Specific gas emissions in Bowen Basin longwall mines, Australia

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Abstract

Longwall coal mines in the Bowen Basin of Australia are highly productive and gassy, comprising many coal seams above the working seam. Predictive modelling of specific gas emission (SGE) using the conventional Winter model developed in Germany or other European based models often results in significant discrepancies from reality. To improve methane emission prediction and management, significant efforts on measuring gas release from different coal seams were made at three longwall mines by safely drilling core holes into the goaf. The vertical extent of the gas emission zone and the proportion of gas released from different coal seams were quantified. It was found that the Winter model significantly underestimates gas emissions for coal seams 75–150 m above the mining seam. This discrepancy is likely due to the intensive goaf drainage using large-diameter vertical wells in the high production Bowen Basin longwall mines. The Winter model also appears inadequate in estimating the height of the gas emission zone at different mines where the extraction thickness differs. Finally, a new empirical model for predicting the degree of gas emission from roof coal seams is developed for Bowen Basin mines and other mines with similar mining conditions. The measured post-mining gas content data and the newly developed model in this paper can provide guidance to the design of goaf drainage boreholes and capacity, as well as assessing coal mine methane and abandoned mine methane resources.

Keywords: Methane emission; Longwall mining; Specific gas emission; Gas emission zone

1. Introduction

Bowen Basin is one of the major coal mining fields in Australia. The Basin outputs around 250 million tonnes of coal per year, about half of the total coal production in the country. The longwall coal mines in the Basin are gassy, containing many coal seams in the roof and floor. The high production longwalls, with an annual production of 5–9 million tonnes, cause a large amount of methane released from adjacent coal seams, in addition to the working seam itself. Predictive modelling using the historic Winter method is routinely conducted for mine ventilation planning. However, the prediction has been unsatisfactory, with high discrepancies from reality. Belle (2017) reported that the errors using the Winter model could be up to 50% overestimation for some panels to underestimation by 290% using operational data. Therefore, obtaining a reliable understanding of gas emission patterns from different coal seams is critical to improve methane emission predictions and thus to optimise methane capture and design capacities for effective methane management in underground coal mines.

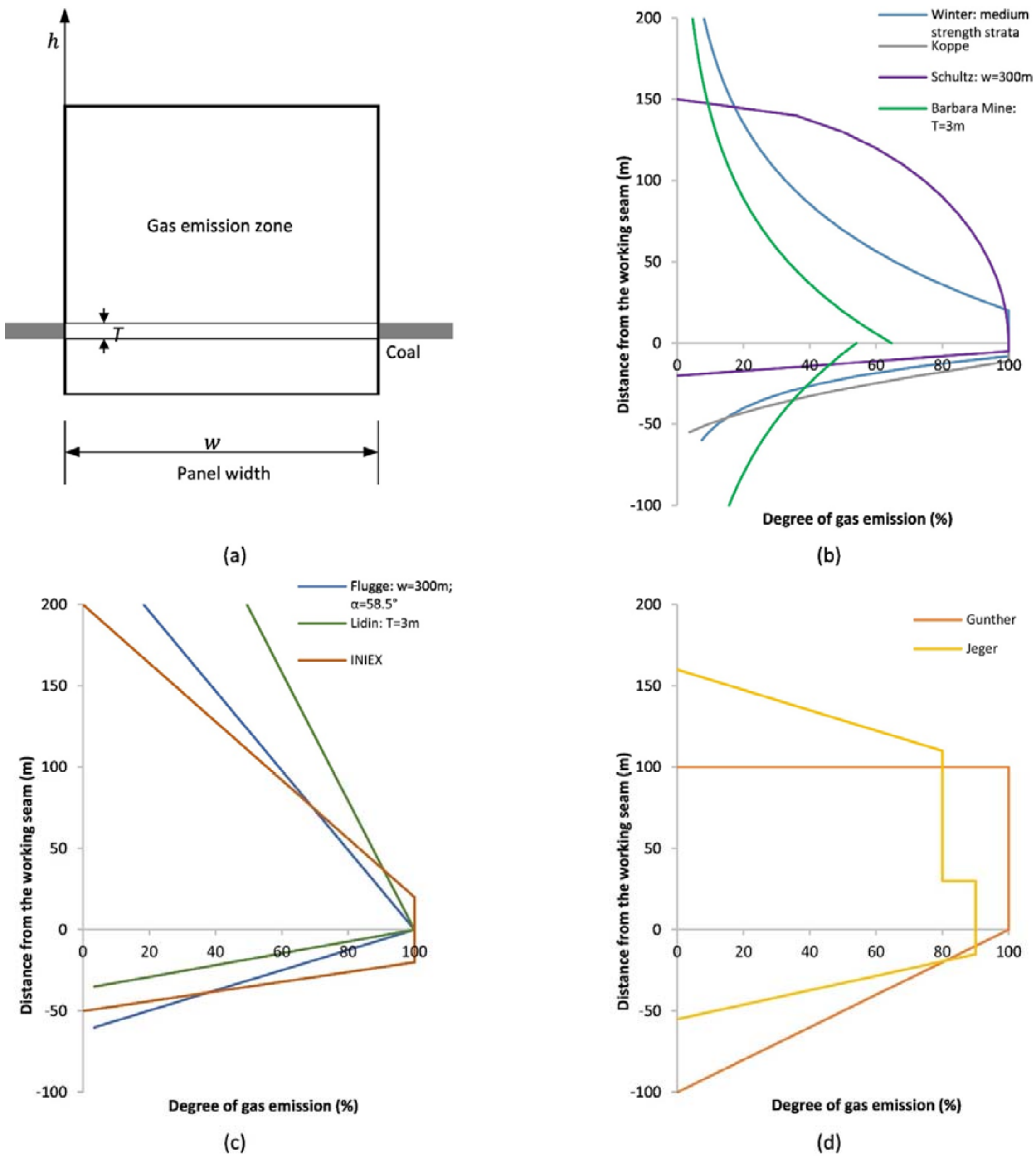

Fig. 1. (a) The rectangular shape of gas emission zone assumed in most predictive methods; (b) non-linear curves of gas emission degree; (c) linear curves of gas emission degree; (d) curves showing constant gas emission degrees in certain sections of the roof gas emission zone. These curves are plotted from equations described in Curl, 1978. Typical panel width (300 m) and extraction thickness (3 m) of Australian longwalls are used as input parameters.

Gas emission prediction can be performed by empirical, numerical, analytical and statistical techniques. Of them, the empirical technique is most widely used by mine engineers due to its fairly simple mathematical expressions and request of only a few input parameters. Between the 1950s and 1970s, a variety of empirical models had been developed in European countries (Curl, 1978; Battino et al., 1988; Noack, 1998; Durucan, 2010). The well-recognised methods include the Gunther and the Jeger methods in France, the INIEX method in Belgium, the Winter, Flugge and Schultz methods in the Federal Republic of Germany, the Lidin method in the USSR, the Barbara Mine method in Poland and the Mining Research and Development Establishment (MRDE) method in the United Kingdom. These gas emission estimation methods are similar in principle. They all predict two key parameters: the gas emission zone (GEZ) and the degree or proportion of gas emission from various coal seams. Most methods assume the GEZ to be a rectangular shape directly above and below the mining panel (Fig. 1(a)), and the gas emission degree varies at different distances from the working seam. The Schultz and Flugge methods, however, define the constant 100% gas release from a semi-cylinder and a triangular prism shaped GEZ, respectively. Later use of these two methods often converts them into the same form as the other methods, i.e., assuming a rectangular shape of GEZ with varying gas emission degrees. The key difference between these methods rests in the curves of gas emission degree, as shown in Fig. 1(b) – (d). These curves can predict substantially different gas emission degrees. For instance, at the 100 m distance from the working seam, the predicted gas emission degrees by these curves vary between 20% and 100%.

Australian coal mines have been long using European methods to predict gas emissions. In 1982, five European methods, including the Winter, Schulz, and Barbara experimental mine method, were compared at a longwall mine in Australia to establish predictions of ventilation gas make, but the results showed significant errors (Lunarzewski and Battino, 1983; Battino et al., 1988). Considering the differences between European and Australian mining conditions, Hargraves (1986) proposed a compound method based on various European methods: (a) a minimum gas emission curve as a combination of Schultz, Barbara Mine, INIEX, and Lidin methods; (b) a maximum gas emission curve as a combination of Flugge, Lidin, Jeger, INIEX and Gunther methods; and (c) an average gas emission curve of all methods. Lunarzewski, 1992, Lunarzewski, 1998 recommended computer simulation programs “Roofgas” and “Floorgas” which could define the strata-relaxation and gas-emission zone shape corresponding to a percentage of gas release. Several other numerical modelling approaches were also developed in Australia (Jensen et al., 1992; Ashelford, 2003; Guo et al., 2009). However, these approaches were not widely used, primarily due to their complexity. To date, in the absence of alternate and improved gas emission prediction methods, the Flugge method and Winter method are commonly used in Australian longwall mines (Belle, 2017).

In the past two decades, methane emissions from coal mines have been increasingly regarded as a substantial source of greenhouse gas emissions (Karacan et al., 2011), in addition to its threat to mining safety. In the meantime, coal mine methane is also recognised as a source of relatively clean energy; methane not captured and used will become a waste (Karacan et al., 2011). Accordingly, extensive studies have been conducted to improve methane capture quantity and quality for utilisation. These studies have covered various aspects of mine methane emissions, including gas content measurement (e.g., Saghafi, 2011, Saghafi, 2017), gas-in-place analysis (e.g., Karacan et al., 2012; Booth et al., 2017), new methods to identify gas emission zone (e.g., Saghafi and Pinetown, 2015; Karacan et al., 2021), correlations between mining-induced strata stress change, fractures, permeabilities and gas dynamics (e.g., Schatzel et al., 2012, Schatzel et al., 2017; Palchik, 2003, Palchik, 2005; Esterhuizen and Karacan, 2005; Guo et al., 2012; Qu et al., 2015; Si et al., 2015), coupled geomechanics and reservoir modelling for methane emission assessment (e.g., Whittles et al., 2006; Karacan et al., 2007, Karacan et al., 2008; Guo et al., 2009), CFD modelling of goaf gas flow dynamics (e.g., Ren and Balusu, 2010; Qin et al., 2015, Qin et al., 2017), and innovative drilling and borehole design methods for goaf gas drainage (e.g. Brunner and Schumacher, 2012; Hungerford et al., 2013; Guo et al., 2015; Qu et al., 2016). These studies have significantly helped improve methane capture efficiencies to facilitate today's high production longwalls. In contrast, little effort has been made to verify the conventional gas emission prediction models, particularly through measuring gas content pre- and post-mining.

Longwall coal mines in the Bowen Basin consist of a large group of coal seams situated between 30 m and 250 m above the mining seam. To improve gas emission prediction and goaf gas drainage capacity design, measurements of post-mining gas contents in different seams by drilling core holes into the longwall goafs were carried out at three longwall mines. This paper presents the key observations from the measurements and a new model developed based on these measurements.

2. General conditions of typical Bowen Basin longwall mines

The Bowen Basin covers an area of over 60,000 km^2 in Central Queensland, running from Collinsville to Theodore. It contains the most economically important Permian-age coal deposits in Queensland, including virtually all of the known mineable prime metallurgical coal. The Bowen Basin forms the northern extent of the interconnected Bowen-Gunnedah-Sydney Basin system. It has a complex tectonic and depositional history, and subsequently, coal-bearing strata across the basin also vary in their structural complexity, rank and quality. Coal is mined around the flanks of the basin, mainly in its northern triangular extent, where strata are exposed or lay close to the surface. A map of the coal mining regions of Bowen Basin can be found from Mutton, 2003. Coal-bearing formations are categorised into five groups, which reflect their stratigraphic position and geological characteristics (Table 1).

Table 1. Coal groups of the Bowen Basin (adapted from Denaro et al., 2013 and Draper, 2013).

Age	Group	Coal Measures	Mine Type	Localities
Oldest (early Permian)	***I***	Reids Dome Beds	Thermal coal	Minerva Mine, Emerald
	II	Collinsville, Blair Athol, Wolfgang Coal Measures	Coking and thermal coal	Collinsville, Blair Athol, Rugby
	III	Moranbah, German Creek Coal Measures	Coking coal	Emerald, Dysart, Moranbah
	IIIA	Fair Hill Formation, Fort Cooper Coal Measures	Not mined; high ash	N/A
Youngest (late Permian)	***IV***	Rangal & Baralaba Coal Measures; Bandanna Formation	Thermal and coking coal	Moura, Blackwater, Dysart, Moranbah

Three longwall mines are concerned in this study. Mine A and Mine B are located in the northern district of the basin, extracting coal from the Moranbah Coal Measures (Group III).

Mine C is in the central district, and extracts coal from the German Creek Coal Measure (Group III). Seam gas reservoir parameters, such as depth, permeability, gas isotherm adsorption, between the two districts are similar in general, but mining thickness and stratigraphy differ. A more detailed description of the mining and gas reservoir conditions is provided in the sub-sections below.

2.1. Mine A and Mine B

Mine A and Mine B extract coal from the Goonyella Middle (GM) seam of the Moranbah Coal Measures. A stratigraphic section of coal seams is shown in Fig. 2. The GM seam within the two mine leases is between 100 and 400 m deep and typically 4.5–5.5 m thick. The longwall face is typically 302 m wide (rib-to-rib) and range from approximately 1.6 to 6 km long. The mining thickness varies from 3.4 to 4.3 m.

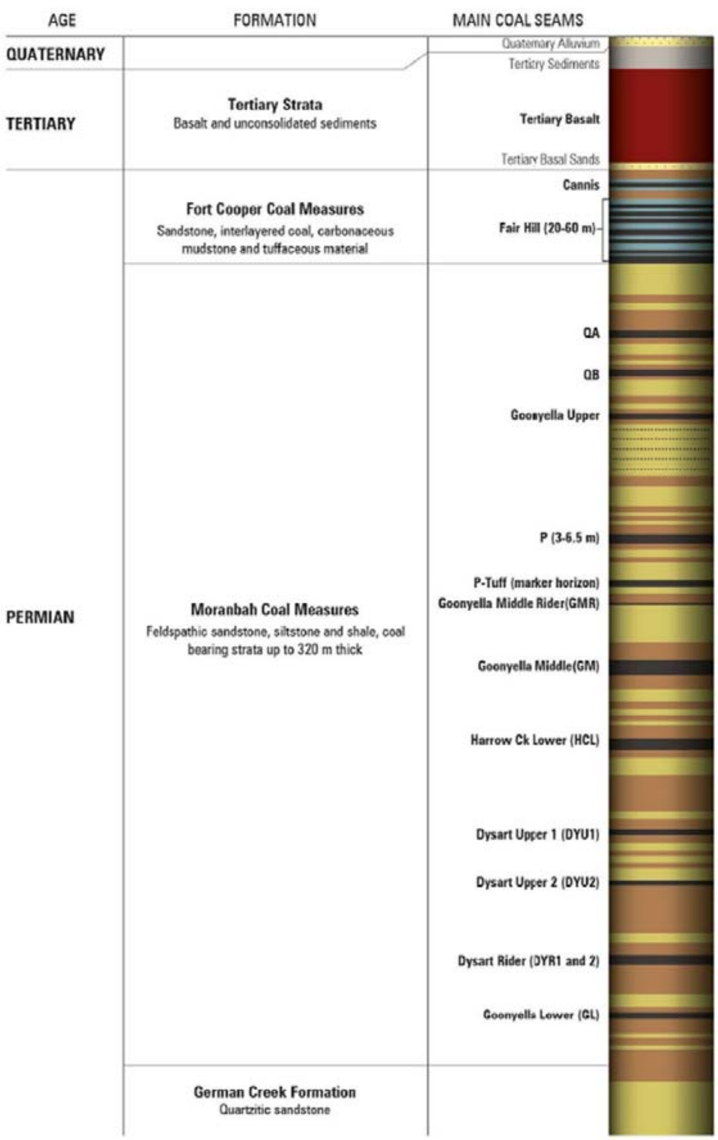

Fig. 2. Typical stratigraphy in the Mine A and Mine B region.

The overburden comprises two coal measures: The Fort Cooper and Moranbah Coal Measures. The former contains coal of the Fair Hill (FH) formation at its base, while the latter contains splits from 9 coal seam groups with an average total coal thickness of 20 m. Specifically, the GM seam is overlain by the GMR, PL2, PL1, GR, QB, QA and FH seams at an approximate distance to the GM seam of 30 m, 55 m, 57 m, 60 m, 120 m, 140 m, and 160 m, respectively. The FH seam is composed of highly interbanded coal (~30% of the total seam composition), tuff and mudstone and ranges in thickness from approximately 35 m to 50 m. The worked GM seam is underlain by the GML, HCL, DYU, DYR and GL seams at an approximate distance of 20 m, 30 m, 55 m, 70 m, and 95 m, respectively. The overlying coal seams are predicted to be major sources of gas emissions during mining.

The gas composition of all coal seams is 97 to 100% methane. Gas content in the coal seams ranges between 4 and 14 m^3/t. Gas is pre-drained from the GM seam (Mine A and Mine B) and the P seam (Mine B) for mine safety and also coal seam gas development and utilisation. The measured permeabilities of the P seam and GM seam were between 100 mD and 10 mD in the depths 150–300 m, and reduced to below 10 mD when the depth is >300 m. A recent downhole hydraulic packer testing conducted at Mine B suggested that the permeabilities of coal seams GM, P, QB, QA and GU ranging in the depths 250–400 m were between 0.1 mD and 5 mD.

Other sediments in the coal overburden and interburden sequence exhibit very low permeability and form discrete confining units between the coal seams. Coal seams are characterised as the primary water-bearing strata. Sandstone and siltstones comprise a majority of the coal measures. The regional water table is typically located several meters below the base of the alluvium (about 20–50 m below the ground level).

The gas content in the GM seam is generally pre-drained to 2–4 m^3/t to reduce the risk of outburst and gas management control. Where gas content remains high, surface to inseam (SIS) holes flanking either side of the development roadway, and underground inseam (UIS) holes are drilled into the longwall blocks to increase gas pre-drainage flow. Vertical wells, with a linear spacing of about 50 m, are used to extract gas from the high production longwall goaf. The goaf wells were cased to about 20 m above the GU seam, generally a few meters below the QB seam floor.

2.2. Mine C

The overburden strata of Mine C contain three main units: The Fair Hill Formation, the MacMillan Formation and the German Creek Formation. The top Fair Hill Formation unconformably contacts the MacMillan Formation, and it contains numerous thick carbonaceous units with interbedded coal and tuff. These seams are very thick compared to other Bowen Basin Coal Measures; however, they have extremely high raw ash and clay content.

Mine C extracts coal from German Creek (GC) seam, which is between 180 and 400 m deep, and up to 4.5 m thick. The GC seam is situated in the German Creek Formation, which contains eight main coal seams, including the two economic coal seams: Aquila and GC. Sandstone is the predominant lithology from the Sandy Creek Siltstone upwards to the Corvus 1 seam (C1), as shown in Fig. 3.

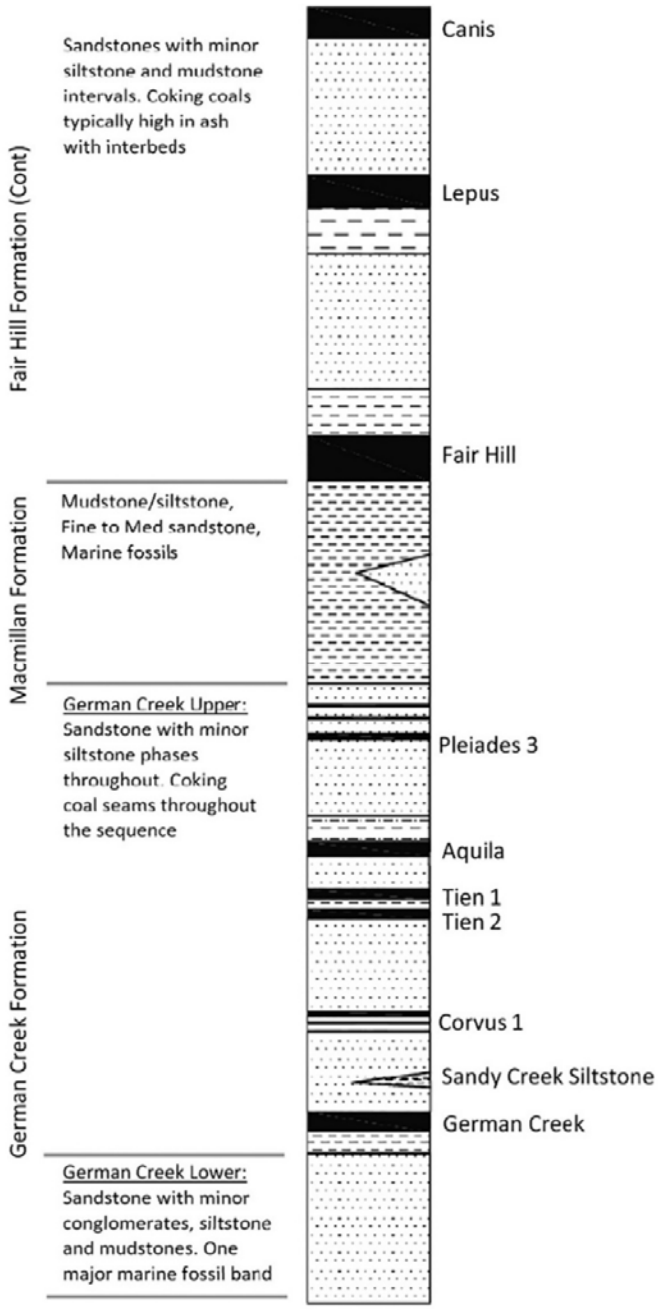

Fig. 3. Typical stratigraphy in the Mine C region.

Permeability of the coal seams is around 1 to 10 mD, as suggested by borehole packer tests. The interburden sandstone and siltstone have a permeability an order of magnitude lower than the coal seams. Groundwater typically occurs preferentially within the coal seams. Jointing is common and can range from tightly closed joints up to 10 mm aperture. The presence of dykes and sills is limited.

The gas composition of the coal seam is mostly methane. Gas contents generally increase with depth, and the typical virgin gas content of various coal seams lie between 3 and 14 m^3/t. The Langmuir volume of the GC seam ranges between 23 and 30 m^3/t, and the Langmuir pressure ranges between 1.95 and 2.5 MPa. Pre-drainage of the mining seam uses similar methods to that at Mine A and Mine B.

3. Experimental method

3.1. The Winter method used in the study mines

The study mines have been using the Winter method as their primary method in gas emission modelling and prediction. The Winter method was originally developed in the Federal Republic of Germany in the 1970s (Winter, 1975; Curl, 1978; Battino et al., 1988). The method assumes a rectangular zone of gas emission for both the roof and the floor strata. Strata within 20 m above and 8 m below the workings are assumed to completely degas. For the remaining strata, the degree of gas emission is assigned by Eqs. (1), (2). The upper and lower limits of the gas emission zone are defined by a minimum degree of emission of 10%, i.e., when the above formula yields $\eta < 10\%$, $\eta = 0$ is used instead. In practice, this cut-off is often neglected.

$$\eta_r = 100\exp(-\mu_r(h-20)) \tag{1}$$

$$\eta_f = 100\exp(\mu_f(h+8)) \tag{2}$$

Where η_r and η_f are the degrees of gas emission in the roof or floor, respectively, %; h is the distance from the working level, m; and μ is the weakness number. The values of μ_r and μ_f depend on how easily the strata surrounding the working seam fracture and permit gas flow. For strong, medium strength and weak strata, μ_r are defined as 0.016, 0.014, and 0.012 respectively, and μ_f are 0.070, 0.050, and 0.030, respectively (Curl, 1978).

3.2. Measurements of gas content after mining

Exploration boreholes are generally drilled in the study mines before mining to determine reservoir size and gas content for gas in place analysis. With the gas emission degree estimated from the Winter method, specific gas emission rate from adjacent coal seams can be predicted. The prediction provides an average gas emission rate for the longwall to be mined. It also informs whether a substantial change in gas emission may be expected.

To verify the conventional methods, post-mining gas content was measured by drilling core holes into the goaf areas at the three study mines. Samples were cored from different coal seams, and sent to GeoGAS laboratory for gas content testing using the fast-desorption method in accordance with the Australian standard AS 3980:2016 (Standards Australia, 2016). After gas content testing, the powdered remnants and remaining uncrushed core were sent to nearby SGS laboratory for coal characterisation (relative density and proximate analysis).

3.3. Gas content analysis

The gas content testing results were reported at sample ash and moisture. However, since coal properties (e.g. ash content) may vary from place to place, direct comparison of these reported values do not approximately reflect the degree of gas emission. For instance, the reported gas content of a sample with an ash content of 40% is not comparable to that of a sample with an ash content of 20%.

To make a like-to-like comparison, the reported gas content (Q_m) at sample ash and moisture were converted to the dry, ash-free (DAF) value (Q_{DAF}), which is calculated using Eq. (3). Q_{DAF} reflects the organic fraction gas content, and is generally used for comparing gas content or storage capacity estimates from samples of differing composition (Mavor and Nelson, 1997).

$$Q_{DAF} = \frac{Q_m}{1-(w_a+w_m)} \tag{3}$$

Where w_a is ash content, %; w_m is moisture content, %.

The ash content of samples were provided from coal characterisation analysis. Many of the pre-mining gas content data do not have coal characterisation results. In that case, the ash content was estimated from empirical formula derived from existing database. The formula is a function between density and ash content, and is expressed in the format of Eq. (4). The coefficients at different mines are slightly different.

$$y = 0.00008x^2 + 0.0048x + 1.3094 \tag{4}$$

Where y is the density of sample, g/cc; and x is the ash content, %.

The moisture content is assumed to be 2% for all samples in this analysis. The actual moisture typically ranges between 1.4% and 3.0%. A variation within this range has a negligible effect on the converted Q_{DAF}. For instance, varying moisture from 2% to 3% for Q_m = 6.6 m^3/t at 23% ash results in a minor change in Q_{DAF} from 8.81 m^3/t to 8.93 m^3/t.

4. Gas content measurement results

4.1. Mine A

A post-mining goaf hole, AG1, was drilled near the central line of the LWA1 at Mine A (Fig. 4). The hole was about 25 m away from the pre-mining hole, AP1, and 950 m from the longwall start-up line. Coal coring from AP1 was conducted in August 2014, about 50 days before the longwall face retreating past. Coal coring from AG1 was completed in January 2015, about 125 days after the longwall face retreated past the hole location or about 933 m behind the longwall face. AG1 was intended to core to below P seam but was only achieved to a depth of 235 m (about 85 m above the worked seam) due to loss of circulation. This drilling issue was also encountered in the drilling of other goaf holes in the study mines.

Fig. 4. Location of the pre- and post-mining holes at Mine A.

Table 2 shows the measured gas content pre- and post-mining and the analysed gas emission degrees. The gas contents of the FH seam and the QA seam, which have high and varying ash content, are scattered. To make the comparison on a like-for-like basis, the measured gas contents at sample ash were converted to the dry, ash-free (DAF) values. Fig. 5 compares the measured pre- and post-mining gas contents and the comparision between measured degree of gas emission and the Winter curves under medium strengh strata and weak strata.

It is clear that QA, QB and GU seams were significant gas emission sources, as shown by the substantial reduction in gas content (from about 6.5 m^3/t DAF to about 2.0 m^3/t DAF). In contrast, no gas appears to have been released from the FH seam, located between 176 m and 216 m above the worked seam. This observation is suggested by both gas content and the initial desorption rate index IDR30 which measures the desorption volume from the coal core in the first 30 min of desorption.

It is worth noting that a considerable variation (about +/− 20% on average) is seen between the measured pre-mining and post-mining gas content of the FH seam, indicating potential errors in the experimental measurements of this high ash content coal seam. This phenomenon is also seen in the other two mines studied in this paper. The large variation may be caused by the combined errors of gas content testing and estimation of ash content, as well as the effect of other factors (e.g., depth, high ash content) on the consistency of gas content in coal. Additional monitoring of pore pressure changes in this coal seam, as that conducted in Qu et al., 2022, may be helpful in verifying the analysis of gas emission from this coal seam.

The measured gas emission degree of coal seams between 100 m and 140 m distance was substantially higher than that predicted by the Winter models. Specifically, the measured values were between 57% and 78%, more than twice the predicted values (22–38%). At distances >170 m, the measured results show zero release, whereas the Winter method predicts 10–15%. The measured gas emission degree reduced quickly from above 57% at 140 m distance to zero at 176 m distance.

Table 2. Gas content testing results and analysed gas emission degrees at Mine A. The reported gas contents at sample ash are converted to dry, ash-free values.

Coal seams	Pre-mining hole AP1					Post-mining hole AG1					Analysis		
	Distance from working seam, m	Q_m at sample ash, m^3/t	IDR30 at sample ash, m^3/t	Ash content, %	Q_{DAF}, m^3/t	Distance from working seam, m	Q_m at sample ash, m^3/t	IDR30 at sample ash, m^3/t	Ash content, %	Q_{DAF}, m^3/t	Directly calculated gas emission degree, %	Refined gas emission degree, %	Predicted gas emission degree, %
FH	215.1	0.73	0.01	54.6	1.68	216.0	0.58	0	58.2	1.46	13%	0%	10%
	213.0	0.55	0.01	63.7	1.60	213.6	0.33	0.01	64.4	0.98	39%	0%	10%
	197.5	1.81	0.05	58.9	4.63	198.7	1.78	0.1	62.4	5.00	−8%	0%	12%
	194.6	1.26	0.05	67.0	4.06	194.0	2.15	0.16	57.5	5.31	−31%	0%	12%
	179.9	1.84	0.11	64.4	5.47	177.5	2.35	0.29	61.7	6.47	−18%	0%	15%
	176.5	2.21	0.19	58.9	5.66	175.8	1.97	0.21	68.9	6.77	−20%	0%	15%
QA	143.1	4.41	0.28	32.5	6.73	145.8	1.14	0.03	59.6	2.97	56%	56%	22%
	142.3	5.53	0.23	47.7	10.99	144.0	1.45	0.01	38.2	2.43	78%	78%	23%
QB	128.9	4.39	0.28	25.1	6.02	129.9	1.39	0.03	31.5	2.09	65%	65%	27%
GU	100.4	4.92	0.33	25.1	6.75	101.6	1.26	0.04	25.1	1.73	74%	74%	38%

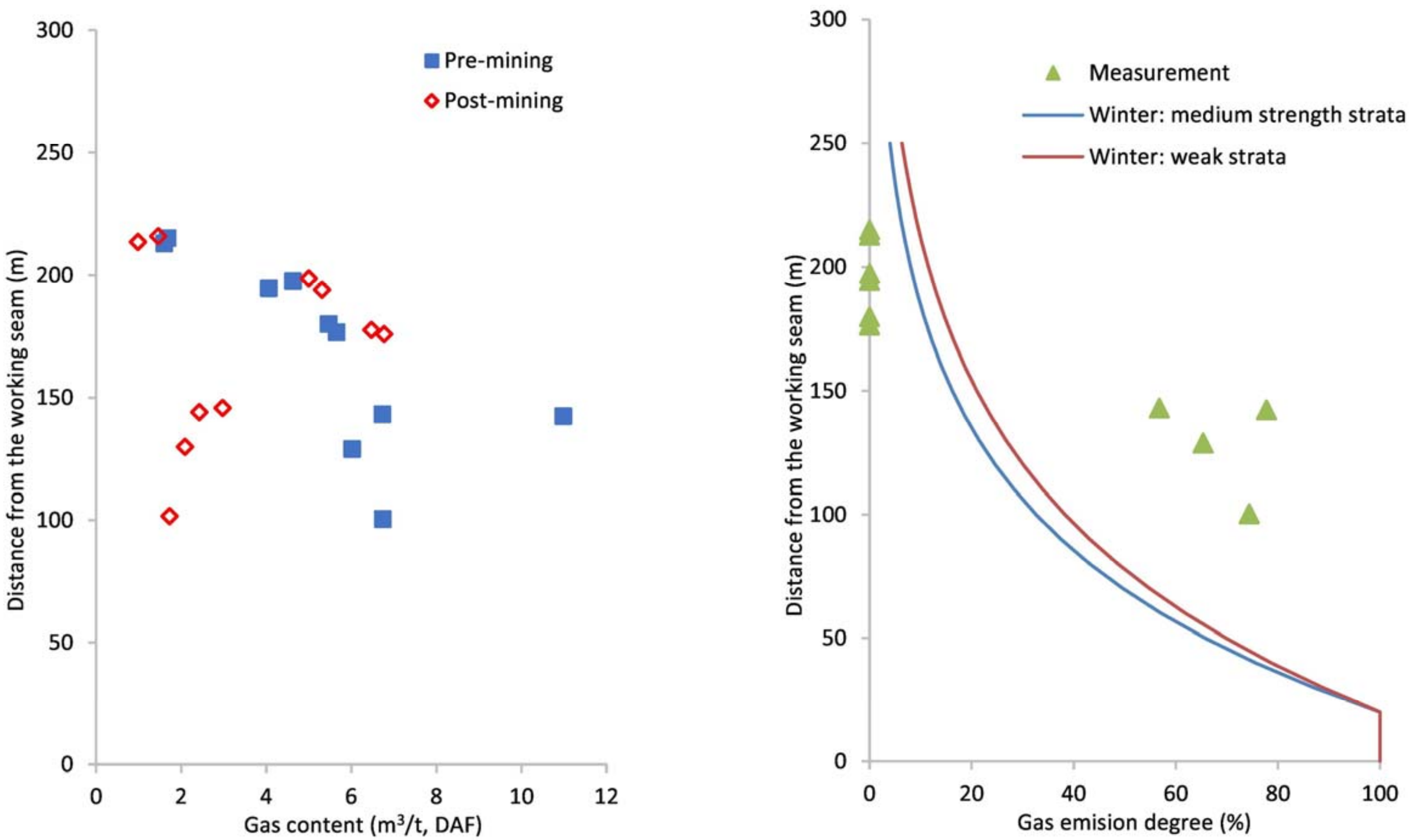

Fig. 5. (a) Measured pre- and post-mining gas content in different coal seams at Mine A; (b) comparison of analysed gas emission degree with the Winter models for weak and medium strength strata.

4.2. Mine B

A post-mining goaf hole BG1 was drilled at about 370 m from the start-up line of LWB1 at Mine B (Fig. 6). LWB1 was 312 m wide (including the two roadways), and the mining thickness was about 4 m. Coal cores were sampled in late July 2017, about 375 days after the LWB1 retreated past BG1 or 1778 m behind the longwall face. BG1 was compared to the closest pre-mining gas content hole BP1, located in the next longwall. The depth of cover around BP1 was only 5 m greater than BG1, and their in-situ gas content for each seam was assumed to be very close.

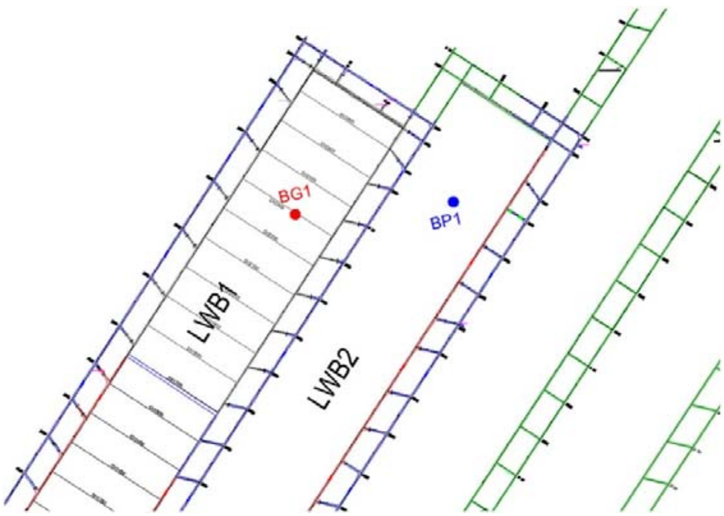

Fig. 6. Location of the pre- and post-mining holes at Mine B.

Table 3 and Fig. 7 show the measured results and their comparison to the Winter prediction. Like that observed at Mine A, the Winter model underestimates gas emission degrees for the GU seam and QB seam, which lie about 100 m and 130 m above the working seam, respectively. Regarding the FH seam, gas contents and IDR30 were reduced in the lower sections of the seam, suggesting that the seam had gas desorbed, in contrast to the observations at Mine A. This is likely, because the FH seam was closer to the mining seam (150–200 m) at Mine B than at Mine A (175–215 m). The gas emission degree within the FH seam reduced from about 36% to 0%.

4.3. Mine C

Two core holes, CG1 and CG2(as shown in Fig. 8), were drilled at Mine C in the mined area for measuring post-mining gas content. The two holes were located on the edge of the longwall goaf. The longwall panels at Mine C had a width of 352 m (including the two roadways). The working seam German Creek is 2.75 m thick, about 1.3 m thinner than the mining thickness of Mine A and Mine B. Two exploration boreholes drilled before mining, CP1 and CP2, were selected as references to the post-mining holes. The distances between the two sets of pre and post-mining holes were 326 m (between CP1 and CG1) and 297 m (between CP2 and CG2), respectively. The two exploration holes were drilled around September 2011, about four years earlier than the two goaf holes drilled around December 2015.

Table 3. Gas content testing results and analysed gas emission degrees at Mine B.

Coal seams	Pre-mining hole BP1					Post-mining hole BG1					Analysis		
	Distance from the working seam, m	Q_m at sample ash, m³/t	IDR30 at sample ash, m³/t	Ash content, %	Q_{DAF}, m³/t	Distance from working seam, m	Q_m at sample ash, m³/t	IDR30 at sample ash, m³/t	Ash content, %	Q_{DAF}, m³/t	Directly calculated gas emission degree	Refined gas emission degree	Predicted gas emission degree
CA	271.4	2.59	0.12	48.3	5.21								
	264.0	2.27	0.17	53.4	5.09	265.8	2.35	0.07	45.1	4.44	13%	0	5%
	259.5	2.27	0.18	54.7	5.24	258.4	3.02	0.10	41.6	5.35	−2%	0	6%
FH-Sec1	199.9	5.36	0.50	33.9	8.36	199.9	2.93	0.04	33.0	4.51	46%	0	12%
	197.6	3.84	0.45	50.5	8.08	197.0	3.19	0.14	59.9	8.35	−3%		12%
FH-Sec2	184.6	5.18	0.52	50.5	10.90	184.0	5.21	0.30	49.2	10.69	2%	2%	14%
	183.1	5.82	0.49	41.9	10.38								
FH-Sec3					10.90	174.3	4.25	0.26	52.4	9.33	14%	14%	16%
					10.90	166.0	2.69	0.16	67.7	8.89	18%	18%	17%
FH-Sec4	151.8	5.00	0.51	61.9	13.87	157.8	2.86	0.20	64.8	8.64	38%	36%	19%
						153.2	4.09	0.30	52.9	9.07	35%		20%
QA	150.3	4.66	0.59	51.9	10.12	150.3	4.39	0.58	41.6	7.79	23%	23%	21%
	149.0	6.60	0.62	23.1	8.81	146.2	4.81	0.28	47.6	9.54	−7%	0	22%
QB	128.9	8.51	0.60	16.5	10.44	130.4	4.69	0.32	20.6	6.07	42%	42%	27%
QB	123.0	6.07	0.47	41.9	10.82	129.6	4.05	0.27	55.2	9.47	13%	–	27%
GU	106.6	10.62	1.39	13.5	12.57	105.4	1.35	0.05	31.9	2.04	84%	84%	36%

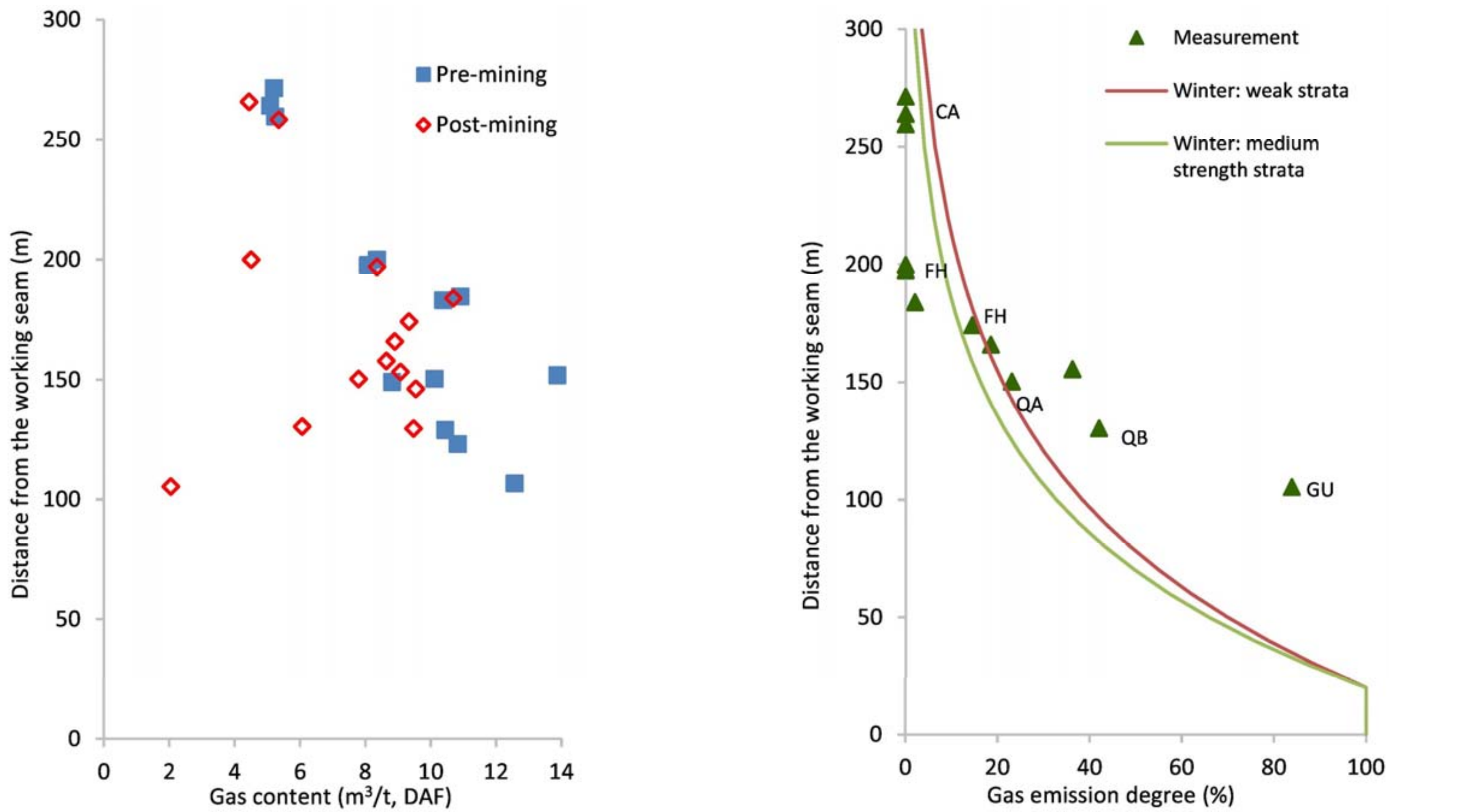

Fig. 7. (a) Measured pre- and post-mining gas content in different coal seams at Mine B; (b) comparison of analysed gas emission degree with the Winter models for weak and medium strength strata.

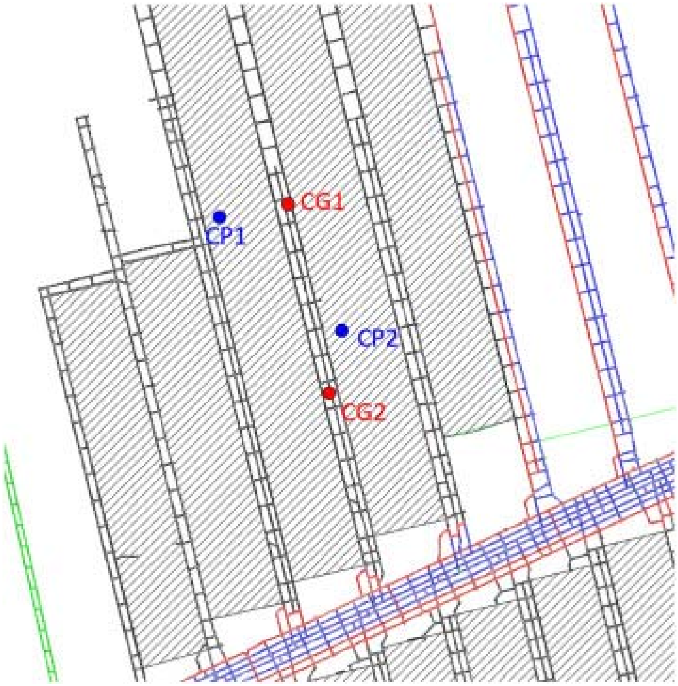

Fig. 8. Location of the pre- and post-mining gas content measurement holes at Mine C.

The gas content testing data are shown in Tables 4 and 5. Fig. 9 compares the gas emission degrees between measurements and the Winter-model predictions. Again, the Winter model underestimates the gas emission degrees for coal seams located between 75 m and 120 m above the working seam. However, at a slightly higher level of 140 m (P seam), the Winter model has overestimated the gas emission degree. The Winter model predicts around 24% gas emission, whereas the measurement shows a zero-emission (Table 4 and Fig. 9 (b)). No gas was desorbed from the FH seam, which lies 250 m above the working seam. This result agrees with the Winter model at this distance.

The gas emission degree reduced quickly from 66% to zero over an interburden distance of 23 m (from 117 m to 140 m). The transition zone at this mine is thinner than that at Mine A (Fig. 5).

The 66–86% of gas emission degree measured at a distance around 115 m on the goaf edge is comparable to that measured at a similar distance in the central region of the goaf at Mine A and Mine B. This demonstrates that the shape of the GEZ is at least a rectangle shape, if not more laterally extensive.

Table 4. Gas content testing results and analysed gas emission degrees from holes CP1 and CG1 at Mine C.

Coal seams	**Pre-mining hole CP1**					**Post mining hole CG1**					**Analysis**		
	Distance from working seam, m	**Q_m at sample ash, m^3/t**	**IDR30 at sample ash, m^3/t**	**Ash content, %**	**Q_{DAF}, m^3/t**	**Distance from working seam, m**	**Q_m at sample ash, m^3/t**	**IDR30 at sample ash, m^3/t**	**Ash content, %**	**Q_{DAF}, m^3/t**	**Directly calculated gas emission degree**	**Refined gas emission degree**	**Predicted gas emission degree**
CN						289.6	1.86	0.10	70.6	6.79		0%	4%
						288.7	1.87	0.10	70.0	6.68		0%	4%
FH						256.5	2.85	0.19	52.5	6.26		0%	6%
						255.6	2.18	0.14	59.6	5.68		0%	6%
						250.9	3.57	N/A	44.4	6.66		0%	6%
	247.7	3.35	0.10	22.6	4.44	249.7	4.22	0.40	40.8	7.38	−66%	0%	6%
P	139.5	7.72	0.53	16.1	9.42	140.0	7.74	0.57	21.1	10.07	−7%	0%	24%
AQ/AQL	115.6	11.38	7.10	4.4	12.16	116.8	3.51	0.17	12.6	4.11	66%	66%	31%
						116.0	2.99	0.18	21.4	3.90	68%	68%	32%
						115.2	2.18	0.13	41.2	3.84	68%	68%	32%

Table 5. Gas content testing results and analysed gas emission degrees from holes CP2 and CG2 at Mine C.

Coal seams	**Pre-mining hole CP2**					**Post mining hole CG2**					**Analysis**		
	Distance from working seam, m	**Q_m at sample ash, m^3/t**	**IDR30 at sample ash, m^3/t**	**Ash content, %**	**Q_{DAF}, m^3/t**	**Distance from working seam, m**	**Q_m at sample ash, m^3/t**	**IDR30 at sample ash, m^3/t**	**Ash content, %**	**Q_{DAF}, m^3/t**	**Directly calculated gas emission degree**	**Refined gas emission degree**	**Predicted gas emission degree**
FH					–	263.3	2.07	0.14	72.9	8.25		0%	5%
					–	253.8	4.70	0.48	42.4	8.45		0%	6%
	249.9	2.26	0.07	57.7	5.61	253.1	4.83	0.19	42.6	8.72	−55%	0%	6%
	249.1	0.67	0.00	89.9	8.27	251.9	4.94	0.28	39.7	8.47	−2%	0%	6%
P	133.3	6.55	0.99	13.4	7.74								
AQ	108.8	13.01	1.71	1.1	13.43	108.3	2.36	0.05	10.6	2.70	80%	80%	35%
						107.5	1.93	0.04	28.5	2.78	79%	79%	35%
AQL	108.0	10.72	1.87	4.1	11.41	106.9	3.14	0.09	20.3	4.04	65%	65%	35%
T1	78.5	6.95	0.55	1.9	7.23	78.1	2.16	N/A	21.6	2.83	61%	61%	50%
	77.2	8.14	0.43	8.2	9.07	77.3	2.62	0.13	41.2	4.61	49%	49%	50%
						76.6	1.47	0.04	46.0	2.83	69%	69%	51%

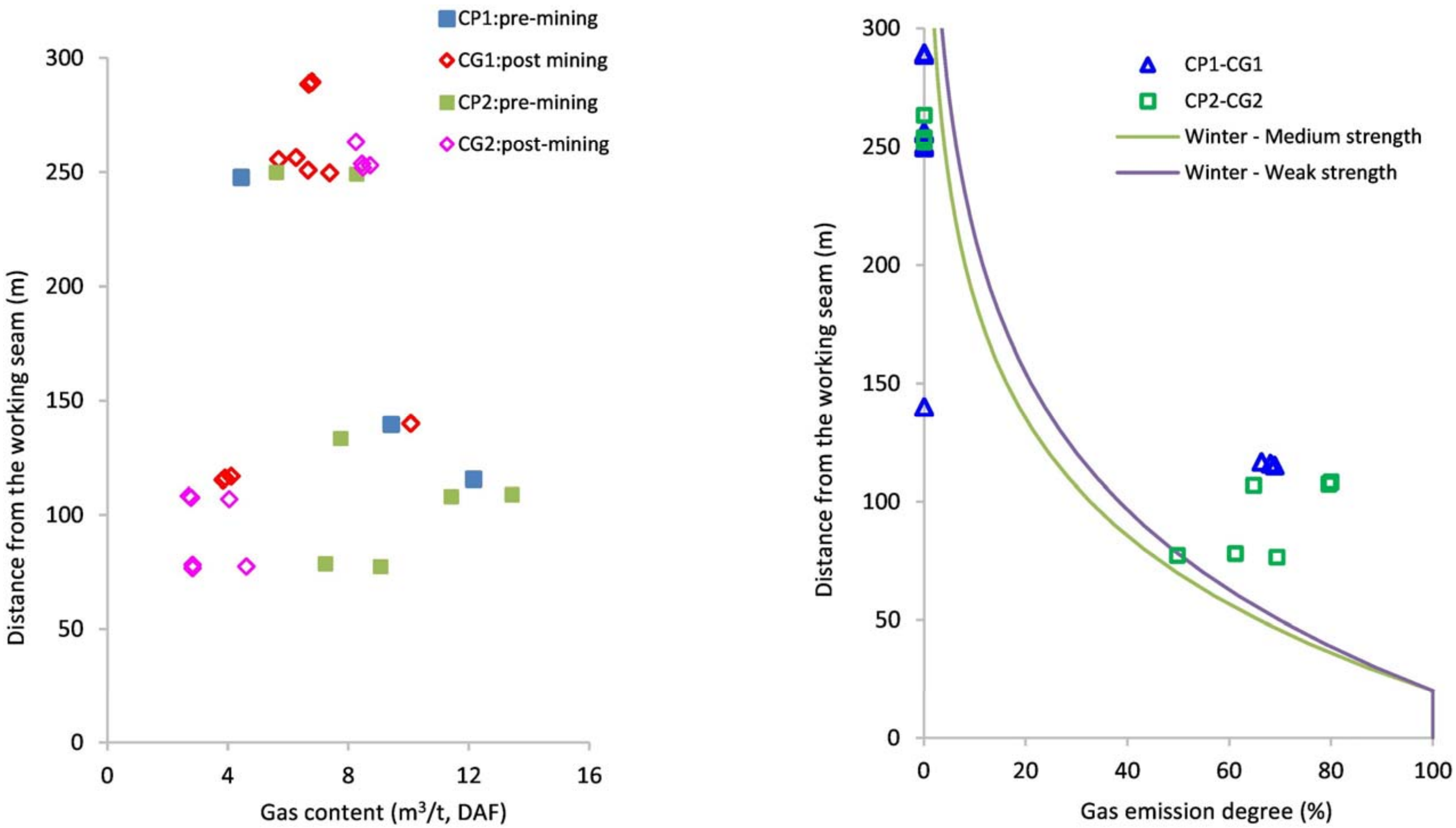

Fig. 9. (a) Measured pre- and post-mining gas content in different coal seams at Mine C; (b) comparison of analysed gas emission degree with the Winter models for weak and medium strength strata.

5. Development of a new empirical model

5.1. Integrated analysis of all measurement data

Fig. 10 shows the measured gas emission degrees at the three study mines. The measured coal seams were all located over 75 m from the working seam, and there was no measurement for coal seams below that distance. To complement the analysis, the measured data of two roof seams at Mine D of Hunter Coalfield of New South Wales, Australia, were included (more details can be found from Qu et al., 2022). Mine D was a multi-seam longwall mine operated approximately 70 m below a previously mined-out seam. Pre and post-mining gas content measurements suggested that the two roof seams, 55 m and 42 m above the worked seam, released about 88% and 74% of their virgin gas content, respectively.

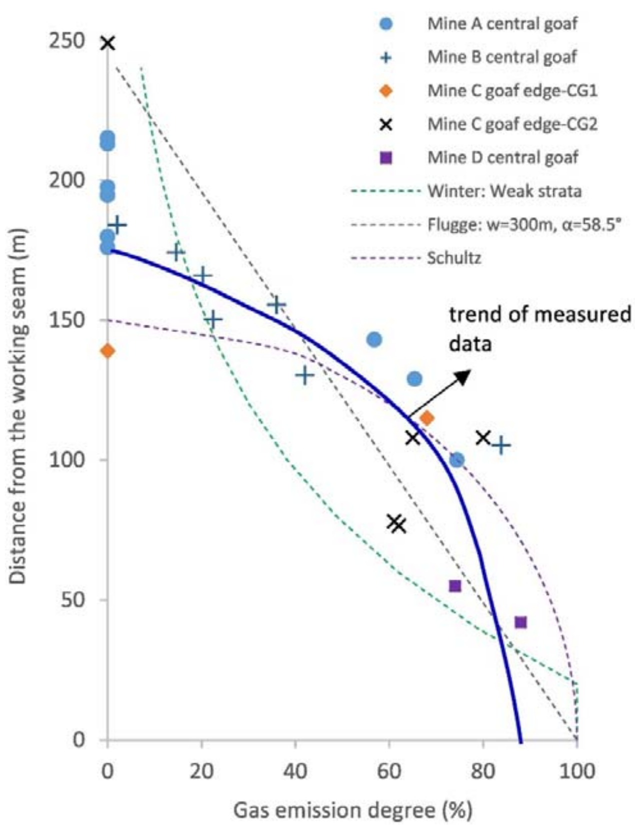

Fig. 10. Comparison of all measured gas emission degrees with three conventional predictive models.

The measured degree of gas emission at different mines decreases with the distance from the mining seam. The decreasing trend exhibits a concave down curve. In addition, the height of the GEZ varies at different mines. For example, the GEZ extends to about 185 m above the working seam at Mine B, whereas it is only 140 m at Mine C.

The measured data were compared to three empirical models in Fig. 10. In addition to the Winter model, the other two models compared are the Flugge model (Flugge, 1971), which is also widely used in Australian mines (Meyer, 2006; Black, 2017; Booth et al., 2017; Belle, 2017), and the Schultz model, which shows a similar concave down curve of gas emission variation to the measured data. The gas emission degrees of the Flugge model and the Schultz model are expressed in Eqs. (5), (6), respectively.

$$\eta_{Flugge} = 100\left(1 - \frac{2h}{w} \cot \alpha\right) \tag{5}$$

$$\eta_{Schultz} = \frac{100}{w} \sqrt{w^2 - 4h^2} \tag{6}$$

Where: η is the degree of gas emission, %; h is the distance into the roof or floor, m; w is the longwall width, m; α is the internal angle. The possible values of α for roof strata are 45°, 54° and 58.5°, respectively for no drainage, medium drainage and intensive drainage scenarios (Curl, 1978). The value of α for floor strata is a constant value of 22.5°.

The Winter model overall underestimates gas emission for the majority of the GEZ. The linear Flugge model seems to predict an average line of measured data, but it overestimates gas emissions from coal seams 150 m and above. The Schultz model predicts a similar trend as the measured data, but the predicted values match poorly. In addition, the Schultz model can significantly underestimate gas emissions from coal seams above 150 m from the mining seam. None of the models adequately matches the measured data, and a new model is needed to improve gas emission predictions.

5.2. Gas emission degrees vs mining thickness

Extraction thickness is a crucial factor controlling the extension of strata fracturing in the overburden. Typical overburden fracture models (e.g., Bai and Kendorski, 1995; Peng, 2006; Mark, 2007) are generally expressed as a multiplier of mining thickness in their vertical extents. For instance, the model illustrated by Bai and Kendorski (1995) suggests that the heights of the fractured zone and the dilated zone are 5–30 and 30–60 times the extraction thickness, respectively. However, none of the three empirical models discussed in Section 5.1 considers the extraction thickness (T) in its prediction.

Converting the distance of Fig. 10 into a multiplier of mining thickness results in Fig. 11. Disregarding the influence of longwall face width and the geological conditions, the variation of gas emission degree correlates much better with the multiplier of mining thickness than the distance (Fig. 10). There is a clear boundary of the GEZ, the height of which is about 45 times of mining thickness (T). Overall, the variation trend of gas emission degree exhibits a three-zone characteristic:

• Zone I (0 - 25 T): the degree of gas emission is high (80–90%) and reduces gradually with increasing distance

• Zone II (25 - 45 T): the degree of gas emission reduces quickly from about 80% to zero

• Zone III (> 45 T): no gas is released from this zone.

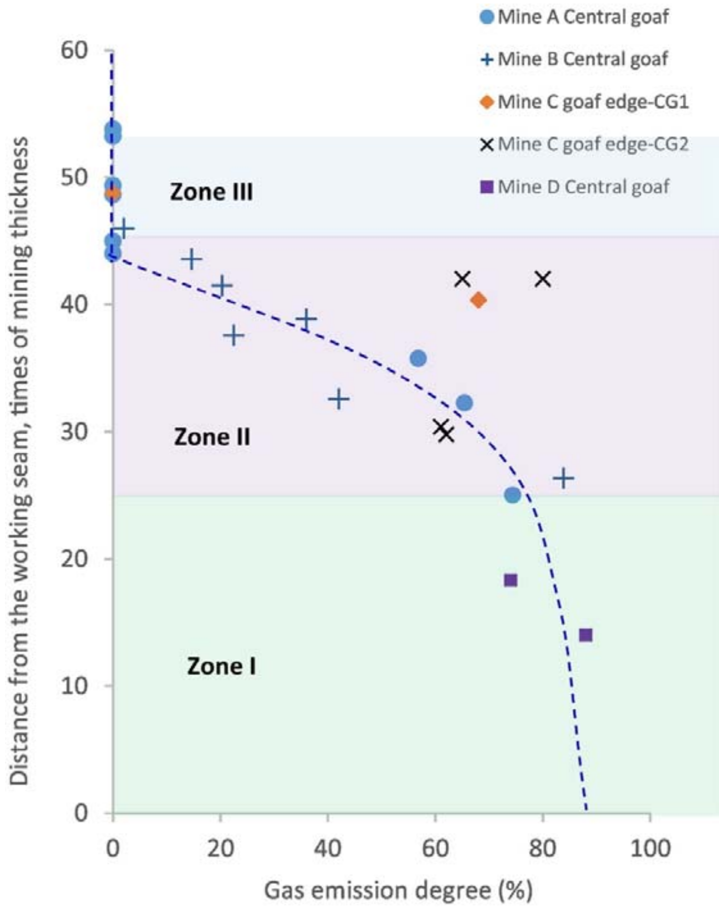

Fig. 11. Measured gas emission degrees expressed as multipliers of the mining thickness.

The three-zone division of gas emission patterns in the roof strata conforms with the zoning of overburden strata regarding gas migration patterns proposed by Qu et al. (2015). Zone I in Fig. 11 reflects the connective fracture zone where gas released from coal seams can flow into the goaf almost unimpededly. Zone II corresponds to the de-stressed dilation zone where horizontal permeability is well developed, and vertical gas migration is hampered and depends on strata permeability.

Reasons behind the deficiencies of the Winter model in today's Bowen Basin mines can be analysed based on the three-zone model. In addition to the differences in the reservoir and geomechanical conditions between Bowen Basin and European mines, the intensive goaf gas drainage and rate of production is also significantly different. The dense, large-diameter vertical wells (with a spacing of 50 m and a diameter of 300–400 mm) used to facilitate highly productive Bowen Basin longwalls would have allowed substantially more gas in the de-stressed zone (Zone II in Fig. 11) to release than cases without drainage boreholes intersecting the zone. Such gas emission environment induces a higher degree of gas emission than that experienced in European coal mines several decades ago.

5.3. Development of a new empirical model

The post-mining gas content measurements at various coal mines in the Bowen Basin mines have provided a valuable dataset to improve gas emission predictions. Based on the data and the above analyses, a new empirical model, as expressed in Eq. (7), was preliminarily developed for predicting gas emission degrees from roof coal seams.

$$\eta = A - \exp\left(\mu \bullet \frac{h}{T}\right) \tag{7}$$

Where *T* = mining thickness, m; *h* = height of the coal seam above the working seam, m; μ is the attenuation coefficient controlling the decrease rate of gas emission degree with increasing distance. *A* determines the maximum degree of gas emission in the roof seam. *A* = 90 and μ = 0.1 is preliminarily specified for the Bowen Basin longwall mines to correspond to the measured data, as shown in Fig. 12. Different mining, reservoir and geomechanical conditions (e.g., longwall face width, desorption rate and overburden strength) may result in different *A* and μ. For a height of GEZ between 30 T to 60 T, the value of μ ranges between 0.15 and 0.07.

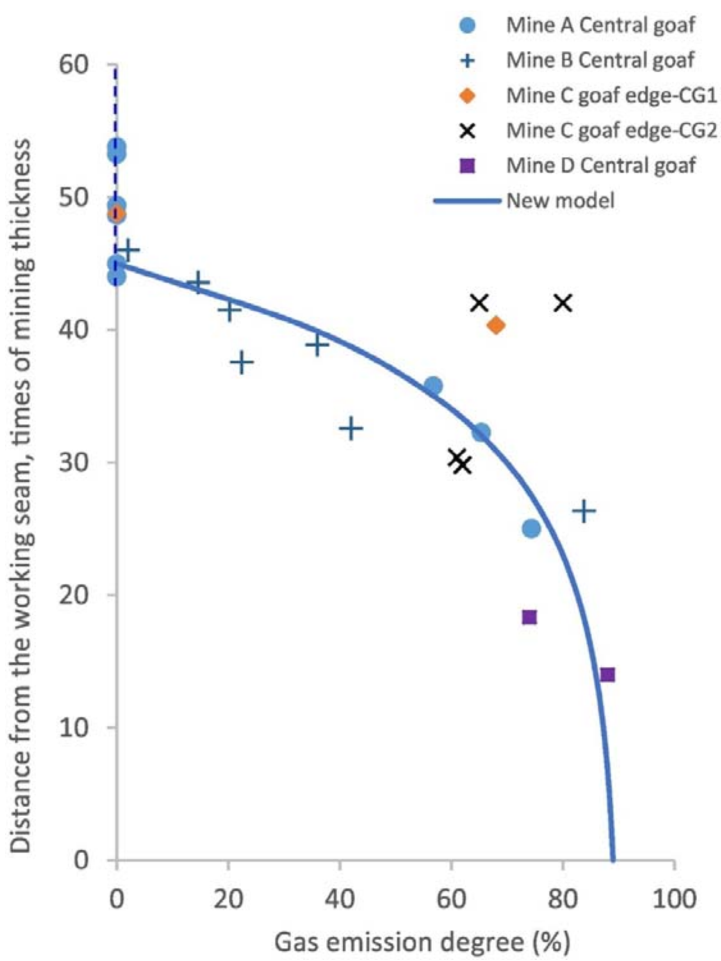

Fig. 12. Comparison of the proposed model with measured gas emission degrees at different mines.

It is noted that the maximum degree of gas emission at the mining level is assumed to be 89%, which is lower than the maximum value (100%) used in most European models. However, there are also few models assuming a maximum value lower than 100%, such as the Barbara Mine method (64.7%) and the Jeger method (90%). Gas emission from closed coal mines can last as long as 15 years (Duda and Krzemien, 2018), and a 100% emission within the extraction period of a longwall panel seems impossible. However, the value *A* can be further refined when there are measured data available from coal seams located even closer to the worked seam.

5.4. Comparision with conventional models

Fig. 13 compares the new model with the conventional Winter model and the Flugge model that are used in Australian coal mines. Two mining thicknesses are considered: *T* = 2.5 m and *T* = 4 m. The longwall width is assumed to be 300 m. The two conventional models do not vary with changing mining thicknesses. The differences between the three models are minimal for coal seams within 50 m from the mining seam. In other words, if a coal mine mainly contains coal seams within 50 m in the roof, prediction using any of the three models would not make appreciable differences.

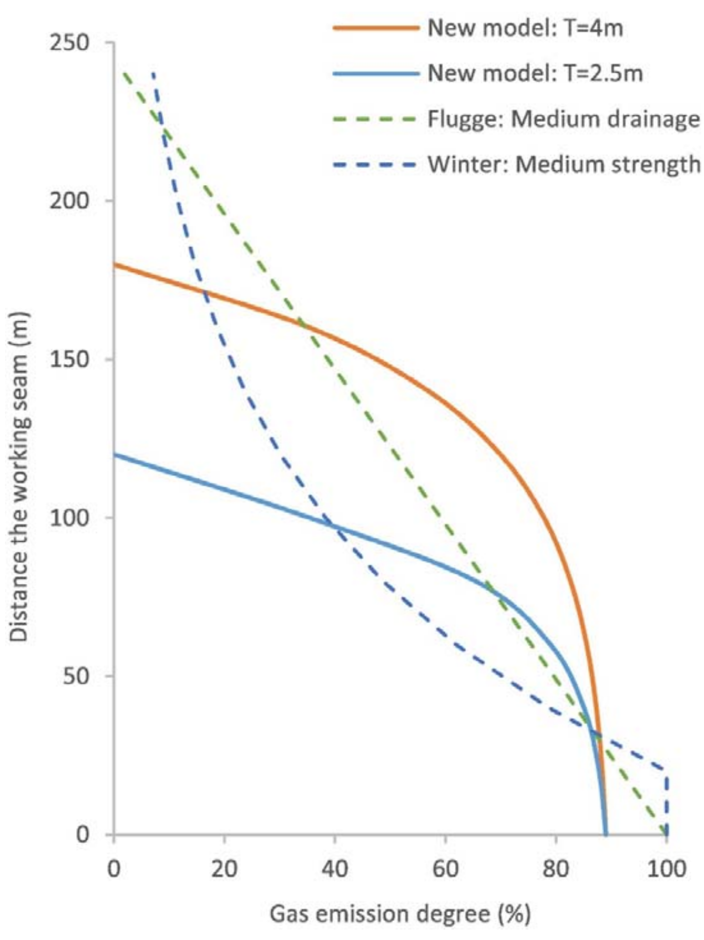

Fig. 13. Comparison of the new model with the conventional Winter model and Flugge model based on a panel width of 300 m and two different extraction thicknesses.

However, if coal seams are located between 50 m and 200 m, significant differences can be resulted from these three models. The differences are also dependent on the thickness of the mining seam. For a mining seam with a small thickness (e.g., T = 2.5 m), the conventional models may significantly overestimate gas emissions. For a mining seam with a relatively large thickness (e.g., T = 4.0 m), the conventional models may significantly underestimate gas emissions from remote coal seams (50–170 m in the example case) but overestimate from distant coal seams (> 170 m in the example case).

Based on the measurement data, the newly developed model is expected to predict more accurate gas emission degrees for individual seams than conventional models. However, calibrating the model against the actual gas emission rate at a longwall requires inputs of many other parameters, such as coal production rate, the lateral extent of the GEZ, leakage from adjacent goaves, gas contributions from rock strata and background rib gas emissions in the intake air. Further statistic studies with longwall gas emission data are essential to establish a robust method of gas emission prediction to meet the needs in mine methane emission management.

6. Summary and conclusion

Residual gas contents in different coal seams after mining were measured at three Bowen Basin longwall mines, Australia. The results enabled quantification of the height of the gas emission zone at different mines and the degree of gas emission at varying distances. The results were compared with the conventional Winter model that has been used in the study mines for many years, as well as two other empirical models. The following conclusions can be drawn.

1) The Winter model significantly underestimates gas emissions for coal seams 75–150 m above the mining seam. The measured gas emission degrees range between 60 and 80% in these distances, whereas the Winter model predicts only 20–55%. Such significant discrepancies are likely due to the intensive goaf gas drainage practised in today's high production longwall mines.
2) In general, the measured degree of gas emission decreases with the increasing distance from the working seam. The decreasing curve exhibits a concave down shape, which is different from the Winter model and the Flugge model widely used in Australian longwall mines.
3) The vertical extents of the gas emission zone vary in different studied mines but appear to be approximately 45 times the mining thickness.
4) The variation of gas emission degree in the overlying coal seams correlates better with multipliers of extraction thickness than distance and presents a three-zone characteristic: Zone I (0–25 T): the degree of gas emission is high (80–90%) and decreases gradually; Zone II (25–45 T): the degree of gas emission reduces from about 80% to zero; Zone III (>45 T): no gas is emitted.
5) Based on the measured results in various mines, a new predictive model expressed as $\eta = 90 - \exp\left(0.1 \bullet \frac{h}{T}\right)$ is developed for gas emission prediction in Bowen Basin longwalls. Unlike the historic models used in Australian mines, the new model takes into account the mining thickness that may vary in different mines or areas of a mine.

6) The newly developed SGE model outputs are based on the current knowledge and measured data from Australian operations. The new model aims to provide guidance on likely gas emission with greater confidence than heretofore. However, when using this model for longwall gas emission predictions and gas management, coal mining operations must ensure to incorporate adequate and flexible goaf drainage capacity to manage appropriate safety risks and underground gas levels.

CRediT authorship contribution statement

Qingdong Qu: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Rao Balusu:** Conceptualization, Methodology, Formal analysis, Writing - review & editing. **Bharath Belle:** Conceptualization, Methodology, Investigation, Resources, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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