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Patrick Booth
University of Wollongong

Heidi Brown
University of Wollongong

Jan Nemcik
University of Wollongong

Ting Ren
University of Wollongong

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DETERMINATION OF GAS EMISSION IN THE MINING LIFE CYCLE

Patrick Booth[1], Heidi Brown, Jan Nemcik, Ting Ren

ABSTRACT: Design of optimal gas drainage and gas management programs throughout the mining cycle is contingent upon a thorough understanding of the gas emission mechanisms specific to the geological and operational conditions in a particular location. As mining progresses from exploration, through development and into production, the resolution of data typically used for gas emission prediction improves spatially and with respect to time.

Quantification and management of risk associated with sudden gas release during mining (outbursts) and accumulation of noxious or combustible gases within the mining environment is reliant on gas emission prediction, which is spatially relevant and applicable to the mining stage being undertaken. Using iterative spatial interpolation techniques, appropriate resolution gas emission model input data may be used to continually improve both the resolution and accuracy of model outputs and also determine triggers where model recalculation is required.

Proposed techniques are validated through a case study of gas core samples obtained from two southern Sydney basin mines producing metallurgical coal from the Bulli seam over a period of 10 years. Alignment of data in various geospatial and extraction time-based context, including relationships to hydrological features and geological structures, combined with experimental results assessing the influence of changes in confining stress and gas pressure, appear to align with modelled outputs and recent historical gas emission data. The results suggest variability and limitations associated with the present traditional approaches to gas emission prediction and design of gas management practices may be addressed using predictions derived from improved spatial datasets, and analysis techniques incorporating fundamental physical and energy related principles.

INTRODUCTION

Underground mining methods account for approximately 20 per cent of total black coal production in Australia (Geoscience Australia 2015). In NSW, metallurgical coal is exclusively mined from the Illawarra coal measures in the southern region of the Sydney basin. Co-located with these coal reserves are significant quantities of methane (CH_4) and carbon dioxide (CO_2) gas (Geoscience Australia 2015). Gas reserves are not limited to economically recoverable coal seams, but also include coal measures and other porous stratigraphy both above and below the working seam (Karacan et al. 2011). Emission predictions are essential for the quantification and management of risk associated with sudden gas release during mining (outbursts), and accumulations of noxious or combustible gases within the mining environment. Unexplained variation in gas 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. Gas core samples from two southern Sydney basin mines producing from the Bulli seam have been analysed in various geospatial contexts including relationships to hydrological features and geological structures. Improved spatial datasets, particularly those containing a vertical dimension and derivatives thereof, may be applied to prediction and management of gas emission using fundamental principles. The application of the physical and spatial techniques described enhance the potential future use of high volume and high resolution real time measurement data for proactive management of gas emission risk much earlier in both the gas and mining life cycle.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.

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[1] *Corresponding Author, Patrick Booth. University of Wollongong. Email: peb987@uowmail.edu.au*

2011). Gas emissions will increase well beyond the practical management capacity of ventilation and current pre and post drainage systems at several Australian underground coal mines (Balusu et al. 2010). Hence the traditional approach of increasing ventilation quantity is unlikely to be sustainable due to practical constraints such as roadway area and maximum air velocity therein. The identification and use of gas management controls which are fundamentally based and incorporate improved spatial and time resolution will not only make mining safer, delivery of this outcome will reduce interruptions for reasons of safety management and lift overall coal and energy productivity.

HISTORICAL GAS EMISSION PREDICTION

The prediction of methane emissions arising from underground coal mining has been the subject of extensive research for several decades (Creedy 1993; Curl 1978; Karacan 2008; Lunarzewski 1998) and techniques range from simple geometric models to modern finite element models (Ashelford 2003; Guo et al. 2012). Despite improvement in computation processing power and speed over this time period, calculation techniques remain empirically based and are hence limited to the origin of information in both application and resolution. Gas emissions due to mining extraction are transient and a complex function of the *in-situ* resource character, the space where *in-situ* character and gas equilibrium is affected by extraction, the degree to which character and equilibrium is affected, and the system response (Lunarzewski 1998). In order to simplify the calculation process of most current prediction techniques, key inputs for gas content, material properties and spatial attributes are generally either provided as input variables at low resolution, held constant, or neglected altogether. Of the many prediction techniques available, the Flügge technique continues to be used for the purpose of total specific gas emission calculation at many Australian mines (Black 2011; Meyer 2006). However, limitations in describing spatial and time based gas emission character with any resolution renders this technique ineffective for design of gas drainage programs. Evidence provided through finite element analysis and micro seismic observations suggest the triangular prism representation is only valid in specific geological conditions and does not cater well for changes in either geology or operational practices (Kelly et al. 1998). Limitations of the technique also extend to neglecting from calculation of fundamental mechanisms driving gas emission behaviour from coal and surrounding strata (Barker-Read andand Radchenko 1989; Gray 1987; Lama andand Bodziony 1998). The significance of localised cleat and joint geometry and net effective stress in the control of fluid movement is similarly neglected. All gas emission prediction techniques require initial measurement of gas content, and the resolution of this measurement may range from kilometres to sub-metre depending on the mining cycle stage. A detailed description of the process for measurement of gas content and its' contributing components may be found in AS 3980 (Standards 2013). Limitations of some of the measurement techniques used, specifically including assumptions of the timing of initial desorption and the lost gas component Q_1, are discussed further by Saghafi (2016). The GeoGAS Longwall "Pore Pressure" model described by Ashelford (2003) took account of many gas reservoir and geological parameters of coal seams and allowed variation of mining operations in arriving at a gas emission value. The model relies upon measured gas reservoir properties for the determination of gas release such as; measured gas content (Q_m), gas desorption rate, gas composition, gas sorption capacity, seam thickness and mineral matter above and below the working section, pore pressure and coal and sandstone porosity. The model parameters and how they are measured are described by Williams *et al* (2001). The advantage of this model over prior techniques was its' ability to accurately predict the magnitude of gas emission from the floor seams below the Bulli seam in the southern Sydney basin. This was due to the significant deformation and order of magnitude changes in horizontal and vertical stress in the floor strata recognised and displayed by finite element software. Whilst the pore pressure model remains the most adaptive and fundamentally based calculation of gas emission for longwall operations, the input assumptions limit the application of this technique to the increasing spatial and time resolution required for design of gas drainage programs. The availability of increasing computational processing capability has enabled the management of the increased size and complexity of the data available for gas emission analysis in recent years. Studies including those by Karacan (Karacan 2008; Karacan andand Goodman 2012; Karacan andand Olea 2014) used statistical, Principle Component Analysis (PCA) and Artificial Neural Network (ANN) based approaches to predict the ventilation methane emission rates of U.S. longwall mines. Critically, all techniques, which involve the use of large historical data sets for gas emission prediction by analysis using statistical, PCA or ANN approaches rely on a fundamental assumption that input conditions will not materially change. Model outputs are based on fundamental scientific principles, however the model design and structure limit the ability for its use in locations where input conditions change rapidly, such as adjacent to or across geological structures. Comparison of the output of various prediction models is difficult due to lack of a common gas, material and spatial datum reference and also for the reasons discussed in Jensen et al (1992).

RELEVANT GAS FUNDAMENTALS USED

Gas Generation

Coalbed or coal seam gas are general terms used to describe gases contained within coal measures that are generated as part of coalification and other geological and hydrogeological processes (Flores 1998). Similar to the creation of coal itself, coal bed gas generation pathways are also dependent on fundamental physical and chemical characters and changes in both the level and form of energy within the environment. Coal bed methane can be classified as either biogenic or thermogenic in origin (Moore 2012). Biogenic methane is generated at low temperature by anaerobic microbes (methanogens) when coal beds are exposed to groundwater recharge after basin deformation. Two significant factors must be carefully considered in the characterisation of the origin of biogenic gas. Firstly, for carbon dioxide reduction to methane, Hydrogen must be present. Secondly, in addition to the methane, the two-part acetate fermentation process also produces CO_2 (Burra et al. 2014). The flow pathway of water is therefore an important factor in characterising gas reservoir conditions. The relative rate of change of coal seam gradient and orientation hence provide information on available potential energy under the influence of gravity. The effect of gravity on hydrogeological and material deposition character has remained constant over geological time. Thermogenic gas is generated at high temperature during late stage coalification and generally contains heavier carbon isotopes than biogenic gas. The results described from (Moore 2012) indicate that the first gas generated via thermogenic processes is CO_2 at approximately 50 °C. Above this temperature, increasing amounts of hydrocarbons (methane, ethane and higher) and nitrogen are produced at maximum volume at approximately 150°C. At higher temperature, gas generation reduces, producing a parabolic maximum gas volume trend with temperature and/or rank. Such parabolic gas content trends have been reported from a number of Australian Basins including the southern Sydney basin which is the subject location of this research (Faiz et al. 2007).

Gas Storage

Over ninety per cent of gas storage in coal occurs by physical adsorption to the surface of the coal matrix, including the surfaces of all internal pores and cleats or fractures (Flores 1998). The remaining is free gas, which may also reside within internal pores depending on pore geometry, and also within cleats or fractures. Adsorption concepts between gas and a solid surface are usually described in terms of isotherms, where the amount of adsorbate on adsorbent is shown as a function of pressure at constant temperature as depicted for three gases (CO_2, CH_4 and N_2) at one of the study sites in Figure 1. The figure also demonstrates the range of potential variation in sorption capacity from upper, middle and lower sections within the 2-3 metre thickness of the Bulli seam.

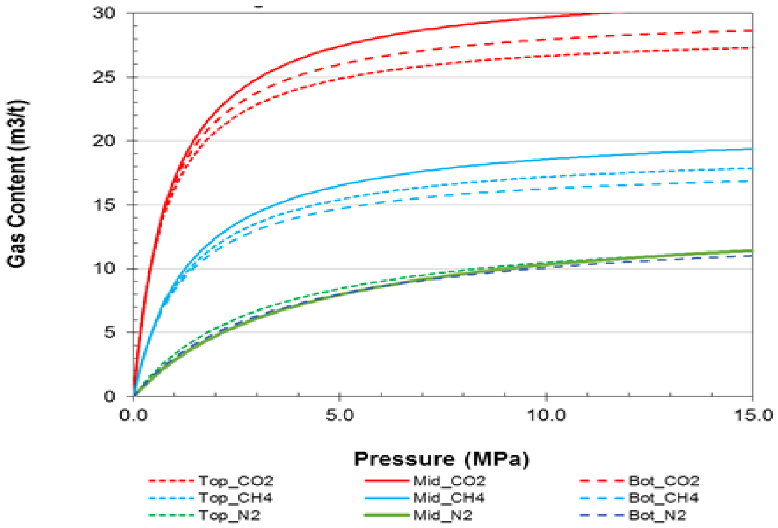

Figure 1: Range of calculated sorption capacities for Bulli seam with typical seam pressure range (shaded)

Gas composition is a fundamental controlling variable in determining total possible sorption capacity due to the relative size, structure and energy levels of relevant gas molecules, particularly CH_4 relative to CO_2 (Booth et al. 2016; Mosher et al. 2013). However, the availability of adsorption sites or coal internal surface area remains the key limiting parameter. The coal structure hence sets the adsorption and desorption character, which also changes with gas type, but this does not necessarily mean that a coal of certain properties and whose sorption capacity is described by a particular isotherm actually contains that amount of gas for a given volume (Black 2011). The ratio between actual measured gas content and the theoretical sorption capacity is known as the *degree of saturation* and is expressed as a percentage. Lower insitu degree of saturation is an indicator that other mechanisms, such as lowering of hydrostatic pressure through fluid movement, have potentially allowed gas to migrate or otherwise be released from the coal after initial gas generation. Gas storage capacity is hence defined by the combination of gas composition and coal properties and structure. Using fundamental physical, chemical, energy and geometric relationships, it is postulated that for gas emission prediction, dynamic response of the gas reservoir to mining extraction can be reliably predicted using higher resolution input spatial parameters, and measured coal property data which is largely available through proximate characterisation parameters such as rank, carbon content, macerals, and moisture content. The range of possible variation in coal properties within the Bulli seam at a single location is demonstrated in Table 1. Coal structural properties are also unlikely to remain constant over a given mining horizon, but rather be significantly influenced by the landscape at time of deposition. Hence these properties are influenced by spatial factors, which may be either measured directly or reliably interpolated using fundamental spatial relationships. Mineralisation also influences internal structure, geometry, pore availability to gas adsorption, ability of gas to flow, shrinking and swelling, gas content, gas recoverability, and potential for enhanced gas recovery. (Flores 2013) Experimental evidence closely correlates increasing coal rank with higher proportions of micropores (Mosher et al. 2013). An increase in micropore distribution per unit of coal volume also increases surface area available for gas adsorption, hence explaining observed experimental increase in gas storage capacity with coal rank, and increase in rate of change of volumetric capacity per unit pressure change as described by Kim in the review by Moore (Moore 2012).

Gas Flow

The movement of gas molecules through either other gases, fluids or solids are described by Fick's Laws (Saghafi 2016). On reducing spatial component of both equations (dx), it becomes more probable that molecules will be subjected to much larger external energy forces (e.g. pressure gradients) in shorter timeframes.

Darcy's law is an expression of conservation of momentum and describes a proportional relationship between the instantaneous discharge rate through a porous medium, viscosity of the fluid and pressure drop over a given distance. This equation can also be solved for permeability, allowing for relative permeability to be calculated. In practice, this measurement is difficult and expensive to complete in situ, but is the only method of obtaining a true permeability result which reflects the reservoir conditions (Gray 1987).

In the case of coal, permeability is a complex, multi-dimensional function of several influences such as width, length, height, aperture spacing, frequency or density, and connectivity of cleats or fractures(Flores 1998). Many of these influence functions are non-linear, however, they have components that can be either readily measured directly or indirectly or otherwise grouped without affecting materially affecting calculation results. Changes in permeability in coal may be summarised into two main components; the effective stress effects, and the shrink and swell strain effects on the coal matrix with desorption or adsorption which may increase or decrease relative permeability (Cai et al. 2014). Coal composition hence controls a broad range of gas reservoir properties including gas adsorption capacity, gas content, porosity, permeability and gas transport.

Table 1: Coal properties at a single location within the Bulli seam

Sample	Proximate analysis (wt.%)				Coal grain density (kg/m^3)	Intraparticle porosity (%)	Surface area (m^2/g)
	Moisture	Ash	Volatiles	Fixed Carbon			
Top	1.35	12.53	17.98	68.14	1466	4.37	0.333
Middle	1	10.53	23.55	64.92	1579	1.92	0.144
Bottom	1.15	25.88	15.06	57.91	1311	3.83	0.292

All Proximate analysis on percentage by weight air dried basis;
Surface area data is calculated based on the pores whose diameter above 30nm.

CALCULATION OF RELEVANT SPATIAL PROPERTIES

The fundamental nature of the physical and chemical interactions between the principal components of coal, coal seam gases and other substances found in the mining environment are significantly influenced by the various forms of energy applied over time. However, the potential energy involved in sedimentary deposition, gas generation and flow is of particular relevance to analysis of gas emission at higher resolution. An overview of the process for calculation of the relevant spatial properties is depicted in Figure 2. In the absence of vertical dimension data specific to the location of gas core samples, alternate sources of vertical information or interpolation can be used to inform predictive modelling of gas emissions.

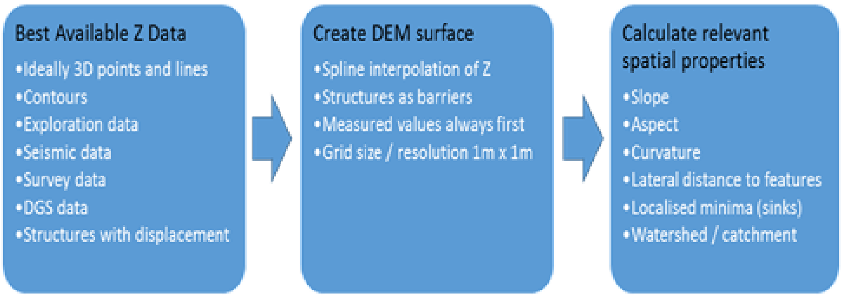

Figure 2: Process for calculation of spatial properties.

Derivation of the elevation surface

The goal of the first stage of model development is to obtain the best possible representation of the Relative Level (RL) of the floor of the coal seam in the subject area using a common datum. To achieve this, original sources of data included but were not limited to, manual survey, drilling records and seismic interpretation. Ideally, all input data is provided in the form of three-dimensional points, however this is not always available. Care must be taken to ensure the use of a common reference datum for all available location and level measurements entered as input data. The Map Grid of Australia (MGA) Zone 56 and

Australian Height Datum (AHD) were selected as the common reference datum for all location and level information used, and several data sources initially required conversion to this datum. The dimensional convention used throughout this study is X related to longitudinal co-ordinates, Y related to latitudinal co-ordinates, and Z related to height or RL co-ordinates. Although sources of RL data may include contours, these are generally previous interpolations of X, Y, and Z point data sources. To allow for future model prediction, development and improvement in real time location measurement technology, all RL input data sources were converted to X, Y and Z point data before proceeding to the next stage.

Selection of the interpolation technique suitable for creation of the elevation surface used in this study considered a range of selection criteria. Input data and processing constraints, and future use of the interpolation outputs in later model processes received higher weighting in the assessment process. Of the many techniques described and compared in the literature (Li and Heap 2008), the spline with barriers interpolation was selected due to the use of exact measured point data as input data, the ability of the technique to manage known abrupt changes in level (e.g. geological faults), the maintainability of the interpolation process with updated input data, and the ability to balance competing requirements for processing time and output resolution.

The result of the interpolation is a raster surface of configurable grid cell size, using barriers, from measured points using a second-order minimum curvature spline technique which is more reflective of natural depositional processes. The barriers are entered as polyline features, and the resulting smooth surface is constrained by the input barrier features. Input datasets may also have several points with the same x and y coordinates. An important feature of this technique is that if the values of the points at the common location are the same, they are considered duplicates and have no effect on the output.

Several tests were undertaken of total surface calculation area versus raster resolution (individual cell size) and processing time. The final selected Digital Elevation Model (DEM) configuration for the two study sites covered an area of approximately 200 km^2 each, contained multiple barrier features of both two and three-dimensional data types, at a 1 m x 1 m resolution and processed in approximately 10 minutes. This configuration was deemed acceptable for future use and maintainability of the modelling process, and considering development to multi-stratum environments. Figure 3 provides an example three-dimensional DEM representation of the Illawarra coal measures viewed from the north looking south.

The Bulli seam is the uppermost seam in the sequence displayed in light grey, conformably overlying up to 5 other seams with ten times vertical exaggeration. Surface elevations appear in green, generally above the AHD zero reference shown in blue. The study area is shown in light tan with relevant geological structures shown in red.

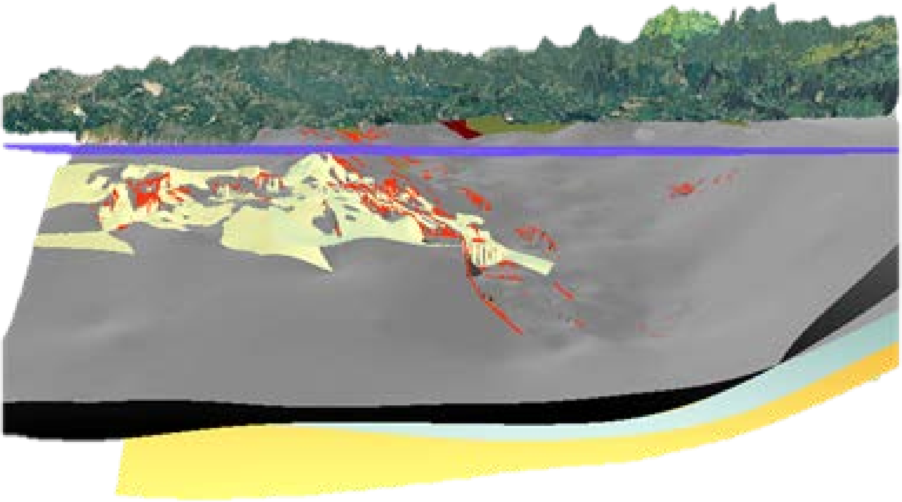

Figure 3: Example three-dimensional DEM of study area.

Spatial parameters derived from elevation surface

Spatial parameters deemed essential for calculation of gas emission character across the mining environment, and potentially calculated at the required higher resolution (i.e. each 1 m x 1 m cell) are; the vertical dimension Z in metres (AHD), the maximum slope in degrees (0°-90°) the aspect in degrees (0°-360°), and the curvature in metres per metre, overall and then separately in plan and in profile. The process used for DEM calculation allows selection of the appropriate cell size commensurate to the resolution and sensitivity of the input data to the calculation outcome, and the limited benefit of recalculation if no material variation in input data is observed. Calculation of the above italicised terms all involve the evaluation of the cell in consideration against each of up to eight of its neighbouring cells in the X.Y plane. The slope is a representation of the maximum rate of change of elevation (Z) with respect to both X and Y. The aspect represents the orientation of the slope, where values near 0° and 360° indicate a north facing area, 90° an easterly facing, 180° a south facing, and 270° a west facing area.

The calculation of curvature is the derivative of the slope (i.e. d^2z/dxy^2) using a similar process to the slope calculation, but using the slope value for each cell as the input to the curvature calculation. By definition, the curvature at a point with zero slope (flat) will also be zero. This phenomenon may be used to determine areas likely to retain fluid, also known as sinks. Curvature may be further defined into profile and plan curvatures, which are useful for describing the acceleration or deceleration of flow paths in the case of the profile curvature, or convergence or divergence of flows in the case of plan.

Application of spatial parameters

Over 2500 gas core sample locations from two mine sites were initially provided in the form of AutoCAD drawing files, complete with two-dimensional X and Y co-ordinates. Two-dimensional drilling trajectories to obtain the core samples were also provided in most cases. Laboratory sample analysis results containing a range of gas properties were provided in the form of MS Excel spreadsheets. Gas parameters included gas content, gas composition and concentration, and desorption characteristics with a unique reference to a sample or core identification number.

The first stage of assessment of spatial parameters involved referencing AutoCAD two-dimensional location information for each unique sample to the laboratory analysis results. Once gas core sample locations were confirmed as two-dimensional X, Y points, the next stage of assessment involved the allocation of all previously calculated values for elevation, slope, aspect, and curvature to each of the gas samples. The output of these previously calculated spatial parameters was, in each case, a raster surface of 1m x 1m resolution. Subject to the quality and resolution of input data, similar interpolation techniques may be applied for the calculation of the distance and direction to geological structure. Structures may include faults, dykes or other anomalies and may be represented as either a two or three-dimensional features. It is anticipated that inclusion of full three-dimensional structure geometry, complete with appropriate attributes for the description of other geological observations, may allow a pathway for stress magnitude and orientation data to be included in overall gas emission modelling without exhaustive computational overhead. Finite element stress modelling for the southern Sydney basin described by many researchers appears to be capable of providing such data (Heritage et al. 2017; McGregor 2003; Tarrant 2006).

OBSERVATIONS AND RESULTS

As existing mining threshold limits are determined primarily by measured gas content and gas composition, these dependent variables were considered initially. Assessment of the full dataset's gas content result by X, Y and Z location did not reveal any significant first order linear trend. However, assessment of gas composition using CO_2 concentration by X, Y and Z dimensions revealed a localised trend with respect to the Z dimension at each individual mine as shown in Figure 4.

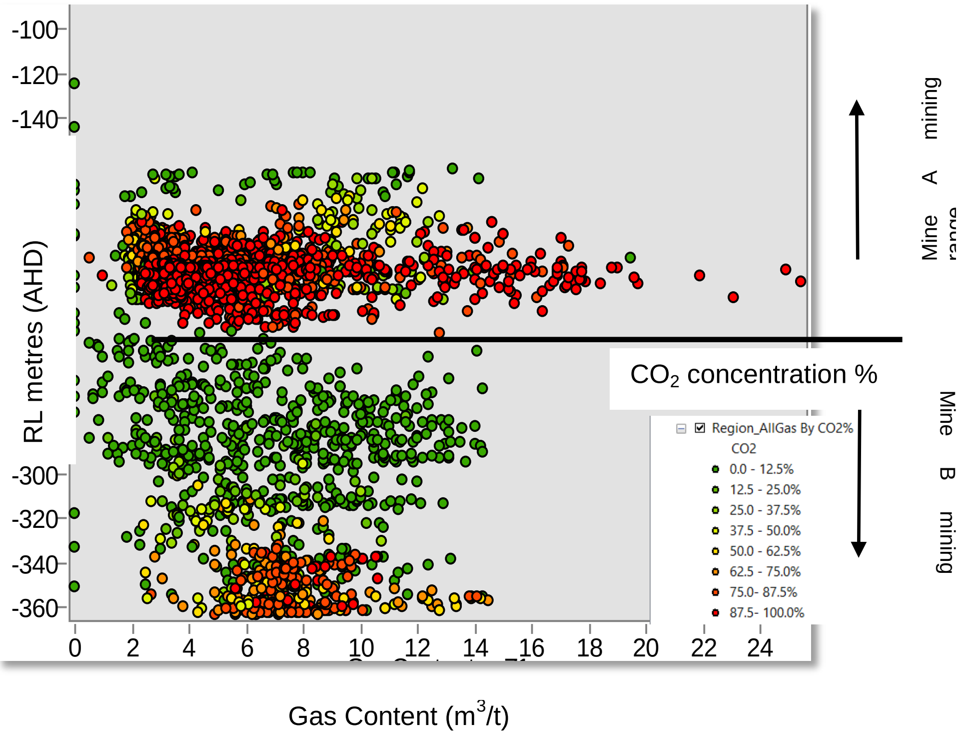

Figure 4: Analysis of Gas content and RL(m) by Gas composition by CO_2 concentration.

Localised trends appeared at each mine with increasing CO_2 concentrations being observed downslope of higher CH_4 concentrations and geological features. Increasing observed gas content with CO_2 concentration aligns with the experimentally determined isotherms for the mine (Figure 1), recognising that coal structural properties and hence sorption capacity is also likely to vary relative to many spatial parameters. Difference in localised seam hydrostatic pressure may also account for such observations, however in the absence of in situ pressure measurement, this could not be confirmed.

The introduction of further independent spatial variables for slope, aspect, curvature and geological structures suggested a strong dependence between higher gas content and areas where localised fluid accumulation or flow restriction was likely to occur. The number of core samples taken in these areas over an extended time period, combined with the number of gas drainage holes drilled in the immediate area, suggest that these areas were also difficult to drain.

An example of these areas within Mine A is depicted in Figure 5. The gas composition of this particular area was greater than ninety percent CO_2, however the dependence between areas of likely fluid accumulation and higher gas content appeared to be independent of gas composition. Other areas of Mine A with higher CH_4 composition also demonstrated a similar relationship. The seam reservoir gas pressure for this area was estimated to be in the order of 3 MPa.

Datasets collected from each mine include features and attributes, which allow calculation of gas drainage quantities and timing. Spatial relationships between various attributes may be assessed using the same process as described previously. Furthermore, the inclusion of inclination data from Drill Guidance Systems (DGS) allows direct calculation of effective horizonal and vertical permeability and hence dynamic drainage rate.

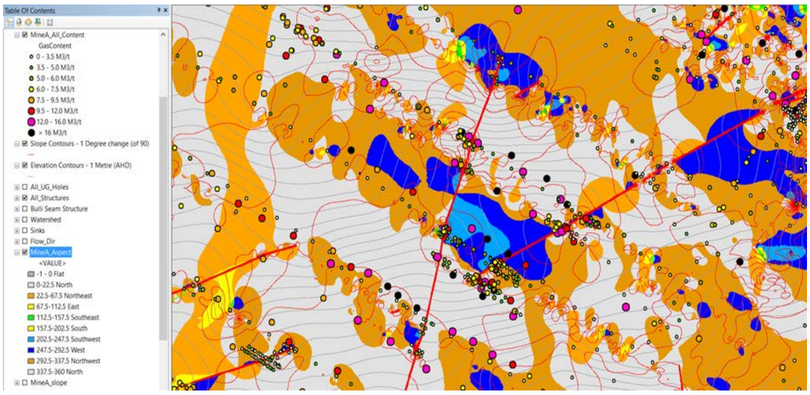

Figure 5: Example gas content distribution analysis at Mine A using aspect and slope parameters.

Data from Mine B also suggests a similar strong relationship between spatial characteristics and higher gas content. At this mine, such spatial relationships also appeared to be independent of gas composition. Areas dominated by higher CO_2 concentration were laterally separated from areas of higher CH_4 concentration by over 2000m. However, a similar localised trend of higher CO_2 concentrations downslope of geological features and higher CH_4 concentrations was observed.

In summary, each observed high gas content sample location exhibited one or more of the following spatial characteristics:

- Immediately adjacent to and upslope from structures forming flow barriers or restrictions to the general trend of within seam flow,
- An adjacent high rate of change of slope (curvature) tending to localised minima where both slope and curvature tends to zero,
- A coincident or immediately adjacent change in aspect from the general aspect trend.

In general, very localised areas featuring all of the above characteristics tended to exhibit higher gas content towards the upper extreme of the sample range. As these gas content observations also approached the sorption capacities displayed on the experimentally derived gas isotherm, it is suggested these areas are at or near saturation for the given seam reservoir pressure.

CONCLUSIONS AND FUTURE DIRECTIONS

Over 2500 gas core samples from two southern Sydney basin mines producing metallurgical coal from the Bulli seam have been analysed in various geospatial context. A robust foundation for the process to obtain, prepare and load the relevant spatial input datasets into a predictive model has been described. Spatial relationships between measured gas content, gas composition, and spatial parameters such as RL, slope, aspect and curvature have been determined. The relevance and importance of determining these relationships at a localised or site-specific, rather than regional level has been demonstrated.

Further development of the predictive model to include material property dimensions, full three-dimensional assessment of proximity to adjacent structures and gas drainage holes will significantly improve model outcomes. This will allow further application of the model to site specific and more complex geology. The results suggest variability and limitations associated with the present traditional approaches to gas emission prediction and design of gas management practices may be addressed using predictions derived from improved spatial datasets, and analysis techniques incorporating fundamental physical and energy related principles. This foundation will allow increasingly complex factors, such as strata material properties, and stress directions and magnitude to be incorporated into predictive models.

The application of physical and spatial techniques described enhances the potential for use of high volume and high resolution real time measurement data in management of gas emission risk. By proactively addressing such risks earlier in both the gas and mining life cycle, material reduction of costs and improvement production and environmental outcomes are more likely to be obtained.

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