International Journal of Coal Science & Technology (2022) 9:88
https://doi.org/10.1007/s40789-022-00553-6

RESEARCH

Application of long-reach directional drilling boreholes for gas drainage of adjacent seams in coal mines with severe geological conditions

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Received: 16 March 2022 / Accepted: 1 September 2022

Abstract
This study aimed to demonstrate the application of Long Reach Directionally Drilled Boreholes (LRDD) for gas drainage of adjacent seams before and during the longwall face operations of low permeability-high gas content coals Staszic-Wujek Hard Coal Mine in the Upper Silesia Coal Basin (Poland). Five LRDD Boreholes (TM1a-TM5) with a length of 300 and 400 m were located over coal seam 501 in the fractured zone and monitored over six months of longwall face operations. LRDD Boreholes were combined with Cross-Measured Boreholes. Reservoir characterization and geological modeling supported the results obtained from gas drainage. The drainage efficiency of LRDD Boreholes was the approximately 70% level, while conventional Cross-Measured Boreholes were only 30%. The highest goaf gas quality (94% methane concentration) was reported for TM4, placed at an average elevation of 41 m above coal seam 501. The highest goaf gas production (average 6.2 m^3/min) was reported for LRDD Borehole TM3. This borehole was placed within the fracture zone (average elevation of 24.4 m) and drilled through the sandstone lithotype with the best reservoir properties, enhancing drainage performance. LRDD Boreholes TM2 and TM4 achieved similar performance. These three LRDD Boreholes were drilled close to the maximum principal horizontal stress direction, providing borehole stability during under-mining. The lowest goaf gas production was reported for LRDD Boreholes TM1a and TM5. Both Boreholes were placed in the rubble zone.

Keywords Coal Mine methane · Methane control strategy · In-seam horizontal boreholes · Long reach directionally drilled boreholes

1 Introduction

Coal mine methane (CMM) released during underground mining operations is a serious safety hazard worldwide, being one of the main causes of mine gas explosions and gas outburst incidents resulting in many fatalities each year (United Nations 2010; Skiba 2013; Krause 2020). If correctly captured and processed ahead of or during mining, it improves safety in the underground working environment and the efficiency of mining output. It will also have substantial impact on the utilization of a relatively clean energy source and mitigation of greenhouse gas (GHG) emissions (Salmachi and Karacan 2017; Zheng et al. 2018). Due to these advantages, there is a continuous need for improvement of coal mine methane drainage technology. This effort can significantly decrease the release of coal mine methane during mining operations, which is, for safety reasons, diluted and ventilated via the roadways and return shafts to the atmosphere as Ventilation Air Methane. Highly efficient coal mine methane drainage can benefit three sectors: safety, economics, and the environment (Jura 2014).

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Published online: 24 November 2022

Current drainage techniques for underground CMM utilisation/reduction involve Cross-Measure Boreholes and in-seam horizontal boreholes (EPA 2009; United Nations 2010; Zhang et al. 2019). Another method, which has been proven to be much more efficient than Cross-Measure Boreholes, utilizes “drainage galleries”, which are driven above the mined longwall coal panels, from which boreholes are drilled behind the coal face (United Nations; 2010; Krause 2017). The efficiency of drainage galleries was confirmed by coal mine methane drainage operations in many hard coal basins globally e.g., in China (Huainan and Yang coal mines) and Europe (Saar coalfield). From the above-listed methods, in-seam long horizontal/directional boreholes have the advantage of being less labour intensive while having a high utilisation rate (Bojarski 2014). The ambitious target is to replace the efficient but expensive drainage galleries with long boreholes developed above the longwall panels (Krause 2017). In cases where these boreholes can be placed in an overlying coal seam, their purpose is to reduce the in-situ gas content of adjacent virgin coal seams and shield longwall operations from the migration of methane from surrounding virgin coal seams (United Nations 2010).

The share of coal in the Polish energy mix is decreasing yearly in favor of renewable energy sources. Nevertheless, this process is time-consuming and costly. The conclusions coming from best practices in the domain of closure of underground hard coal mines in Europe – and effectively capturing and utilizing CMM are clear – no matter how ambitious the closure targets, the coal mine methane emission mitigation process requires definitive and sustainable actions. It is proven globally that the closure of gassy underground coal mines is not the ideal solution to stopping coal mine methane emissions (Prusek 2020). The more methane captured during the operational phase of the coal mine, the less the emissions after the closing of the mine. Capturing and utilizing CMM is also less costly and more efficient (Krause 2013).

Ambitious goals of the European Commission related to the mitigation of methane emissions expressed in its new legislative act (European Commission 2021) as well as in the Global Methane Pledge put certain obligations on the energy sector – including the hard coal mining industry. Although goals relating to the mitigation of coal mine methane emissions are thought to be “low hanging fruit”, they are not so easy to achieve since mining is heavily dependent on geology. The largest source of the ‘world’s coal mine methane emissions is constituted by Ventilation Air Methane (VAM) from the roadways (Skiba 2004; European Commission 2021). Even with low concentrations of methane in VAM, its utilization is technically feasible and has been proven on an industrial scale (Holmes 2016). However, it is still too expensive, and therefore more effort is being put into CMM production using drainage technology, in which higher concentrations of methane are directly transported through gas drainage pipes with high negative pressure contributing to high gas yields (Krause 2017).

This pilot project aimed to design and test Long Reach Directionally Drilled (LRDD) Boreholes placed in strata lying above coal mining panels as a method for goaf gas drainage to prove its higher effectiveness and lower costs compared to conventional drainage methods in particular, drainage galleries. The study also discusses the influence of technical and geological conditions on goaf gas drainage performance.

2 Geological conditions

2.1 Geological setting

The study area is located within the multi seam Staszic-Wujek Coal Mine in the central part of the Upper Silesian Coal Basin (USCB), in southern Poland. The USCB is situated in the Upper Silesian Block, the northeastern part of the Brunovistulicum terrane (Kotas 1985; Buła and Jachimowicz 1996; Buła et al. 1997; Buła and Żaba 2008; Nawrocki and Poprawa 2006; Buła et al. 2014; Buła et al. 2015).

The productive carboniferous complex in the Staszic – Wujek Coal Mine consists of the Pensylvanian strata, within which the following parts can be distinguished: Cracow Sandstone series, Upper Mudstone series, Upper Silesian Sandstone series and Paralic series.

The zone of particular interest in this study is the Upper Silesian Sandstone series developed as poorly sorted sandstones interbedded with shales and mudstones with coal seams belonging to the Rudzkie beds, deposited below coals seam 407 and between coal seams 501 and 510 belonging to the Siodłowe beds (Stankiewicz 1955; Hanzlik 1963; Dembowski et al. 1964; Kotas and Malczyk 1972; Dembowski 1972).

The I-C longwall was developed in coal seam 501, which belongs to the Siodłowe Beds of the Upper Silesian Sandstone Series. The No. 501 coal seam was deposited at depths of approximately 550–590 m below sea level in the study area and gently dips towards the SW direction, and this trend is maintained in the C field district, limited by the fault system consisting of the Książęcy fault, the Kostuchna fault, the Murckowski fault, and the Jakub fault (Fig. 1). The thickness of the No. 501 coal seam in the study area varies between 0.6 and 4.5 m. The location of the study area is shown on Fig. 1.

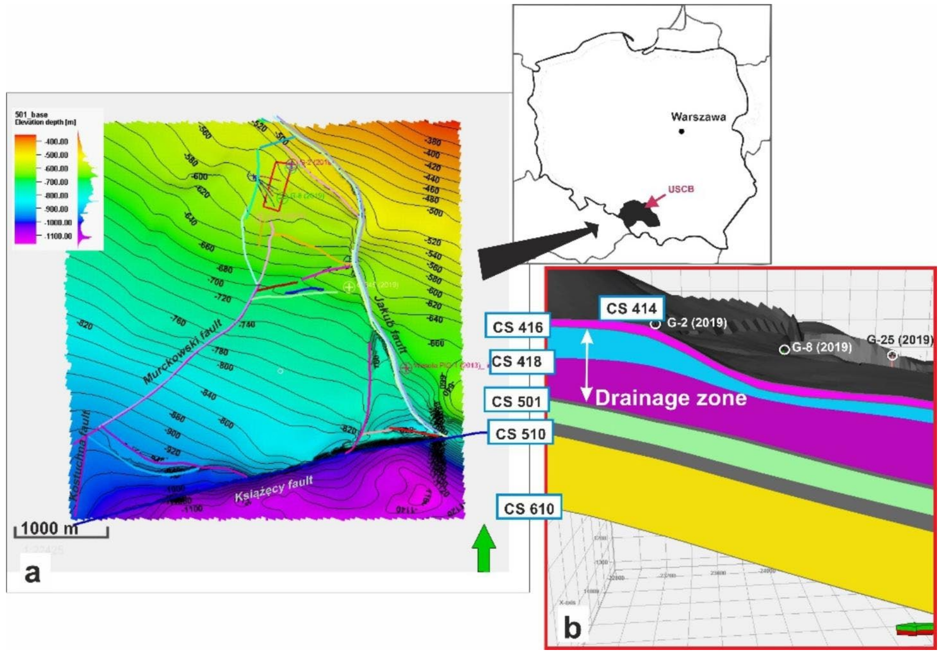


Fig. 1 Location of the study area in the vicinity of the I-C longwall marked with the red polygon with five horizontal degassing boreholes system visualized on the structural map of the coal seam (CS) 501 bottom within the C field in the Staszic-Wujek Coal Mine limited with major faults (a) and the interval of the interest subjected to the drainage (b)

2.2 Reservoir characterization

The zone subjected to degasification, using a system of five LRDD Boreholes drilled from coal seam 501, penetrates the Upper Silesian Cracow Sandstone series developed as poorly sorted sandstones interbedded with shales and mudstones (Dembowski 1972; DD-MET report 2021). Wojciecki (2013) classified these sandstones as sublithic, subarkose arenites, lithic arenites, and subarkose and lithic wackes. The cement of these sandstones contributes slightly more than 15% of the relative weight% and is composed of clay minerals with a small admixture of calcite. The results of this study showed that effective porosity of sandstones ranges between <1% to 34.02% (average 6.3%). Despite high maximum porosity, the porosity values higher than 10% were determined in 158 samples, while porosity higher than 20% was measured only on eight samples. The permeability ranged between 0.001 and 1000 mD with an average of 4.02 mD. Permeability greater than 100 mD was determined in seven samples, while only four had permeability greater than 200 mD (Wojcicki 2013).

2.3 Source of gas emissions

Methane emissions into mine working faces mainly come from the mined coal seam and its neighboring rock layers (Lunarzewski and Battino 1983; Krause 2013; Prusek 2020). It depends on the progress of the longwall and the associated destruction of the rock mass structure, which causes methane desorption from neighboring coal seams and the outflow of free methane from macropores and sandstone fissures.

Longwall Panel I-C was exploited in the KWK Staszic-Wujek Mine at 550–590 m below sea level in coal seam 501. The panel I-C excavated with a crosswise system with a roof collapse system had the following technical parameters: coal panel height up to 3.7 m, coal panel width: 159–161 m, longwall panel length – 400 m, max. The transverse slope in the coal panel, measured along with the longwall workings, is approximately 6°, average inclination 4°, max. The longitudinal slope in the coal panel, measured as the difference in height between the longwall headings, is approximately 4°, desorption range (hg) for roof layers: hg = 87 m above the top of the No. 501 coal seam.

The absolute methane-bearing capacity forecast for longwall panel I-C in coal seam 501 in field C, was developed following the method of the Central Mining Institute (Instruction No. 18 issued by the Central Mining Institute). The forecast was prepared based on the profiles of the boreholes, the results of the methane-bearing capacity of the 501 coal seam, and the coal seams and layers of coal occurring in the desorption zone of the longwall panel I-C, taking into consideration the results of the methane-bearing capacity studies carried out in the adjacent T field in coal seams 501, 510 and 407/1, and also based on the movement parameters of the designed coal panel. The methane bearing capacity forecast of the longwall panel area captures the amount of methane emitted in the longwall panel I-C environment. It considers the presence of free methane in the pores and fractures of the Carboniferous sandstone. To calculate the projected methane release during the exploitation of coal seam 501 by the longwall panel I-C, the following average values of methane content in individual sections were adopted:

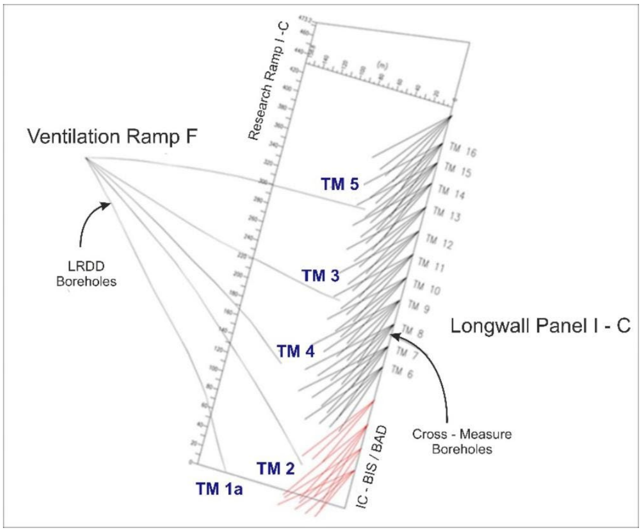


Fig. 2 Plan view of Longwall Panel I-C with the two goaf degasification systems

(1) S1 section (from the commencement of operation to 100 m) – 5.933 m^3 CH_4/Mg_{daf}.
(2) S2 Sects. (100–300 m) – 5.743 m^3 CH_4/Mg_{daf}.
(3) S3 Sects. (300–400 m) – 6.444 m^3 CH_4/Mg_{daf}.
(4) S4 Sect. (400-to the end) – 7.075 m^3 CH_4/Mg_{daf}.

The release of methane during the exploitation of longwall panel I-C to its environment will depend on the daily progress of the longwall and the corresponding extraction and the location of its front line on the run. During the commissioning of the longwall, following the mine's preliminary assumptions, the output will be at the level of about 2500 Mg/d (with an advance rate of about 2.25 m/d). The forecast value of methane production will be about 15.99 m^3 CH_4/min. At a later stage, methane emissions will increase and amount to a maximum of 26.07 m^3 CH_4/min, with the extraction of 4527 Mg/d (with an advance of about 6.0 m/d). The distribution of methane from the floor seams will amount to 23%–30%, with the roof seams accounting for 28%–44% and 26%–48% from the No. 501 seam, operated on the I-C longwall.

3 Methane control strategy in coal seam 501 longwall panel 1 C

Coal production from Longwall Panel I-C began on September 3, 2019, and ended on February 25, 2020 (176 days).

Goaf degasification for Longwall Panel I-C was performed with two systems: (1) conventional Cross-Measure Boreholes placed along the Panel I-C Bis/Bad (the ventilation return gate road along the low-pressure side of the goaf), and (2) LRDD Boreholes developed in the overlying strata from Ventilation Ramp F over the longwall panel as shown in Fig. 2. Due to the necessity of minimizing the methane hazard during longwall operations, it was necessary to ensure optimum (highly effective) ventilation and maximum methane drainage in the area of longwall I-C in seam 501. Longwall I-C was exploited using the transverse system with roof collapse and was ventilated in the "U" type mode with air led across the longwall face via the gate roads.

4 Field application and analysis

4.1 Comparison of conventional and LRDD drainage approaches

4.1.1 Cross-measure boreholes

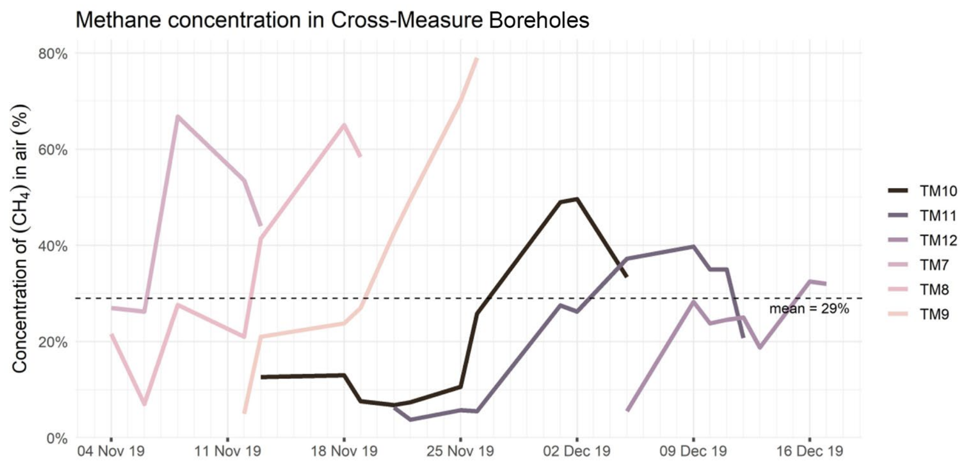
Conventional Cross-Measure Borehole drilling was performed in advance of longwall mining. Each set of Cross-Measure Boreholes (typically five at each drilling station) produced goaf gas when the longwall face advanced from the proximity of the end of each set of boreholes to the proximity of their respective wellheads, depending on wellhead and borehole integrity and connectivity to the goaf and mine infrastructure. The Cross-Measure Boreholes were installed in an overlapping fashion to maintain a continuous low-pressure zone to control goaf gas emissions in the proximity of and outby of the intersection of the longwall face and return gate road. Due to the overlapping layout, up to three sets of Cross-Measure Boreholes could be in production concurrently.

Cross-Measure Boreholes were installed with nominal horizontal projections that range from 68 m to 20 m across the longwall panel. Borehole lengths varied from 95 m to 70 m, with the majority of the boreholes reaching approximately 90 m in measured depth. The borehole diameter was 95 mm.

Average methane flow rates for each Cross-Measure Borehole set were derived using an average performance period based on the average longitudinal projection (76.7 m) and the average longwall face advance rate of 2.25 m per day. Assuming an average production period of 34 days per set of Cross-Measure Boreholes, each set produced on average 183,600 m^3 of methane, or 408 m^3 of methane per meter of borehole based on an average Cross-Measure Borehole length of the 90 m and accounting for 5 Cross-Measure Boreholes per set.

As conventionally drilled Cross-Measure Boreholes are developed from gate roads, wellheads and borehole collars are not well protected from active mining and therefore draw significant ventilation air through mining-induced fractures when operated under vacuum (United Nations

Fig. 3 Average methane concentrations collected by cross-measure borehole sets TM7-12. The date on the *x*-axis indicates the indicates the day, month and year



2010). The average concentration of methane produced from the Cross-Measure Borehole sets TM7 through TM12 was approximately 29%, as shown in Fig. 3. Because of the number of wellheads in production (five per set with overlap of up to three sets), vacuum management to control goaf gas methane concentrations is difficult, and typically not practiced. As a result, explosive mixtures of methane and air are collected and transported in underground pipelines in some cases.

4.1.2 LRDD boreholes

Five Long Reach Directionally Drilled (LRDD) Boreholes were drilled from Ventilation Ramp F, approximately 190 m west of Panel I-C, as shown in plan-view in Fig. 2. The LRDD Boreholes were placed between 9 and 44 m above the top of the No. 501 coal seam over Longwall Panel I-C and were operated under vacuum (average 50 mm Hg) as they were under-mined. The LRDD Boreholes were drilled at a diameter of 95 mm. The five LRDD Boreholes were drilled over Longwall Panel I-C and were under-mined by the longwall face in the following progression: TM1a, TM2, TM4, TM3, and TM5.

(1) Borehole TM1a.

Borehole TM1a was directionally drilled from Ventilation Ramp F to a measured depth of 402 m. The borehole crossed Research Ramp I-C (the intake gate road) at a vertical elevation of 17.5 m above coal seam 501, then extended 61 m (this length is based on Plan View Data) and past the gate road to the longwall setup room. It terminated at a vertical elevation of 9 m above the top of the No. 501 coal seam.

TM1a was immediately undermined as the longwall face advanced. Based on the measurements collected, once the face had advanced 50 m, methane production from TM1a measured approximately 2 m^3/min with an applied wellhead vacuum of around 40 mm Hg, as shown in Fig. 4. As the longwall advanced another 30 m (to 80 m), methane production increased to over 3 m^3/min and then began to steadily decrease as wellhead vacuum was increased, as shown in Fig. 4. TM1a was undermined entirely after the longwall face advanced a total of 53 m on October 1, 2019, and produced high-quality goaf gas through November 13, when the longwall face advanced 175 total meters (Fig. 4). After November 13, the borehole primarily produced ventilation air (less than 30% methane) from underlying mining, likely due to its low elevation above coal seam 501 and the increase in the application of wellhead vacuum.

(2) Borehole TM2.

Borehole TM2 was directionally drilled from Ventilation Ramp F to a measured depth of 401 m. The borehole crossed Research Ramp I-C at a vertical elevation of 36.5 m above the No. 501 coal seam, then extended 149 m past the gate road over the Longwall Panel, terminating approximately 30 m from the longwall setup room at a vertical elevation of 26 m above the top of the No. 501 coal seam.

The end of Borehole TM2 was undermined on September 20, 2019, when the longwall face advanced 30.5 m. Methane production was measured after the longwall face advanced an additional 18.4 m past the end of the borehole and continued to increase with the longwall face advance. A peak methane flow rate of 7.1 m^3/min was reached on December 16, recovering goaf gas at 90% methane with 29 mm Hg of applied wellhead vacuum (Fig. 4). Wellhead vacuum pressure was gradually increased (up to 86 mm Hg on December 11), drawing more goaf gas at a higher methane concentration over the end of the measured production period. TM2 produced high-quality goaf gas through December 17, 2019, after which individual LRDD Borehole measurements of methane concentration were suspended.

(3) Borehole TM4.

Borehole TM4 was directionally drilled from Ventilation Ramp F to a measured depth of 301 m. The borehole

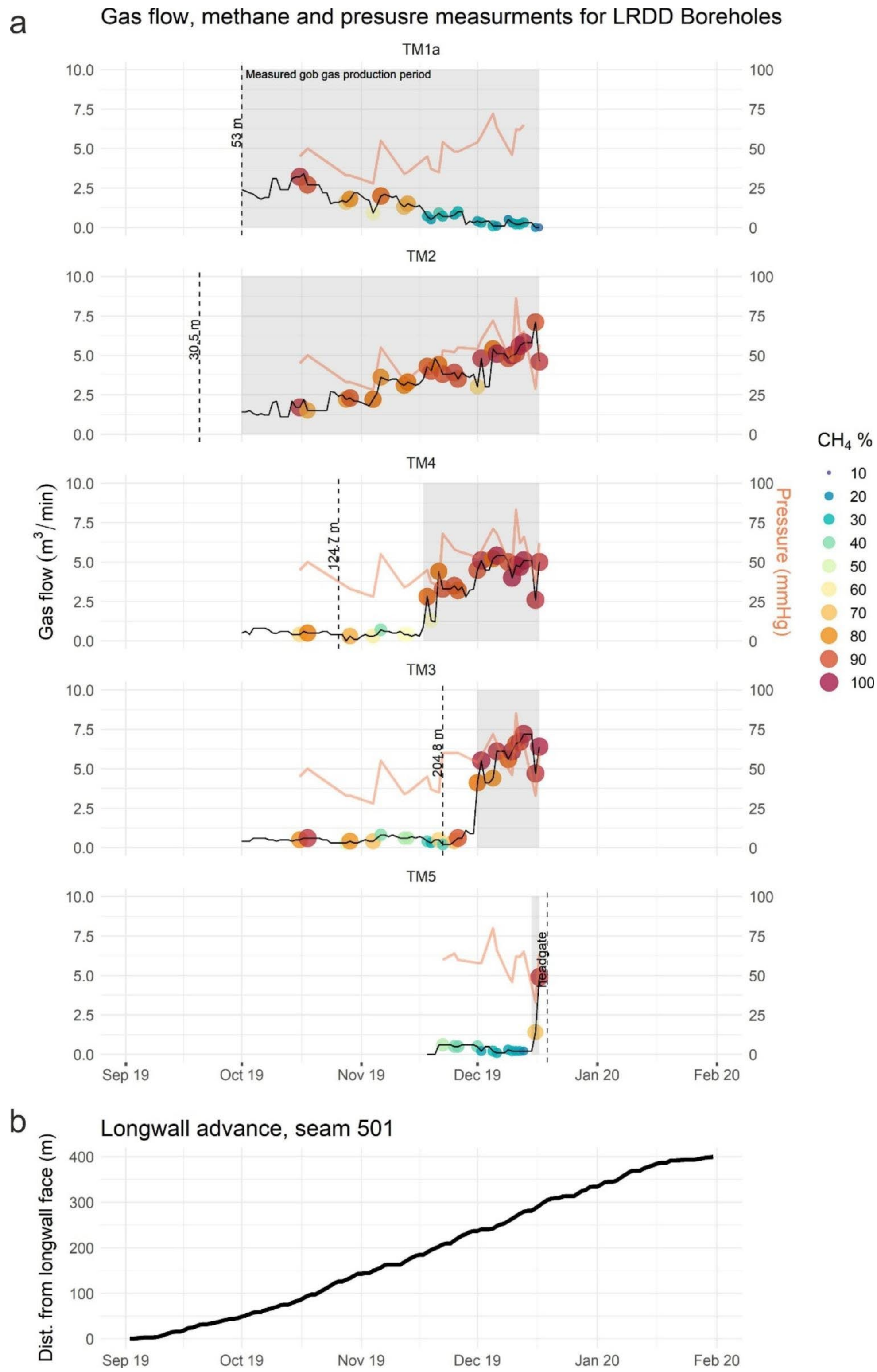


Fig. 4 Gas flow, methane, and vacuum pressure measurements for LRDD boreholes: **a** With longwall advance for the No. 501 coal seam; **b** Vertical dashed lines represent the moment when longwall advance undermined individual LRDD Boreholes. Shaded gray areas represent the measured goaf gas production period. The date on the *x*-axis indicates the month and year

crossed Research Ramp I-C at a vertical elevation of 38.6 m above the No. 501 coal seam, then extended 73.3 m past the gate road over the longwall panel, terminating approximately 125 m from the longwall setup room at a vertical elevation of 44.1 m above the top of the No. 501 coal seam.

TM4 was undermined on October 26, 2019, after the longwall face advanced 124.7 m. Before undermining, the borehole produced an average methane flow rate of 0.5 m^3/min from the overlying gas-bearing formation (sandstone). Once the face was mined 50 m past the end of the borehole, methane production increased to an average of 3.9 m^3/min, and TM4 recovered high-quality goaf gas at 90% methane with an average applied wellhead vacuum of 56 mm Hg (Fig. 4). TM4 produced high quality goaf gas through December 17, 2019.

(4) Borehole TM3.

Borehole TM3 was directionally drilled from Ventilation Ramp F to a measured length of 300 m. The borehole crossed Research Ramp I-C at a vertical elevation of 20.3 m above the No. 501 coal seam and then extended 94.7 m past the gate road over the longwall panel. The TM3 terminated approximately 205 m from the longwall setup room at a vertical elevation of 28.5 m above the top of the No. 501 coal seam, as shown in Fig. 4.

After producing gas inherent in the overlying strata for approximately two months, the end of Borehole TM3 was undermined on November 22, 2019, after the longwall face advanced to 204.8 m. Methane production increased slightly during the following week, and gas production significantly increased after the face mined an additional 31.7 m past the end of the borehole. TM3 produced an average of 5.9 m^3/min of methane between December 1 and December 17 with an average applied wellhead vacuum of 60 mm Hg (Fig. 4). A peak goaf gas flow rate of 7.5 m^3/min was reached on December 13 at a methane concentration of 96%. Wellhead vacuum pressure peaked at 85 mm Hg on December 11, with an average applied vacuum of 50.4 mm Hg (Fig. 4).

(5) Borehole TM5.

Borehole TM5 was directionally drilled from Ventilation Ramp F to a measured length of 302 m. The borehole crossed Research Ramp I-C at a vertical elevation of 22 m above the No. 501 coal seam, then extended 97 m past the gate road over the longwall panel, terminating at a vertical elevation of 3.6 m above the top of the No. 501 coal seam (Fig. 4). Borehole TM5 was drilled at an obtuse angle relative to the advancing longwall face and terminated 300 m from the longwall setup room.

TM5 was undermined on December 17, 2019 at its intersection with the headgate. The end of the hole was undermined shortly after on December 19, 2019. Approximately 0.5 m^3/min, methane production was measured one month before undermining. Goaf gas production increased to over 5.0 m^3/min on December 17, at a methane concentration of 95%, as shown in Fig. 4. Wellhead vacuum pressure peaked at 80 mm Hg on December 5, with an average vacuum of 59.1 mm Hg through the measured goaf gas production period (Fig. 4). Although placed very close to the No. 501 coal seam, methane concentration data suggests that TM5 produced high-quality goaf gas through December 17, 2019, after which measurements were suspended.

4.1.3 Drainage time and efficiency

Measured methane flow rates for the Cross-Measure Boreholes and the LRDD Boreholes, including dates when the ends of the LRDD Boreholes were under-mined, are shown in Fig. 5 throughout goaf gas recovery. Note that measurements of methane flow for both systems started September 13 and extended through February 28, 2020 (169 days Period of Goaf Gas Recovery). Between October 1 and December 17, 2019, methane flow rates were measured for each individual LRDD Borehole "("Individual LRDD Measurement Data Period")" as shown in Fig. 5. Following December 17, 2019, only measurements to derive the total methane flow rate for the LRDD Borehole System were collected.

Over the period of goaf gas recovery, the LRDD Boreholes produced 2.3 times the volume of methane produced by the Cross-Measure Boreholes. The average production rate of the Cross-Measure Boreholes and the LRDD Boreholes was 3.75 m^3/min, and 8.6 m^3/min, respectively. The cumulative methane production by both goaf gas drainage systems for Longwall Panel I-C is presented in Table 1.

4.2 Influence of technical and reservoir parameters on drainage performance

The performance of the five LRDD Boreholes was compared considering their lateral placement across Longwall I-C, their vertical placement above the active mining seam, and reservoir parameters. Performance relates to goaf gas and methane recovery flow rates and the duration of production of the boreholes as the longwall is mined. Unlike conventionally drilled Cross-Measure Boreholes developed from gate roads with a much shorter production duration as wellheads and collars are not protected from active mining, the LRDD Boreholes produced goaf gas for an extended period as the longwall panel was mined.

LRDD Boreholes are typically drilled along the longitudinal axis of the longwall panel between the ventilation return gate road and mid-panel to target strata that will be under tension when the goaf is formed (Zoback 2003; Zoback 2010; Bojarski 2014; Zoback et al. 2019). This study placed the LRDD Boreholes across the panel and angled them toward the advancing face, similar to Modified Cross-Measure Boreholes (Fig. 2). In all cases, overlying goaf boreholes produce gas inherent in the overlying strata before under-mining. Still, they are intended to produce goaf gas after under-mining and under a high vacuum. Goaf gas production from overlying boreholes depends on many factors, including lateral placement across the longwall goaf, vertical placement above the mining seam, the vacuum applied at the wellhead, geological conditions, and mining parameters (Zhang et al. 2019).

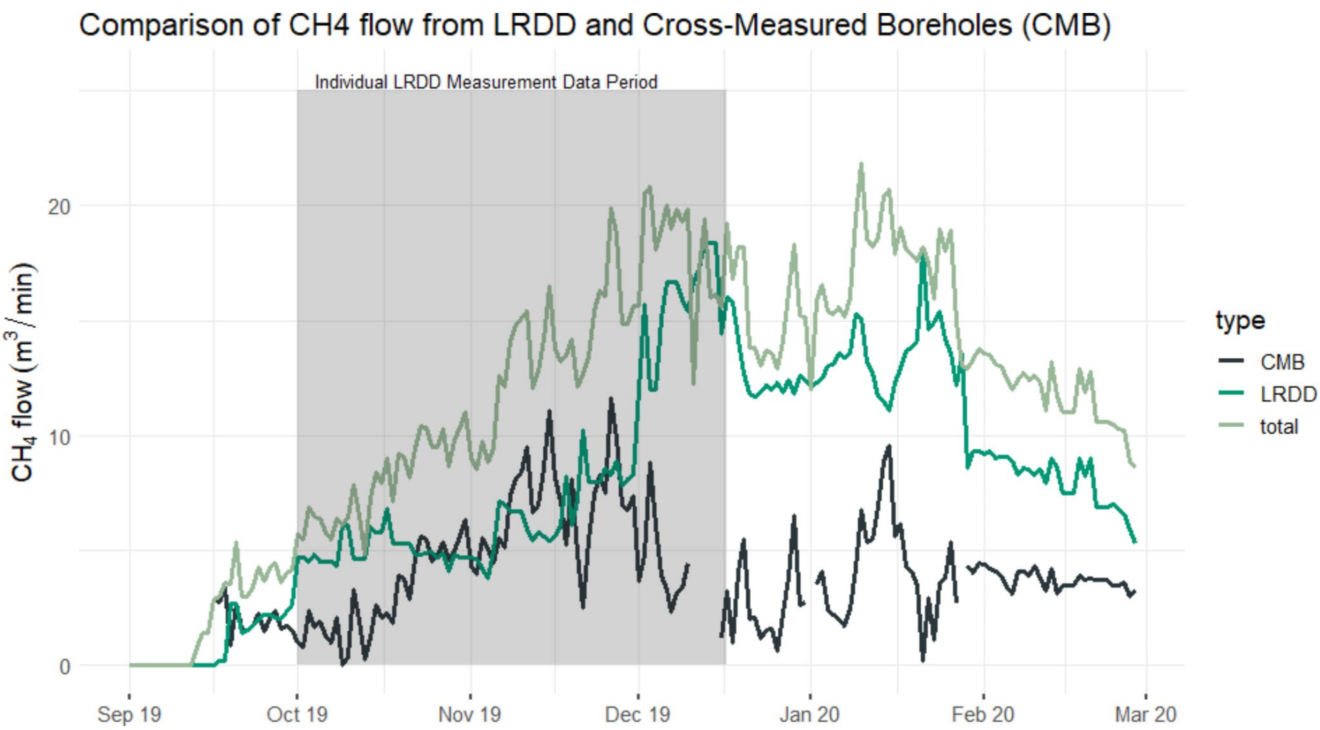


Fig. 5 Methane produced from cross-measure and LRDD boreholes over the longwall mining period. The date on the *x*-axis indicates the month and year

Table 1 Cumulative methane production from goaf gas drainage systems implemented on Panel I-C

Month	Methane production LRDD boreholes (m^3 CH_4)	Methane production cross-measure boreholes (m^3 CH_4)	Goaf degasification of coal panel IC (m^3 CH_4)
September	37,152.00	48,787.20	85,939.20
October	223,804.80	130,060.80	353,865.60
November	290,880.00	298,987.20	589,867.20
December	638,496.00	111,600.00	750,096.00
January (2020)	582,768.00	174,153.60	756,921.60
February (2020)	321,552.00	149,328.00	470,880.00
Total	2,094,652.80	912,916.80	3,007,569.60
Methane Produced by LRDD Boreholes		69.65%	
Methane Produced by Cross-Measure Boreholes		30.35%	

4.2.1 Effect of lateral placement

The LRDD Boreholes were developed over the higher pressure side of Longwall Panel I-C (over the ventilation intake gate road), at different lengths and angles relative to the longitudinal axis of the longwall panel, and therefore placed with different horizontal and longitudinal projections across the panel. Cross-Measure and Modified Cross-Measure Boreholes with longer longitudinal projections produce goaf gas for extended periods than boreholes with shorter longitudinal projections (Brunner et al. 2012). As measurements of individual LRDD Boreholes were suspended after December 17, the impact of longitudinal projection on the duration of production could not be assessed.

Cross-Measure and Modified Cross-Measure Boreholes with shorter horizontal projections over the low-pressure side of the longwall goaf (along the ventilation return gate road) are as effective as boreholes with longer horizontal projections (Brunner et al. 2012). Typically, these boreholes are drilled near the edges of the longwall panel, where the overlying strata are in tension once the goaf is formed, avoiding the zone of goaf re-compaction along the centerline of the panel (Brunner and Schwoebel 2001; Brunner et al. 2012). Table 2 indicates that although the LRDD Boreholes were placed along the goaf's high-pressure side, some boreholes were placed across the zone of goaf re-compaction (TM2, 3, and 5). However, the length of the horizontal projections of the LRDD Boreholes did not obviously impact the goaf

Table 2 LRDD Borehole Lateral Projections and Goaf Gas Production, including Measured Duration

Well	LRDD length (L), lateral placement (P), and horizontal (P_H), and longitiunal projection (P_L), and Face Length (F)						Goaf gas flow rate (Q)			Days on line production goaf gas	
	L (m)	P (m)	P_H (m)	P_L (m)	$P_{L/H}$ (m/m)	$P_{H/F}$ (%)	Q_{min} (m^3/min)	Q_{max} (m^3/min)	Q_{avg} (m^3/min)	Data range	Days
TM1a	402	61.5	30.7	53.3	1.7	0.19	0	3.4	1.8	Oct 1-Dec 17	78
TM2	401	146.2	104.8	101.9	1	0.66	1.8	7.9	4.5	Oct 1-Dec 17	78
TM4	301	71.5	56.8	43.3	0.8	0.36	2.4	6.1	4.5	Nov 17-Dec 17	31
TM3	300	100.2	98.4	19	0.2	0.62	4.8	7.5	6.2	Dec 1-Dec 17	17
TM5	302	99.2	99.1	-3.7	0.0	0.62	2	5.2	3.6	Dec 15-Dec 17	3

gas production rate. For example, TM4, with a horizontal projection of 36% relative to panel width (compared to over 60% for TM2, TM3, and TM 5), produced goaf gas at an equivalent average rate of LRDD Borehole TM2, as shown in Table 2.

4.2.2 Effect of vertical placement

The LRDD Boreholes were developed over the higher pressure side of Longwall Panel I-C in the overlying strata over the longwall abutment at Research Ramp I-C (intake gate road). They were terminated at different elevations over the top of the mining seam. Table 3 compares the impact of the LRDD Boreholes elevation on recovered gas quality and methane flow rates. The term DQ in Table 3 refers to the distance that the face was advanced beyond the end of the LRDD Borehole prior to the start of goaf gas production; H_{RR} and H_{TD} refer to the beginning and the end high of individual LRDD Boreholes.

Modified Cross-Measure and LRDD Boreholes are strategically placed in elevation based on the proximity of the lowest producing overlying gas source seam and the height of the rubble and fracture zones above the goaf (Brunner et al. 2000). The intent is to place the boreholes at an elevation where they remain intact and can produce goaf gas over their entire length when under-mined. If the overlying boreholes are placed too high in elevation (end of fracture zone), they are less effective at controlling goaf gas emissions into the 'longwall's ventilation system. This is caused by lower goaf permeability and the effective height of the low-pressure sink that they create in the goaf relative to the mining horizon. If the overlying boreholes are placed too low (near the rubble zone), they may not remain intact when undermined. Depending on longwall mining activities, they may produce goaf gas only from the end of the borehole and draw in ventilation air (An et al. 2016). The optimal elevation of overlying goaf boreholes is a function of lateral position over the longwall panel and is typically optimized by field trials (Brunner et al. 2000). Placement elevations between 20 and 30 m over the mining seam are typical depending on the lateral position. This, on the other hand,relies on the elevation of overlying source seams, the geo-mechanical characteristics of the overlying strata, and the formation of the goaf, which is affected by panel width, depth below the surface, mining height, adjacent mining, and mining rates (Brunner et al. 2000; Schumacher and Brunner 2012).

The analysis of the field data derived from evaluating the vertical placement of the LRDD Boreholes, the lengths of the boreholes under-mined until goaf gas is produced (D_Q), and the goaf gas flow rates and recovered gas concentrations revealed that:

(1) The highest recovered goaf gas quality was produced from the borehole placed at the highest elevation in the goaf. TM4 was placed at an average elevation of 41 m above the No. 501 coal seam and produced, on average, goaf gas at a methane concentration of 94% by volume in the air over its measured production period of 31 days.
(2) The lowest recovered gas quality was produced from the boreholes placed at the lowest elevation. TM1a and TM5 were placed at an average elevation of 13 m above the No. 501 coal seam. At the total measured depth of 402 m, TM1a was placed 9 m above the No. 501 coal seam. At the total measured depth of 302 m, TM5 was placed 3.6 m above the No. 501 coal seam. These boreholes produced goaf gas at a weighted average concentration of 69% methane.
(3) The highest goaf gas production was obtained from TM3, which was placed at an average elevation of 24.4 m above the No. 501 coal seam and produced on average 6.2 m^3/min. TM3 produced goaf gas at an average concentration of 79% methane in air by volume through its measured goaf gas production period of 17 days.
(4) The lowest methane production was obtained from TM1a and TM5, which were placed at an average elevation of 13 m above the No. 501 coal seam and produced on average 2.7 m^3/min of goaf gas during their measured goaf gas production periods.
(5) Distance under-mined to the start of goaf gas production depends on the elevation of the end of the overlying borehole. The under-mined distance is greatest for TM4

Table 3 LRDD Vertical Placement and Goaf Gas and Methane Production Rates and Methane Concentrations

Well	LRDD vertical placement (m)			Start of gas production (D_Q) and goaf gas flow rates (Q) (m^3/min)				Methane flow rates (m^3/min)			Methane concentration (%)		
	H_{RR}	H_{TD}	H_{avg}	D_Q	Q_{min}	Q_{max}	Q_{avg}	M_{min}	M_{max}	M_{avg}	C_{min}	C_{max}	C_{avg}
TM1	17.5	9	13.3	0	0	3.4	1.8	0	3.4	1.4	15	95	42
TM2	36.5	26	31.3	18.4	1.8	7.9	4.5	1.1	7.1	3.1	65	98	88
TM4	38.6	44.1	41.4	59.8	2.4	6.1	4.5	0.9	5.4	3.9	85	98	94
TM3	20.3	28.5	24.4	31.7	4.8	7.5	6.2	4.1	7.2	5.8	28	98	79
TM5	22	3.6	12.8	-21.5	2	5.2	3.6	0.2	4.9	2.2	70	95	83

(almost 60 m from the end of the borehole) which was placed at an elevation of 44.1 m (end of the borehole) above the top ofthe No. 501 coal seam. Boreholes TM1a, TM2, and TM3 (end of borehole elevations 9 m, 26 m, and 28.5 m over coal seam 501, respectively), produced goaf gas after under-mining the ends of the boreholes for distances of 0 m, 18.4 m, and 31.7 m, respectively. TM5 produced goaf gas prior to under-mining the end of the borehole as it was placed at an obtuse angle relative to the longwall panel and advancing face.

4.2.3 Effect of reservoir parameters

To better understand the effect of reservoir parameters on gas drainage from LRDD Boreholes, a 3D distribution of lithotypes was developed, reproducing the spatial distribution of the lithotypes in the study area. This 3D lithotype model guided the modeling of porosity and permeability distribution as there is a general strong link between the lithological type of rock and its petrophysical characteristics (Abdulmutalib et al. 2015).

The model of lithotypes distribution was constructed based on lithofacies profiles from 6 horizontal boreholes and five short research vertical boreholes drilled from the coal seams. In the borehole profiles, five main lithotypes were distinguished, further marked in the model with a specified color and numerical code: 0 – coal (gray), 1 – coal shale (blue), 2 – shale (purple), 3 – sandy shale (beige), 4 – sandstone (yellow).

The 3D model was developed using geostatistical tools available in the Petrel software utilizing a stochastic algorithm – Sequential Indicator Simulation SIS to estimate the spatial distribution of lithofacies. Visualization of the 3D model of lithotypes is shown in Fig. 6.

In the profile of the drained interval, two zones can be distinguished, (1) the zone, directly overlying coal seam 501 with a higher contribution of sandstones which, according to the modeling results, contribute approximately 64% (Fig. 6b left), and (2) the zone between coal seams 418 and 416, which is dominated by shales, contributing approximately 60% (Fig. 6b right).

Based on well-log interpretations from borehole W PIG-1 (Fig. 7a), drilled within the I-C field at the Staszic-Wujek Coal Mine, the derived porosity for sandstones ranges from 0.2% to 15.0%, with an average of 7% (Fig. 7b). The derived permeability varies from 0.0001 to 33 mD with an average permeability of 3.9 mD (Fig. 7c) (DD-MET report 2021). Note that the estimates of porosity and permeability from the well logs fall within the ranges reported by Jureczka et al. (2015), and the average values of these petrophysical parameters are generally consistent (Wojcicki 2013).

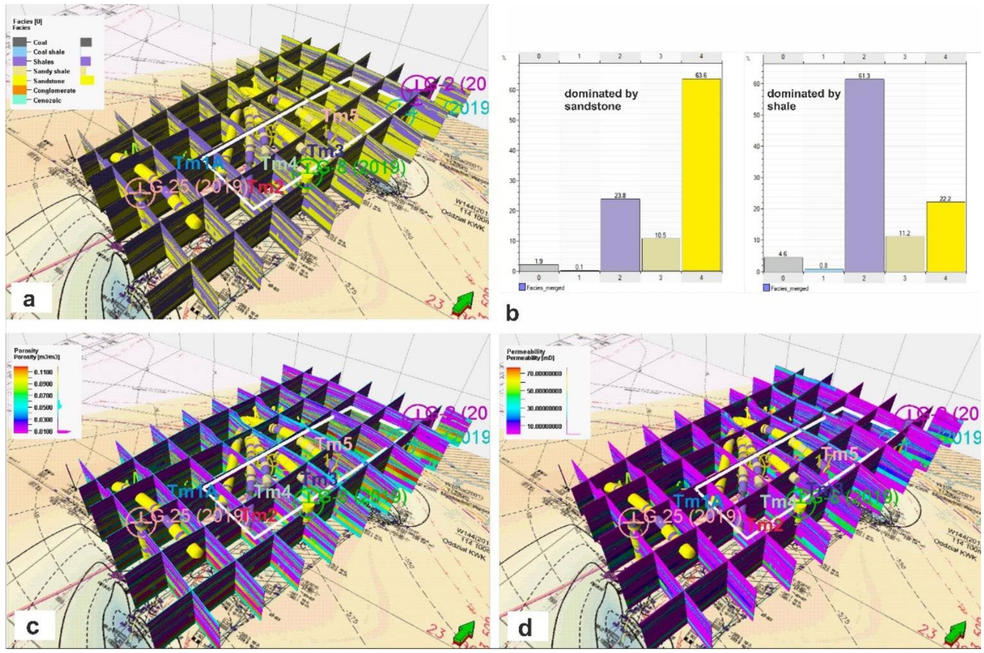


Fig. 6 **a** Visualization of 3D distribution of lithotypes; **b** With histograms of zone dominated by sandstones (left) and shales (right); **c** 3D models of porosity; **d** permeability

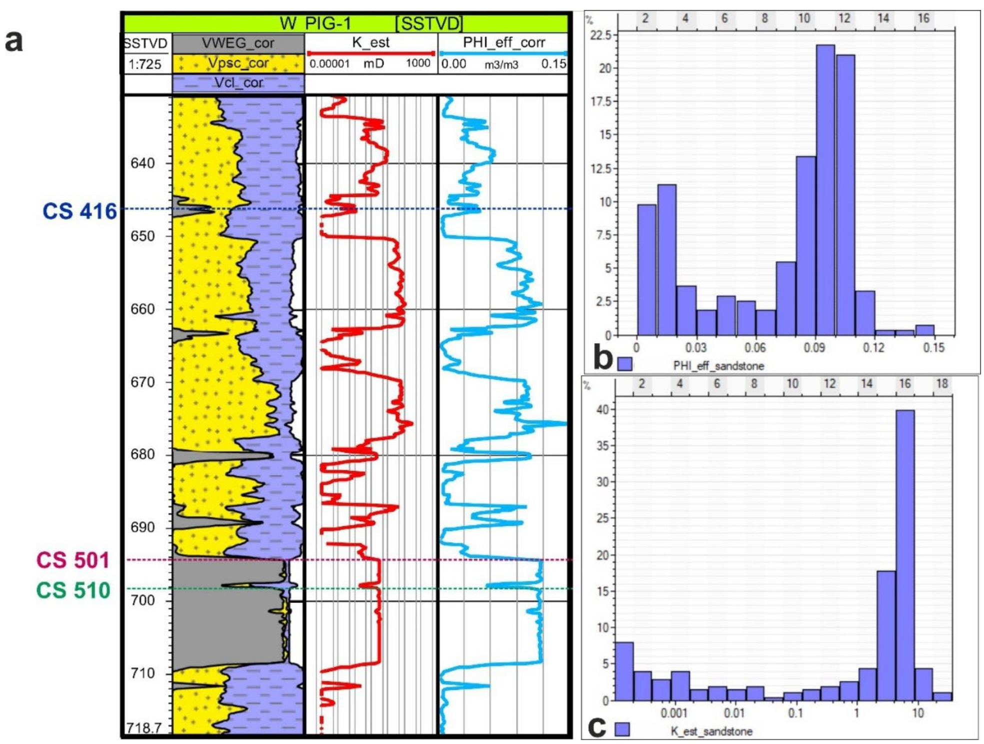


Fig. 7 Lithological profile of the strata subjected to drainage by the LRDD boreholes with estimated petrophysical properties in the reference borehole W PIG-1: **a** With histograms depicting the distribution of effective porosity; **b** Permeability; **c** In the sandstone lithotype in the drainage zone

The best production rates were achieved from the LRDD Borehole TM3, which was drilled through the sandstone lithotype with the best reservoir properties (Table 4). The high average porosity and permeability of the sandstone layers play a significant role in methane storage and migration (Zhang et al. 2019; Liu et al. 2013). Optimal contact within the sandstone lithotype along the well trajectory was also achieved for TM1a and TM5. However, these wells exhibited low drainage performance due to their vertical placement above the No. 501 coal seam (in the rubble zone) (Table 4). The moderate production performance achieved for TM2 and TM4 could be the result of the contribution of carbonaceous shale in the borehole lithological profile, which deteriorates reservoir properties and gas migration.

The high production rates obtained from TM3 and the moderate performance from TM2 and TM4 were also attributed to drilling in the direction closest to the maximum principal horizontal stress, which in the oil and gas industry

Table 4 Lithology assemblage, drainage performance parameters, and the azimuth of LRDD Boreholes

Well	Coal (%)	Coal shale (%)	Shale (%)	Sandy shale (%)	Sandstone (%)	Q_{avg} (m^3/min)	C_{avg} (%)	Vac_{avg} (mm Hg)	Azimuth (°)	H_{avg} (m)
TM1a	6	0	29	13.4	51.6	1.8	42	48.4	156	13.3
TM2	8.6	1	41.4	19.1	29.9	4.5	88	49.5	152	31.3
TM3	6.7	3	22.7	12.7	54.9	6.2	79	59.7	124	24.4
TM4	6.1	0	38.9	29.9	25.1	4.5	94	58.3	130	41.4
TM5	3.5	0.2	23.8	15.8	56.7	3.6	83	48.5	93	12.8

proved to provide borehole stability in normally stressed sedimentary basins (Tiwari, 2013).

The stress regime in the study area was determined based on local in situ stress measurements in the coal mine, matching the findings by Zuberek et al. (1997) and Dubiński et al. (2019). These in situ measurements provided the principal horizontal stress σh direction (approximately 141°), which in this case would be the optimal direction for horizontal well drilling from a stability perspective.

The enhancement of the transport properties of the strata is likely to occur due to disturbance of the stress and strain field around the boreholes due to longwall mining. Depending on the detailed mechanical properties of the strata and the pressures in these zones, these changes can manifest differently (Wei and Zhang 2010; Szott et al. 2018; Zhang et al. 2019). To assess the detailed geomechanical effects of mining on enhancing transport properties of the overlying strata, an analysis involving numerical methods and coupling of geomechanical and fluid flow models will be considered in the ongoing works in the project.

5 Conclusions

The results proved the efficiency of LRDD Boreholes and demonstrated a feasible technology for goaf gas control in the Staszic-Wujek Coal Mine, bringing valuable environmental benefits and ensuring the effectiveness of the coal production process. The drainage efficiency during the six months of LRDD borehole operation was high, with an average of about 70% compared to Cross-Measure Boreholes (30%).

The highest recovered goaf gas quality was obtained for LRDD Borehole TM4, which was placed at an average elevation of 41 m above coal seam 501 and produced goaf gas at a methane concentration of 94% by volume. Similar performance was reported for LRDD Borehole TM2, placed at an average elevation of 31.3 m above the No. 501 coal seam (88% of methane concentration).

The highest goaf gas production, an average of 6.2 m^3/min, was achieved by LRDD borehole TM3. Similar to LRDD Boreholes TM4 and TM2, this borehole targeted the optimal location within the fracture zone above the No. 501 coal seam (average elevation of 24.4 m above the top of the seam). In addition, LRDD Borehole TM3 was most effectively drilled through the sandstone lithotype with the best reservoir properties, providing the best drainage performance.

All three LRDD Boreholes (TM2, TM3, and TM4) were drilled close to the maximum principal horizontal stress direction (approximately 141°), enhancing borehole stability in the disturbed stress and strain field around the boreholes during under-mining.

The lowest goaf gas production was reported for TM1a and TM5, which were placed at an average elevation of 13 m above the No. 501 coal seam. Although these LRDD Boreholes were placed in a favorable zone dominated by sandstones, they were placed near the rubbished zone of the goaf, which affects goaf gas drainage performance and may draw in ventilation air.

Acknowledgements The authors would like to express their gratitude to the research partners at Coal Mine Staszic-Wujek (PGG S.A.) for their contribution to the project, and to Marek Stadmuller for valuable discussions and well logs interpretation.

Compliance with Ethical Standards

This research was carried out as part of the European Commission Research Fund for Coal and Steel (RFCS) funded project "Advanced methane drainage strategy employing underground directional drilling technology for major risk prevention and greenhouse gases emission mitigation" GA:847338-DD-MET-RFCS-2018/RFCS-2018.

We confirm that this work is original and has not been published elsewhere nor is currently under consideration for publication elsewhere.

Conflict of interest The authors declare that they have no conflict of interest.

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