, but in either case the geometry and properties of the coal are critical as demonstrated in Figure.

Figure 3: Generalised effect of stress change on critical gas emission geometric parameters

Coal is a heterogeneously complex and combustible sedimentary rock made of plant debris and plant derivatives. Originally deposited firstly as peat, and secondarily as mud, coal undergoes physical and chemical processes resulting from compaction and heat over time. At
Coal properties are a combination of three primary parameters, each of which is determined by factors involving the source matter and geological history. The three primary parameters are: organic including the maceral constituents, inorganic including the minerals, ash or other inorganics associated with the structure of maceral components, and the rank reflecting the temperature and pressure to which the source matter has been subjected over time (O'Keefe, et al, 2013).

Maceral types typically used to describe coal are vitrinite, liptinite and inertinite. Within humic coals there is a range from bright (vitrinite-rich) to dull (liptinite- and inertinite-rich) materials (O'Keefe, et al, 2013). Macerals present in coal may be identified through coal petrographic analysis, using reflected light microscopy (Black, 2011). Coal rank is generally reported as increasing by a function of temperature, depth of burial, geothermal gradient, and the length of time the organic material remains in each environment. However, O'Keefe, et al (2013) suggested the maximum temperature to which the source matter has been exposed, and the time for which it was held at that temperature, as the most critical factor in determining coal rank.

Coal rank is typically measured using the vitrinite reflectance technique detailed in Australian Standard AS 2856.3-2000 (SAI Global, 2013). Higher rank coals are typically harder and stronger, containing a bright black vitreous lustre, also characterised by reduced moisture levels, increased carbon content and calorific values.

Prior research within the study region has identified and quantified several coal properties which influence both absolute gas sorption capacity and rate of sorption and desorption (Saghafi, et al, 2007; Black, 2011; Zhang, 2012). Critical coal properties, such as those obtained by proximate analysis, including; carbon content, ash, volatile matter and moisture, have been found to consistently influence coal sorption capacity in a similar way. Conversely, some coal sorption isotherm tests, reportedly undertaken on coal from the same location, yielded results varying by more than 20% on a cubic metre per tonne (m3/t) basis. Such variability in results suggest other factors may also influence sorption capacity.

To examine the relative influence of potential alternate parameters in this study; the drilling, coring and laboratory history of core samples used for isotherm testing during Zhang’s study were obtained. As isotherm tests were completed on crushed coal core after original gas content analysis, the original core descriptions and results from those analyses were considered in spatiotemporal context. Results reported by Saghafi, et al (2007), Black (2011) and Zhang (2012), while holding coal source and gas type constant, are consistent with previous studies of coal sorption capacity influenced by the parameters summarised in Table.

Isotherm tests are typically carried out using crushed coal samples to reduce sorption equilibrium time to practical experimental timeframes. However, using crushed samples may not be a reliable indicator of accessibility of gas to coal surfaces for sorption and desorption processes in real time, considering the rapid rate of change of stress conditions induced by mining processes.

The coal structure hence plays a significant role in the adsorption and desorption character, but this does not necessarily mean that coal of certain properties, and whose sorption capacity is described by a particular isotherm, actually contains that amount of gas for a given coal volume. Measurement of gas content must therefore be undertaken to determine the degree of saturation of the coal. Limitations in the direct measurement of key gas content inputs for emission calculation remain the subject of debate between researchers (Diamond, et al, 1981; Williams, et al, 1992; Black, 2011), but are addressed concisely in Saghafi (2016). In the latest revision of AS3980-2016, “Determination of gas content of coal and carbonaceous material - Direct desorption method” (SAI Global, 2016), notable modifications include; a changed Q3
Table 1: Summary changes in coal sorption capacity with various influencing factors.

<table>
<thead>
<tr>
<th>Controlling Parameter</th>
<th>Parameter change</th>
<th>Reported capacity trend</th>
<th>Reported sensitivity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Increase</td>
<td>Decrease</td>
<td>25-50% per 10°C Δ Temp</td>
<td>Aligns to kinetic theory</td>
</tr>
<tr>
<td>Moisture</td>
<td>Increase</td>
<td>Decrease</td>
<td>10-20% per 5% Δ Moisture</td>
<td>Competes for sorption sites</td>
</tr>
<tr>
<td>Ash content</td>
<td>Increase</td>
<td>Decrease</td>
<td>10-20% per 5% Δ Ash</td>
<td>Blocks access to sorption sites</td>
</tr>
<tr>
<td>Particle size</td>
<td>Decrease</td>
<td>Increase</td>
<td>10-20% per 2 x Δ Particle Size</td>
<td>Faster access to more surfaces, but faster desorption rates too.</td>
</tr>
<tr>
<td>Micropore proportion</td>
<td>Increase</td>
<td>Increase</td>
<td>10-20% per 10% Δ μPores</td>
<td>More surface area is available, subject to accessibility to the area</td>
</tr>
<tr>
<td>Confining Stress*</td>
<td>Increase</td>
<td>Decrease</td>
<td>10-50% per Δ MPa</td>
<td>Reduces access pathways for fluids to sorption sites</td>
</tr>
</tbody>
</table>

* Not applicable if the gas is generated prior to stress being applied

method to extend measurement until an equilibrium is reached, addition of a Q3 method “if required”, inclusion of a measurement uncertainty requirement and upgraded reporting requirements (Bull, 2017).

Detail and examples of the required calculations for lost gas determination, temperature correction, measurement uncertainty, and calibration are presented within the Standard. However, it is now critical to establish and standardise site field procedures for core recovery and treatment of samples, to ensure that gas content and composition measurement uncertainties are minimised, and repeatability is maximised. Many authors have compared the slow and fast desorption gas content testing techniques (Williams, et al, 1992; Black 2011). Fundamentally however, it must be recognised that fast desorption testing technique to acquire Q3 deliberately alters the core sample, by crushing to <200 µm coal particle size, in the interests of timely gas content measurement.

The direct effects of the crushing process are a reduction of the diffusive length for which desorbing gas needs to pass through the coal matrix, and the complete removal of any in-situ fracture network and stress orientation which may contribute to directionally sensitive gas migration, be that diffusion or pressure driven.

Recording of initial gas desorption rates, core condition and appearance properties, whilst the sample is intact and before the crushing process, therefore becomes even more critical to identification of potentially hazardous or abnormal conditions for which the gas content measurement process is designed. These include Initial Desorption Rate of an intact sample in the first 30 minutes (IDR30), and other desorption rate based derivative measurement concepts.

**SAMPLING AND EXPERIMENTAL METHODS**

For validation of the use of spatially interpolated input data for modelling of gas emission response, a series of bulk coal samples were obtained from several locations at one mine and subjected to various characterisation experiments. Experimental methods were designed to maintain three-dimensional spatial integrity and traceability of samples and sub-samples back to source. Statistically significant factors determined experimentally may then be compared on a spatially representative basis at various resolutions. Where available, experimental results
may also be compared with other characterisations previously undertaken at study sites. Critically, these include any of the available gas content testing datasets.

Collection of fresh bulk coal samples was limited in some situations due to production and maintenance activities, however complete roof to floor samples were obtained and subjected to the characterisation experiments outlined in Figure including;

- High resolution external imaging for general appearance and geometry
- CT analysis for quantification of relative density, joint and cleat geometry
- Coring in various alignments parallel and perpendicular to bedding joints
- Proximate, porosity and pore size distribution analysis
- Permeability in various gas pressure, gas composition and tri-axial stress context
- Sorption and desorption response to mixed gases and controlled pressures
- Petrographic analysis and Uniaxial Compressive Strength (UCS) testing

Permeability, sorption and desorption experiments have involved the augmentation of a high pressure triaxial apparatus originally constructed for measuring a range of material behavioural characteristics under the influence of variable stress and fluid pressures. The apparatus has been fitted with a real time supervisory, control and data acquisition system which has allowed a range of novel experimental techniques to be trialled. Most significantly, this includes the observation of gas desorption processes from coal samples under the influence of variable pressure reduction quantity and time. It is expected that simultaneous control of gas pressure and triaxial confinement may more adequately represent and simulate practical gas drainage and mining extraction processes, albeit at laboratory scale.

Figure 4: Outline of experimental characterisation process. (After Booth, et al, 2019)
GAS CONTENT DATABASE ALIGNMENT

The most critical piece of spatio-temporal data alignment in this research was incorporation of laboratory coal core gas analysis results with the influencing factors derived from accurate 3D geometry. Furthermore, analysis of coal core properties and descriptions allowed additional intra and inter-seam context to be applied and aligned with drilling trajectories, underground field observations, and samples obtained for laboratory experimental processes. The detailed process for calculation of the relevant spatial properties used to inform modelling of gas emissions is described in detail in Booth, et al (2016) and includes:

- Establishment of a subsurface strata Digital Elevation Model (DEM) using best available vertical level and geological structure data specific to the mining location.
- Derivation of slope, aspect, curvature, and catchment parameters based on the DEM
- Alignment of other known gas and strata material properties with the DEM
- Alignment of key properties to mining geometry and cycle timing
- Identification of trigger points for reset of input conditions and increased calculation resolution where appropriate.

Through alignment and restructuring of gas laboratory data tables relationships between gas types, gas content component analysis and coal properties can be exposed. Gas type and value pairs may be related to standard gas properties, avoiding the need to repeat calculations of standard factors and facilitating easy analysis by gas type. Similarly, for gas content component analysis, transforming $Q_1$, $Q_2$, $Q_3$ and $Q_T$ data into gas content component and value pairs, facilitates comparison of the influence of core spatial, temporal, and coal structural properties. Examples of analysis of the influence of core appearance, coal density and desorption rate on gas content component and composition measurements are shown in the results.

Relative pre-drainage gas reservoir conditions were established by reference to the closest previously obtained virgin gas content core data. Spatial database alignment allows parameters from original laboratory analysis to be compared critically, including a description of the core analysed. Details of the methods to create seam floor referenced DEMs for the calculation of high-resolution depth-of-cover and in-situ stress values are provided in Booth, et al (2016).

Intra-seam vertical location with respect to seam floor is not currently recorded for gas content coal core. However, informed estimates may be made based on XY location, ash, density, and core description records, specifically noting the core appearance recorded on reference samples. Comparison of density and core appearance data from both gas content laboratory analysis and CT experiments are critical to alignment of estimates and results.

The assembled gas content database has been used to perform critical analysis of core results by many different parameters, however three specific relationships are explored in detail within this paper.

- The relationship between gas content results and sample density due to potential influence of intra-seam coal property change on gas emission behaviour,
- The relationship between core gas content analysis component ($Q_1$, $Q_2$, and $Q_3$) and total gas content for a range of core appearance properties.
- The relationship between core appearance, gas composition and desorption rate.

Core sample coal density

The density probability distribution of the total sample set by core appearance and sample area is presented in Figure . There is a distinct trend to lower density values for cores with a bright appearance. Furthermore, and as expected, the trend is independent of the sample area due
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To the potential for core samples to be drilled and taken from anywhere within a vertical horizon defined by the seam thickness.

Figure 5: Core sample density distribution by core appearance and sample area

Analysis of the density of each sample also allows comparison of gas content results on an uncorrected for apparent relative density (ARD) basis. The apparent relative density changes between distinct coal bedding planes may also be obtained from X-Ray CT based measurement as discussed in following sections. Although both the dip and the azimuth may be recorded by core drilling guidance and survey systems, the dip value is commonly not recorded as part of core sample location or database records.

Gas content component (Q1, Q2, and Q3) vs QT and core appearance

Unlike most assessments of gas content components within total gas content measurements where values of Q1, Q2, and Q3 are analysed in terms of m3/t, for this study the data has been configured to allow analysis of component contribution to total gas content expressed as a percentage. This facilitates exposure of additional core properties, such as core brightness or appearance, and allows these to be considered simultaneously as illustrated in Figure.

As expected, there is a distinct overall trend to lower Q3, and higher Q1 and Q2 contribution as total gas content QT increases. This result supports the fundamental gas transport mechanisms described in Chapter 2, however the rate of decrease of Q3 contribution from bright samples at lower values of total gas contents highlights a potential for higher rates of gas release, particularly where the desorbed gas is CO2. The number of bright samples whose Q1 and Q2 contributions are higher at lower total QT values is also noted. The denser appearance of the dull samples’ facet of Figure purely reflects the greater number of dull samples (2543) of the overall total samples (4388).
Core appearance and gas composition influence on desorption rate

The effect of core appearance and gas composition on measured gas desorption rates was assessed as illustrated in Figure 6. As defined by South32 Cordeaux Gas Laboratory practices, desorption is calculated as the square root of millilitres per minute of gas evolved per kg of core material (Bull, 2017). Higher CO2 core samples are typically observed to have higher desorption rates than mixed gas or High CH4 samples across all core appearance types. However, the rate of increase of High CO2 desorption at total gas contents of above 10m3/t is much greater in the bright samples than other core appearance types.

Furthermore, for High CO2 samples, bright core appearance samples are observed to consistently display higher desorption rates than banded and dull samples. This observation is consistent with the bright samples having a more developed internal microfracture network and is discussed in further detail in light of the experimental results.
EXPERIMENTAL OBSERVATIONS AND RESULTS

Sample Density

Similar to measurement of coal core density in all laboratory gas content tests referenced, the “as received” density of all 110mm x 54mm diameter right cylinder coal cores subsamples retained for this study was measured using a precision microbalance.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Samples</th>
<th>Min</th>
<th>Average</th>
<th>Max</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>3</td>
<td>1371.5</td>
<td>1383.3</td>
<td>1389.2</td>
<td>70.2</td>
</tr>
<tr>
<td>Mid-Roof</td>
<td>1</td>
<td>1392.9</td>
<td>1392.9</td>
<td>1392.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Mid</td>
<td>2</td>
<td>1392.4</td>
<td>1397.9</td>
<td>1403.5</td>
<td>30.4</td>
</tr>
<tr>
<td>Mid-Floor</td>
<td>1</td>
<td>1412.8</td>
<td>1412.8</td>
<td>1412.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Floor</td>
<td>5</td>
<td>1367.9</td>
<td>1382.6</td>
<td>1405.7</td>
<td>188.0</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>1367.9</td>
<td>1388.7</td>
<td>1412.8</td>
<td>187.9</td>
</tr>
</tbody>
</table>

While density measurements may appear relatively consistent, the horizon, orientation and sample sizing of the coal core all mask significant variations that occur in the horizontal plane consistent with bedding. Such variations can be observed with the naked eye on the surface of cores and block samples, however computerised tomography (CT) techniques may also be used to highlight internal structure and density changes as illustrated in Figure . As demonstrated in later sections, density may also be used as an indicator of coal property changes consistent with geochronological sequence, provided the vertical distance from floor of seam is known.

Figure 8: Example intra-seam coal sample sequence with corresponding density CT images.

In the above Figure , reverse contrast has been used in post-processing of raw CT DICOM images. Darker blue areas relate to lower density and light yellow to higher density. In most cases the bright horizontal banding, visible to the naked eye on the raw block sample, was able to be directly correlated to the CT density value. Furthermore, in most cases, the coal directly
above the lower density bright horizontal band was consistently much higher density than surrounding coal material. Cases of vertical orientation of lower density appear to correspond to either face or butt cleat, depending on the original orientation of the sample in-situ. Consistent patterns in roof to floor intra-seam sequence were observed when aligning samples from various Bulli seam locations as illustrated in Figure.

Figure 9: Relative density measurement and core alignment using 3D CT imaging

By tuning CT window and level values using Slicer3D image post-processing software, alternating density banding in the horizontal plane could be used to estimate the relative intra-seam location of the sample, even when the original sample horizon was unknown. This is illustrated in where the sample orientation and intra-seam vertical alignment of the MG 301 sample was unknown. The pattern of horizontal banding was consistent with the F15 B2 and A16 B5 Floor samples, and the lower section of the A16 B4 Mid-Floor sample.

Due to the 5mm slice resolution of CT images in this study, it is unlikely that any consistent relationships between cleat height, thickness, and vitrain boundaries can currently be discriminated. Further measurement and analysis of cleat patterns above and below identified stone ply may allow further insight of this behaviour, if it exists. Furthermore, it is possible that micro-CT analysis will allow discrimination of inter vitrain-durian consistency, particularly within observed brittle bright bands.

Proximate analysis

Similar to density results, proximate analysis results shown in appear relatively consistent, with the exception of two results showing much higher ash and consequently lower carbon content. Depending on the horizon, orientation and sample sizing of the coal sample analysed, results may mask variations that occur in the vertical dimension consistent with bedding. In general, there appears to be a trend to higher ash and lower carbon content with intra-seam depth from roof to floor. All Bulli seam density and proximate analysis results appear consistent with those obtained from publicly available AGL Bootleg program and other surface exploration boreholes drilled in the north of the study area in the 1980's.
Where intra-seam referenced proximate analysis has been performed, also illustrated in Booth et al (2018), results show similar intra-seam trends from roof to floor except where a 25-50mm thick shale band has been included in analysis. In the Bulli Seam, this typically reflects a much denser and stronger stone ply band commonly observed throughout the mines studied. Furthermore, this may explain the high ash results from this study shown from two locations in red in Table . Proximate analysis results in this table are reported on an Ash-dried, Fixed Carbon and Moisture air-dried and Volatile Matter dry-ash-free basis.

### Table 3: Proximate analysis results - Bulli Seam by intra-seam location

<table>
<thead>
<tr>
<th>Horizon / Sample</th>
<th>Ash (Ad%)</th>
<th>Fixed Carbon (Fcod%)</th>
<th>Moisture (Mad%)</th>
<th>Volatile Matter (Vdaf%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Roof</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A16-B1-1N</td>
<td>10.71</td>
<td>70.22</td>
<td>0.96</td>
<td>20.76</td>
</tr>
<tr>
<td>C16-B1-1N</td>
<td>7.61</td>
<td>73.67</td>
<td>0.77</td>
<td>19.65</td>
</tr>
<tr>
<td>MG27-B2-1A</td>
<td>7.90</td>
<td>72.76</td>
<td>0.76</td>
<td>20.66</td>
</tr>
<tr>
<td><strong>Mid-Roof</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A16-B2-1B2</td>
<td>9.03</td>
<td>71.72</td>
<td>0.85</td>
<td>20.51</td>
</tr>
<tr>
<td>A16-B2-2C</td>
<td>10.13</td>
<td>72.31</td>
<td>0.87</td>
<td>21.22</td>
</tr>
<tr>
<td>A16-B2-3B2</td>
<td>8.21</td>
<td>72.31</td>
<td>0.84</td>
<td>20.78</td>
</tr>
<tr>
<td>A16-B2-6B</td>
<td>8.72</td>
<td>73.15</td>
<td>0.97</td>
<td>19.04</td>
</tr>
<tr>
<td>A16-B3-2B</td>
<td>9.59</td>
<td>70.86</td>
<td>0.82</td>
<td>20.98</td>
</tr>
<tr>
<td>A16-B3-3A</td>
<td>7.84</td>
<td>73.15</td>
<td>0.88</td>
<td>22.52</td>
</tr>
<tr>
<td>F15-B3-1N</td>
<td>8.76</td>
<td>72.31</td>
<td>0.91</td>
<td>19.62</td>
</tr>
<tr>
<td><strong>Mid</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MG27-B1-1A</td>
<td>9.98</td>
<td>72.00</td>
<td>0.70</td>
<td>19.44</td>
</tr>
<tr>
<td><strong>Mid-Floor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A16-B4-3A</td>
<td>10.01</td>
<td>65.64</td>
<td>1.01</td>
<td>26.33</td>
</tr>
<tr>
<td>A16-B4-6B</td>
<td>8.62</td>
<td>71.28</td>
<td>0.91</td>
<td>22.97</td>
</tr>
<tr>
<td><strong>Floor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300BB-B1-1A</td>
<td>13.56</td>
<td>67.19</td>
<td>0.98</td>
<td>21.43</td>
</tr>
<tr>
<td>A16-B6-2B</td>
<td>25.75</td>
<td>38.34</td>
<td>1.15</td>
<td>20.52</td>
</tr>
<tr>
<td>F15-B1-1A</td>
<td>10.74</td>
<td>73.88</td>
<td>1.09</td>
<td>20.07</td>
</tr>
<tr>
<td>F15-B2-1C</td>
<td>11.56</td>
<td>72.00</td>
<td>0.67</td>
<td>20.18</td>
</tr>
<tr>
<td>F15-B2-48</td>
<td>13.53</td>
<td>72.07</td>
<td>0.95</td>
<td>22.38</td>
</tr>
<tr>
<td><strong>Unknown</strong></td>
<td>5.43</td>
<td>75.25</td>
<td>0.87</td>
<td>21.96</td>
</tr>
<tr>
<td>MG301-2-1B</td>
<td>5.43</td>
<td>75.25</td>
<td>0.87</td>
<td>21.96</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>10.21</td>
<td>70.22</td>
<td>0.91</td>
<td>21.24</td>
</tr>
</tbody>
</table>

**Coal petrography**

Coal petrographic analysis was undertaken during this study to determine if any consistent patterns in coal type or coal rank could be used to explain observed gas emission character and permeability testing results. Distinct bright bands typically associated with higher coal rank were observed in samples obtained from several locations. Coal type refers only to the source matter and depositional origin of the coal. (O'Keefe, et al, 2013) Coal types reflect the nature of the plant debris from which the source matter was derived, including the combination of plant and non-plant components. Coal type also reflects the depositional environment at the time of peat accumulation prior to burial.

Five samples as shown in Figure were crushed, encapsulated in contrast resin, polished, and then subjected to petrographic analysis including photomicrography by SGS Pty Ltd. In accordance with Australian Standards, reflected white light under oil immersion (refractive index of 1.518) at 500x magnification was used. Each example photomicrograph in the lower section of Figure is approximately 265 microns in width by 200 microns in height.
Figure 10: Coal Type and Rank samples with example photomicrographs

Due to the crushing process, images at micrometre scale are completely random in orientation and may contain artefacts of the resin encapsulation and polishing process. Results summarised in Figure 10 show an overall increasing proportion of the Telovitrinite maceral subgroup type from roof to floor. Furthermore, the distinct bright and brittle band (Sample 5) had the highest vitrinite proportion (54%).

Figure 11: Intra-seam maceral subgroup proportion by horizon and sample

Throughout the coalification process, source organic matter undergoes both physical and chemical change. The degree to which the source matter alters, or morphs, as it matures,
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referred to as the “rank” of the coal. Critically, in the case of study sample locations, the heat from localised magmatic intrusion and/or hydrothermal fluids is recognised to have a potential to completely alter certain intra-seam bands over an otherwise consistent regional apparent rank. Results summarised in Table show an overall trend of slightly increasing rank from roof to floor samples, however the bright and brittle sample (MG303-3) again had the highest maximum and mean reflectance of all samples tested.

Table 4: Intra-seam sample rank measurement by horizon using vitrinite reflectance.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Floor</th>
<th>MG303-3</th>
<th>MG303-3-1A</th>
<th>MG303-3-2B</th>
<th>MG303-1-2B</th>
<th>A16-B1-1A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated Mean Random Reflectance (%)</td>
<td></td>
<td>1.35</td>
<td>1.33</td>
<td>1.32</td>
<td>1.32</td>
<td>1.29</td>
</tr>
<tr>
<td>Maximum Value (%)</td>
<td></td>
<td>1.51</td>
<td>1.49</td>
<td>1.50</td>
<td>1.48</td>
<td>1.44</td>
</tr>
<tr>
<td>Mean Maximum Reflectance (%)</td>
<td></td>
<td>1.43</td>
<td>1.41</td>
<td>1.40</td>
<td>1.40</td>
<td>1.37</td>
</tr>
<tr>
<td>Minimum Value (%)</td>
<td></td>
<td>1.28</td>
<td>1.33</td>
<td>1.31</td>
<td>1.32</td>
<td>1.25</td>
</tr>
<tr>
<td>Number of Measurements</td>
<td></td>
<td>50.00</td>
<td>50.00</td>
<td>50.00</td>
<td>50.00</td>
<td>50.00</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td></td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Coal strength

Mechanical properties of coal and adjacent strata play a critical role in determining in-situ permeability, gas reservoir response to fluid withdrawal and mining processes, and eventual gas emission. Ultimately of interest, for both permeability and gas emission calculation, is the stress state at which a coal will fail (fracture) and the nature and geometry of such failure. In practice, sedimentary rock and coal mechanical properties are non-linear, anisotropic, and subject to the character and magnitude of any fluid that may be contained within the porous spaces of the material.

Each of the key mechanical properties of Young’s modulus and Poisson’s ratio have a 3-dimensional response to the same number of dimensions of applied stress. Gray (2017) concluded that stress measurement and modelling are hence reliant on a thorough understanding of material parameters in the context in which measurements are taken or model results are to be applied. Unconfined compressive strength (UCS), measuring the ability of coal to withstand uniaxial loading (stress) without failure is another such mechanical property where the context of measurement is critical. In contrast to other sedimentary rock types adjacent to the Bulli seam, coal has less than one-half or even one-quarter of the strength of typical mudstones and sandstones found in the study area.

Five coal cores of 54mm diameter were prepared from samples obtained from the Bulli Seam within the study area as shown in Figure . Four of the cores were drilled from samples taken at different intra-seam horizons at the same location, and the final core drilled vertically in a hard-to-drain area.

Right cylindrical cores with smooth ends were fitted to the UOW 100kN Instron testing apparatus and compressed at a load rate of 0.2mm/min. UCS test results presented in Table have been corrected for length to diameter (L/D) ratio in accordance with NSW RMS rock testing standards. Furthermore, the scale effects of sample size have been considered by further reduction of laboratory UCS results by a factor of 0.58 in accordance with previous testing of Bulli Seam coal by Tarrant (2006). Recent literature addressing scale effects and strength anisotropy also supports such a reduction in laboratory UCS results.
Table 5: Intra-seam sample UCS test results

<table>
<thead>
<tr>
<th>Horizon - Sample - Orientation</th>
<th>Peak Raw Load (MPa)</th>
<th>Maximum compression %</th>
<th>Corrected I/D Max Load (MPa)</th>
<th>Corrected UCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Roof - A16-B2-6A - Horizontal</td>
<td>10.58</td>
<td>1.37%</td>
<td>9.53</td>
<td>5.72</td>
</tr>
<tr>
<td>Mid - A16-B3-4A - Horizontal</td>
<td>14.17</td>
<td>1.27%</td>
<td>12.75</td>
<td>7.65</td>
</tr>
<tr>
<td>Mid-Floor - A16-B4-6A - Horizontal</td>
<td>5.72</td>
<td>3.83%</td>
<td>5.15</td>
<td>3.09</td>
</tr>
<tr>
<td>Mid-Floor - MG303-2-1B - Vertical</td>
<td>12.20</td>
<td>1.90%</td>
<td>10.98</td>
<td>6.59</td>
</tr>
<tr>
<td>Floor - A16-B5-3A - Horizontal</td>
<td>12.36</td>
<td>2.29%</td>
<td>11.12</td>
<td>6.71</td>
</tr>
</tbody>
</table>

A significantly lower UCS result of 3.09 MPa was recorded for Mid-Floor horizon sample A16-B4-6A. This sample had a noticeable 3-5mm thick horizontal bright band with a crystalline appearance through the centre of the core. Unlike all other cores, which were relatively solid and dull in appearance, this core did not exhibit a sudden failure and reduction in strength as illustrated in Figure. Further discussion of this observed behaviour in the context of permeability is contained in the following section.

Sample Permeability and relationship to stress conditions.

Coal samples from three separate locations, and four vertical horizons within the Bulli seam were tested for permeability under a range of confining stress and gas pressure conditions. The UOW high pressure triaxial apparatus was used for all permeability testing of eight separate 110mm x 54mm diameter cores in total. For the calculation of the permeability in all of the coal samples tested in these experiments, Equation (5) was used, where $k$ is the permeability (mD), $Q_a$ is the volumetric rate of flow (cm$^3$/s) at atmospheric reference pressure, $P_a$ (Pa), $\mu$ is the fluid viscosity (cp), $L$ is core sample length (cm), $A$ is the cross-sectional area of the core specimen (cm$^2$), $P_{in}$ is inlet gas pressure (Pa), and $P_{out}$ is outlet gas pressure (Pa). Generally, permeability tests were executed with gas outlet pressure at (or near) atmospheric pressure.

$$k = \frac{2Q_aP_a\mu L}{A(P_{in}^2 - P_{out}^2)}$$  \hspace{1cm} (5)$$

Permeability anisotropy in coal is well established in prior literature, and hence orientation and geometry of coal core with respect to bedding planes has been recorded for each sample tested in this study. When placed in the triaxial rig, cores drilled in a horizontal alignment parallel to bedding planes have the applied confining stress ($\sigma_3 = \sigma_2$) equivalent to a vertical stress orientation. In this case, the minimum stress ($\sigma_3$) variation is axial in orientation and, due to the
fixed configuration of the apparatus axial loading, is directly proportional to the Poisson’s ratio of the coal. In this configuration, the apparatus measures the effective horizontal gas permeability subject to changes in vertical load (i.e. typically the depth of cover). Cores drilled in a vertical alignment and normal to bedding planes have the applied confining stress (\(\sigma_1 = \sigma_2\)) equivalent to a horizontal stress orientation. In this case, the minimum stress (\(\sigma_3\)) variation remains axial in orientation proportional to the Poisson’s ratio of the coal. In this configuration, the apparatus measures the effective vertical gas permeability subject to changes in horizontal load (i.e. typically the principal horizontal in-situ stress). All gas permeability test results are subject to the specific test conditions applied to the apparatus at time of testing including: confining stress state, applied gas pressure and source (gas bottle regulated, or inlet void free gas), gas type and elapsed time between first admission of gas and flow measurement.

While permeability is clearly a function of fluid gas pressures and viscosity, the effect of varying stress magnitude and orientation on permeability is less obvious. The net effective stress magnitude and orientation (as a function of both confining stress and fluid pressure) must be considered carefully in any experimental or field result. The clear relationship between confining stress, applied gas pressure, and gas permeability for three separate samples is demonstrated in Figure , where \(\log_{10}\) permeability (mD) is plotted against the linear increase in confining stress (kPa). The relative applied gas pressure for each confining stress stage is shown in colour, red being values approaching 80% of the confining stress, to green being approximately 20% of the confining stress. It is acknowledged that simultaneous desorption-based deformation may contribute to the observed permeability illustrated in Figure , however limitations of experimental equipment and unreliability of optical distance measuring transducers made accurate measurement of these competing simultaneous processes complex to achieve in practice.

While initial values of permeability are relatively low, the trend of rapid reduction in permeability, by an order of magnitude per 2-3 MPa increase in confining stress, is also of critical importance when comparing laboratory test results to likely field stress conditions. Summary permeability test results for core samples are demonstrated in Table , and clearly demonstrate the role of observed bright bands aligned to bedding in improved observed permeability. Furthermore, the role of successive horizontal bands within relatively short vertical distance is suggested to allow improved permeability despite increases in applied confining stress. This result of consistent with failure modes exhibited in UCS tests.

### Table 6: Summary permeability test results

<table>
<thead>
<tr>
<th>Core Sample ID</th>
<th>Horizon</th>
<th>Orientation</th>
<th>Features</th>
<th>Initial Permeability (mD)</th>
<th>Additional Stress to reduce one order of magnitude permeability (MPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A16-B2-2B</td>
<td>Mid-roof</td>
<td>Horizontal</td>
<td>1 x 3mm bright band</td>
<td>0.0049</td>
<td>2.5</td>
<td>Band aligned to bedding</td>
</tr>
<tr>
<td>A16-B6-2A</td>
<td>Floor</td>
<td>Horizontal</td>
<td>Solid - no obvious band</td>
<td>0.0015</td>
<td>2</td>
<td>No obvious cleat</td>
</tr>
<tr>
<td>F15-B5-1</td>
<td>Roof</td>
<td>Horizontal</td>
<td>Solid - no obvious band</td>
<td>0.0009</td>
<td>3</td>
<td>Minor cleat/fracture</td>
</tr>
<tr>
<td>F15-B2-1B</td>
<td>Floor</td>
<td>Vertical</td>
<td>2 x 3mm bright bands</td>
<td>0.0005</td>
<td>2</td>
<td>Bands aligned to bedding</td>
</tr>
<tr>
<td>F15-B2-5A</td>
<td>Floor</td>
<td>Horizontal</td>
<td>5 x 2-3mm bright bands</td>
<td>0.0136</td>
<td>10</td>
<td>Bands aligned to bedding</td>
</tr>
<tr>
<td>MG303-1-1A</td>
<td>Mid seam</td>
<td>Horizontal</td>
<td>1 x 2mm bright band</td>
<td>0.0019</td>
<td>2</td>
<td>Band aligned to bedding Core failed CO2 saturation</td>
</tr>
<tr>
<td>MG303-2-1A</td>
<td>Mid-floor</td>
<td>Vertical</td>
<td>1 x 5mm band + 1 cleat</td>
<td>0.0213</td>
<td>2</td>
<td>Band aligned to bedding Cleat orthogonal to bedding</td>
</tr>
<tr>
<td>MG303-3-2A</td>
<td>Floor</td>
<td>Horizontal</td>
<td>3 x 3-5mm bands</td>
<td>0.0053</td>
<td>2.66</td>
<td>Bands aligned to bedding &amp; fully developed along core</td>
</tr>
</tbody>
</table>
Due to an apparent higher initial and stress resistant permeability result obtained from Sample F15-B2-5A latter samples were deliberately cored to attempt to establish any clear relationship between bright band frequency, geometry, and measured permeability. Other distinct features in latter samples included a shale/stone ply approximately 50mm thick observed at 0.8m above the floor, and noticeable bright and brittle plies ranging between 10 and 25mm in thickness at 1.0m above the floor.

The initial measured permeability of samples at constant confining pressure of 2MPa and gas pressure of 1MPa, and the rate of permeability decline with increase in applied stress, was found to be improved in cores displaying bright banding as illustrated in Figure 13. The role of successive horizontal bands within relatively short vertical distance is hence suggested to allow improved permeability despite increases in applied confining stress. The (vertical) permeability of the F15-B2-1B sample is believed to be more typical of the vertical permeability likely to be experienced in the Bulli seam due to the spacing of master cleating being observed in the range between 200-700mm. Importantly the observed increase in vertical permeability along cleat fractures quickly reduced with application of additional (horizontal) stress.

![Figure 13: Observed stress-permeability relationship in selected cores tested.](image)

**Conclusions and further research**

Estimation of in-situ permeability in coal seams is a complex multi-dimensional function of coal and gas reservoir properties and geometry, but necessary for calculation of gas emission and outburst risk. Evidence within this study suggests that by careful observation of intra-seam coal property variation, and separate calculation of potential lateral and vertical stress conditions earlier in the mining cycle, much of the previously unforeseen gas emission behaviors’ due to dynamic permeability change may be explained fundamentally. The determination of permeability, as a result of highly dynamic stress changing mining processes, relative to cleat and bedding plane geometry, in similar time resolution, is very challenging.

Dual acting diffusive and Darcian gas flow processes, combined with the relative geometry of coal matrix to coal cleat, are critical inputs to the calculation of gas emission and outburst risk. Consistency in geometry and coal character on an intra-seam floor to roof basis, and relative permeability, were tested experimentally in this study. Results from the static permeability experiments conducted demonstrate the degree of variability possible in intra seam vertical and horizontal permeability of the Bulli Seam, even within relatively small lateral constraints. Horizontal permeability of samples tested ranged from 0.001 to 0.01mD, and as such would
generally be described as an impermeable coal. Visible features of each of the samples tested may explain the relative range in results. Vertical permeability of samples cored in that orientation ranged widely from 0.0005 to 0.02 mD. The relatively high permeability observed from one sample, is believed to be significantly influenced by the presence of a cleat fracture oriented parallel to the core.

A general log form relationship between increased applied confining stress and reduced gas permeability was found to be consistent with the literature. Effective permeability was also found to increase with increasing gas pressure consistent with Biot’s co-efficient. However, both the initial measured permeability at constant confining pressure of 2MPa and gas pressure of 1MPa, and the rate of permeability decline with increase in applied stress, was found to be improved in cores displaying bright banding. The role of successive bright horizontal bands within relatively short vertical distance is hence suggested to allow improved permeability despite increases in applied confining stress.

Gas content core database analysis suggests that bright core appearance samples’ consistently display higher desorption rates than banded and dull samples. This observation would appear consistent with the bright samples having a more developed internal microfracture network, the experimental results for bright banded core permeability response to increased applied stress, and core UCS test results. One potential explanation, consistent with all of these observations, is that, due to the altered but narrow distribution of mechanical properties within observed bright coal bands, multiple smaller incremental failures occur on application of increased stress. This may present as both an increase in gas permeability and a reduction of coal particle size, due to the increase in the number and random orientation of microstructural failures, and the number of pathways available for gas flow as stress is applied and then released with mining extraction. While this study has not provided any quantitative justification to draw such a conclusion, this explanation would appear consistent with the results observed.

The variation in results from coal sorption isotherm tests undertaken on coal from the same location, but at different vertical horizons, combined with the observed gas emission behaviour of core samples recorded with bright appearance, therefore illustrate the criticality of intra-seam context in the assessment of coal sorption capacity and gas emission behaviour. Considering such appearance and character is generally aligned horizontally with bedding geochronological deposition sequence, the need for intra-seam vertical reference, at a resolution appropriate to the local in-situ conditions and degree of vertical heterogeneity, may be justified.

Given the sensitivity of any gas emission calculation or assessment of outburst risk to several of the coal properties and geometries illustrated, results suggest a level of intra-seam character and context should be incorporated into assessment of outburst risk. This is particularly relevant in the case of either bedding or plies within the seam having significant change in properties, or where plies are known to have a wide distribution range of permeability values. Where geological structure is known to exist and has potential to cause rapid stress magnitude or orientation change, consideration of loss of confinement in orientations other than for standard linear advance should be undertaken. This is due to the potential for high permeability plies to connect laterally and extensively to coal which has failed and significantly reduced in grain size proximate to the structure plane. Critically, this potential exists independent of the relative geometry of structure to the excavation. High permeability pathways may provide opportunity for rapid pressure loss, triggering rapid desorption of gas from the failed coal with limited diffusive restriction. Structure fault planes may also provide vertical conductivity to otherwise relatively disconnected high permeability horizontal plies, further amplifying potential outburst risk.
The data compiled and analysed in this study may be used to critically assess and optimise outburst risk management and gas drainage designs moving forward, but also demonstrate it is essential for all measurement data to retain the context of location and orientation relative to a common co-ordinate system, including in respect of vertical alignment, throughout the process to facilitate ongoing spatiotemporal alignment of results.

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