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Rozprawa doktorska

Wpływ budowy geologicznej złóż węgla na metanowość wybranych kopalń Górnośląskiego Zagłębia Węglowego

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A. Lista publikacji naukowych doktoranta wchodzących w skład rozprawy doktorskiej:

- Kędzior S., **Dreger M.**, 2019: Methane Occurrence, Emissions and Hazards in the Upper Silesian Coal Basin, Poland, International Journal of Coal Geology, vol. 211, 103226. Lista MNiSW: 140 pkt, Impact Factor (IF): 6.3
- **Dreger M.,** 2020: Variabilities in Hard Coal Production and Methane Emission in the Mysłowice-Wesoła Mine, Journal of Mining Science, 2021, Vol. 57, No. 3, s. 421–436, Lista MNiSW: 70 pkt, Impact Factor (IF): 0.85
- **Dreger M.,** Kędzior S., 2021: Methane emissions against the background of natural and mining conditions in the Budryk and Pniowek mines in the Upper Silesian Coal Basin (Poland), Environmental Earth Sciences, 80:746, Lista MEiN: 70 pkt, Impact Factor (IF):2.78
- Kędzior S., **Dreger M.,*** 2022: Geological and Mining Factors Controlling the Current Methane Conditions in the Rydułtowy Coal Mine (Upper Silesian Coal Basin, Poland), Energies, 2022, 15, 6364, Lista MEiN: 140 pkt, Impact Factor (IF): 3.252
- **Dreger M.,** 2021: Methane emissions and hard coal production in the Upper Silesian Coal Basin in relations to the greenhouse effect increase in Poland in 1994-2018, Mining Science, vol. 28, 2021, s 59–76, Lista MEiN: 70 pkt, Impact Factor (IF): 0.46

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B. Lista pozostałych publikacji naukowych doktoranta:

- **Dreger M.,** 2019: Methane emission in selected hard-coal mines of the Upper Silesian Coal Basin in 1997-2016. Geology, Geophysics & Environment, 45, 2, s 121–132, Lista MNiSW: 20 pkt
- **Dreger M.,** Kędzior S., 2019: Methane emissions and demethanation of coal mines in the Upper Silesian Coal Basin between 1997 and 2016. Environmental & Socio-Economic Studies, 7, 1, s 12–23, Lista MNiSW: 20 pkt
- **Dreger M.,** 2020: Changes in the methane emissions and hard coal output in the Brzeszcze mine (the Upper Silesian Coal Basin, Poland), Geology, Geophysics and Environment, vol. 46 (2): 159–174, Lista MNiSW: 20 pkt

Spis treści

STRESZCZENIE:

Emisja metanu do wyrobisk górniczych spowodowana skomplikowanymi warunkami geologiczno-górniczymi staje się coraz poważniejszym problemem w obecnym górnictwie węgla kamiennego. Kopalnie eksploatujące węgiel w Górnośląskim Zagłębiu Węglowym (GZW), emitują ponad 700 – 800 mln m^3 metanu rocznie, z czego 70% trafia wprost do atmosfery. Zakłady górnicze wydobywające węgiel kamienny cechują się odmienną budową geologiczną. Występowanie, miąższość oraz charakter litologiczny utworów nadkładu, zmienność litologii, a także skomplikowany charakter tektoniczny karbonu produktywnego kształtują rozkład metanonośności w złożu i wraz ze zmieniającymi się czynnikami górniczymi, takimi jak np. głębokość eksploatacji mają zasadniczy wpływ na wielkość emisji metanu (metanowości) do wyrobisk górniczych. Kopalnie, które zostały szczegółowo przeanalizowane pod kątem budowy geologicznej oraz warunków górniczych charakteryzują się wysoką metanowością bezwzględną, co czyni je reprezentatywnymi dla wybranych rejonów GZW. Wysokie ciśnienie metanu charakteryzujące głębokie partie złóż oraz pokłady znajdujące się pod szczelnym nadkładem, skutkuje wysoką emisją metanu do wyrobisk podczas robót górniczych. Jednocześnie wraz ze wzrostem głębokości wzrasta zarówno temperatura górotworu oraz ciśnienie w złożu. Równowaga między tymi dwoma czynnikami zwana optimum metanonośnym, sprzyjająca akumulacji metanu, w GZW występuje na głębokości-800 – 1500 m z możliwością wahań. Na poziomach wydobywczych rzędu >1000 m malejąca pojemność sorpcyjna węgli oraz prawie 100% nasycenie pokładów metanem, przekłada się na wysoką emisję podczas eksploatacji. Dodatkowo, metan jako silny gaz cieplarniany, jest w ponad 20% emitowany przez górnośląskie kopalnie (w odniesieniu do całego kraju), co każe się zastanowić nad jeszcze lepszym wykorzystaniem metanu kopalnianego. Coraz głębsza eksploatacja złóż węgla kamiennego w GZW prowadzona jest w skomplikowanych warunkach geologiczno-górniczych, co nasila oddziaływanie zagrożeń naturalnych, w tym metanowego. Niezwykle istotne jest zatem zbadanie wpływu budowy geologicznej złóż węgla kamiennego na metanowość kopalń, wywierającą wpływ na wielkość zagrożenia gazowego w podziemnych zakładach górniczych.

ABSTRACT:

Methane emission to mining works, in modern mining era, has been a serious problem caused by complex geological structure and mining factors. Collieries located in the Upper Silesian Coal Basin (USCB) are characterised by diversified geological structure and emit over 700 – 800 mln m^3 of methane annually and 70% of emitted gas goes directly to the atmosphere. The methane content in the rock mass is controlled by e.g. Miocene sediments sealing the coal bearing series and complicated lithology and tectonics of Carboniferous strata. These factors along with e.g. depth of mining control the methane emission into the mine workings. To analyse the causes of methane emissions, the representative collieries were chosen. The geological and mining factors were carefully investigated and conclusions were set up. Deeper parts of the rock mass, under the hermetic Miocene screen are characterised by higher methane pressure what results in greater methane emission during mining. The temperature and hydrostatic pressure increase with depth. The balance between them is called the optimum methane zone. Under the depth of 1000m, the methane emission increases as a result of almost 100% coal saturation in methane and decreasing sorption capacity at the same time. Methane is also the strong greenhouse gas and 20% of it is emitted by the USCB coal mines. Deeper coal production in complex mining and geological conditions increases the impact of natural hazards, including methane. The influence of the geological structure is extremely important to study, because it affects the methane emission in the underground coal mines.

1. Wstęp

Górnośląskie Zagłębie Węglowe (GZW), jako najbardziej uprzemysłowiony region w Polsce produkuje najwięcej węgla energetycznego oraz koksowego w Europie. Obszar zajmujący łącznie 7250 km^2 (5650 km^2 znajduje się po stronie polskiej) charakteryzuje się bogactwem zasobów naturalnych oraz skomplikowaną budową geologiczną, która wpływa na bezpieczeństwo robót górniczych (Jureczka, Nowak 2016). Węgiel kamienny jest jednym z najważniejszych surowców energetycznych, z którego produkowane jest ciepło, energia elektryczna oraz koks. Eksploatacja węgla oraz roboty przygotowawcze prowadzone są z roku na rok na coraz większych głębokościach, na których następuje zintensyfikowanie oddziaływania zagrożeń naturalnych (Dreger 2019; Dreger, Kędzior 2019). Jednym z najpoważniejszych, jakie występuje we współczesnym światowym oraz polskim górnictwie, jest zagrożenie metanowe. W 2020 roku spośród 20 kopalń eksploatujących węgiel w GZW 15 zaklasyfikowano jako metanowe (GIG 1995-2021). Metan kopalniany (*Coal Mine Methane – CMM*) uwalniany do wyrobisk górniczych, zarówno podczas eksploatacji węgla, jak i po jego zaprzestaniu (zroby), jest źródłem zwiększonego zagrożenia metanowego w rejonie prowadzonych prac przygotowawczych, eksploatacyjnych oraz w pokładach sąsiednich na skutek odprężenia górotworu i migracji gazu poprzez sieć spękań oraz uskoków (Coolen 2003; Karacan i in. 2011; Krause, Smoliński 2013). Metan kopalniany może być także źródłem cennego gazu pozyskiwanego w procesie odmetanowania (produkcja energii elektrycznej, ciepła bądź chłodu). Odmetanowanie prowadzone w pokładach wysokometanowych pozwala na bezpieczniejszą pracę poprzez redukcję ciśnienia złożowego oraz zmniejszenie nasycenia pokładu metanem (Kozłowski, Grębski 1982; Dreger, Kędzior 2021).

Pionowy rozkład metanonośności w złożach węgla kamiennego GZW, charakter litostratygraficzny oraz tektoniczny części fałdowej, jak również blokowej zagłębia są niejednorodne, co skutkuje zróżnicowanym uwalnianiem się CH_4 podczas eksploatacji węgla. Skomplikowana budowa geologiczna, w tym obecność porowatych utworów piaskowcowych, ma również istotny wpływ na nasycenie złoża metanem oraz migrację gazu do sąsiednich, jak i wyżej oraz niżej ległych pokładów węgla i skał otaczających (np. Krause, Smoliński 2013; Dreger, Kędzior 2021).

Celem pracy doktorskiej jest określenie wpływu budowy geologicznej złóż węgla GZW na wielkość emisji metanu do wyrobisk górniczych. Emisja metanu (metanowość) jest jednym z najpoważniejszych problemów we współczesnym górnictwie węgla kamiennego zarówno na świecie, jak i w GZW. W latach 1994-2020 sumaryczna metanowość całkowita kopalń GZW wahała się od ponad 700 mln m^3/rok do przeszło 900 mln m^3/rok, przy jednoczesnym stałym spadku produkcji węgla kamiennego z ponad 130 do 50 mln rocznie (GIG 1995-2021; Kędzior, Dreger 2019). Zaangażowanie tektoniczne złóż węgla kamiennego na tle urozmaiconej budowy geologicznej ma zasadniczy wpływ na rozkład metanonośności złoża oraz metanowość całkowitą podczas eksploatacji złóż węgla (Tarnowski 1898; Kędzior, Dreger 2019). Uskoki regionalne o zrzutach >300 m oraz lokalne, o dużo mniejszych zrzutach, odpowiadają za migrację metanu do środowiska ściany, zmieniając rozkład gazonośności w złożu oraz intensyfikują zagrożenie metanowe. Jednocześnie, zaburzenia tektoniczne mogą mieć charakter uszczelniający, akumulując metan w obrębie nieciągłości. W trakcie robót górniczych metan - jako gaz wolny - zostaje uwolniony do wyrobiska, zwiększając metanowość względną oraz bezwzględną (Tarnowski 1971, 1989). Charakter litologiczny utworów karbońskich oraz nadkładu wyrażony przez drożność lub szczelność skał przyczynia się do odgazowania płytszych części górotworu (tzw. model północny pionowego rozkładu metanonośnego), bądź uwięzienia migrującego gazu pod szczelnym nadkładem mioceńskim, wtórnie nasycając złoża metanem (model południowy) (Kotas 1994; Kędzior 2012; Dreger, Kędzior 2021; Kędzior, Dreger 2022).

Podczas badań pochylono się również nad problemem wpływu emisji metanu z kopalń GZW do atmosfery w stosunku do całkowitej emisji gazów cieplarnianych w Polsce. Metan - jako gaz cieplarniany - ma od 25 do 35 razy silniejszą moc radiacyjną niż dwutlenek węgla (np. Kożuchowski, Przybylak 1995; Archer 2011), a światowe górnictwo węgla kamiennego odpowiada za ok. 6 – 11% całkowitej emisji CH_4, do atmosfery (np. Best Practice Guidance 2010; US EPA 2019). Eksploatacja węgla kamiennego z pokładów wysokometanowych obarczona jest wysoką emisją metanu do atmosfery, co w przyszłości może wiązać się z płaceniem kar oraz sankcji za każdą wyemitowaną tonę CH_4 zgodnie z nowym projektem Unii Europejskiej. Rozliczanie emisji gazu według ekwiwalentu CO_2 będzie stanowiło duże wyzwanie dla całego polskiego górnictwa węglowego (np. Dreger 2020, 2021).

2. Uzasadnienie podjęcia problemu badawczego na tle dotychczasowego stanu wiedzy

Badania nad zagadnieniem metanonośności, metanowości oraz budowy geologicznej GZW były prowadzone przez wielu naukowców, zarówno krajowych jak i zagranicznych. Dotychczasowe badania skupiały się przede wszystkim na rozpoznaniu rozkładu metanonośnego we wszystkich częściach zagłębia (np. Tarnowski 1989; Kotas 1994; Kędzior 2009). Obiekt zainteresowań stanowiły strefy wtórnie nasycone metanem, znajdujące się pod szczelnym nakładem mioceńskim (np. Kędzior 2012) oraz strefy pierwotne, w głębszych partiach profilu (np. Kotas 1994; Kotarba, Ney 1995; Kotarba 2001). Podział GZW przez Kotarbę i in. (1995) na siedem stref gazonośnych uwidocznił zmiany oraz różnice warunków geologiczno-gazowych każdej ze stref. Badania gazonośności złóż stały się podstawą zarówno do klasyfikacji kopalń pod względem zagrożenia metanowego jak i wyjaśnienia genezy metanu w złożach, dróg jego migracji oraz sprecyzowania kwestii gospodarczego wykorzystania. Drugi rodzaj badań obejmował zagrożenie metanowe występujące w wyrobiskach górniczych, sposób ich zwalczania, jak również zapewnienia bezpiecznych warunków podczas robót górniczych w złożu, emisję metanu do atmosfery, odmetanowanie złóż oraz wykorzystanie ujętego gazu (np. Kozłowski, Grębski 1982; Krause, Kobiela 1995; Gawlik, Grzybek 2002). W pracy doktorskiej skupiono się na czynnikach geologicznych oraz górniczych kształtujących zmiany emisji metanu do wyrobisk w czasie w wybranych kopalniach GZW. Zakłady górnicze zostały tak dobrane, aby reprezentowały większość wydzielonych przez Kotarbę i in. (1995) regionów gazonośnych GZW.

Metan wolny oraz zaadsorbowany w węglu i skałach otaczających występuje w górotworze w stanie równowagi wyrażonej przez ciśnienie gazu. Zaburzenie pierwotnej gazonośności złoża wywołane aktywnością tektoniczną czy eksploatacją górniczą skutkuje zmianą rozkładu ciśnienia hydrostatycznego i w konsekwencji migracją metanu, a także emisją do wyrobisk górniczych w ilości przekraczającej objętość zaadsorbowanego metanu w samym węglu (np. Gawlik, Grzybek 2002; Krause 2005; Krause, Smoliński 2013, Kędzior 2015). Eksploatacja węgla prowadzona jest z roku na rok na coraz większej głębokości, nierzadko przekraczającej 1000 m, co wiąże się z nasileniem zagrożeń naturalnych. Wysoka gazonośność głębszych partii złóż połączona z metanem migrującym z warstw otaczających sprawiają, że wydobycie węgla z każdym rokiem jest coraz trudniejsze, wymagające wzmożonego wysiłku technologicznego i obarczone większym ryzykiem. Stały spadek wydobycia węgla w GZW spowodowany zamykaniem lub łączeniem zakładów, wyeksploatowaniem łatwo dostępnych złóż i sięganiem do trudno dostępnych, silnie metanonośnych pokładów skutkuje wzmożoną metanowością względną w całym zagłębiu. Emisja metanu z każdą toną wydobytego węgla w GZW rośnie, przekraczając 10 m^3/tonę w 2007 roku i konsekwentnie 17 m^3/tonę w 2020 (GIG 1995-2021; Kędzior, Dreger 2019). Trudne warunki geologiczno-górnicze wzmagają emisję metanu do wyrobisk górniczych, sprawiając, że wydobycie każdej tony węgla obarczone jest coraz większą emisją gazu do środowiska ściany.

Skomplikowana geologia złóż węgla kamiennego GZW stała się obiektem pracy doktorskiej, celem przeanalizowania jej wpływu na wielkość wydzielania się metanu do wyrobisk górniczych. Rozpoznanie wpływu tektoniki oraz litologii na metanowość wybranych kopalń pozwoli dobierać profilaktykę oraz prognozować zagrożenie metanowe podczas przyszłych robót górniczych. Poznanie źródeł i przyczyn rosnącego zagrożenia naturalnego, jakim jest zagrożenie metanowe, stanowi niewątpliwie silny fundament nowoczesnego górnictwa węgla kamiennego nie tylko w GZW, ale także w górnictwie światowym.

3. Hipotezy badawcze

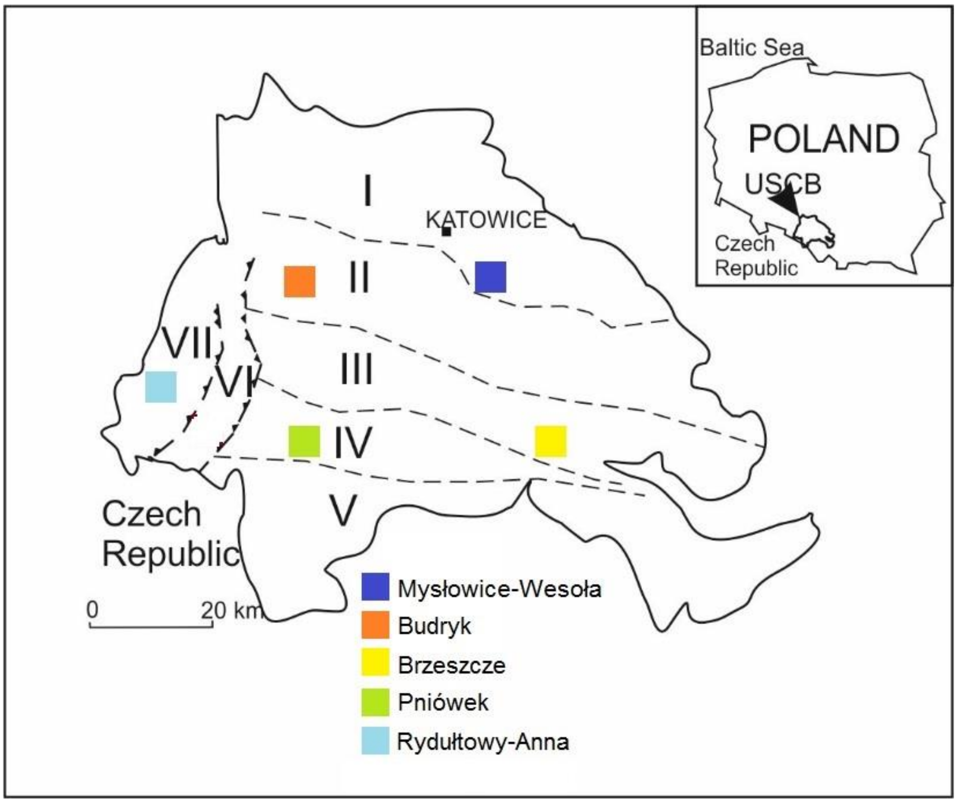
Główne hipotezy badawcze pracy doktorskiej są następujące:

- Czynniki geologiczne wyrażone przez charakter litologiczny nadkładu oraz serii węglonośnej, jak i tektonikę uskokową wywierają wpływ na wielkość emisji metanu.
- Obecność uskoków, nasunięć oraz przepuszczalnych utworów piaskowcowych stanowi czynnik kontrolujący migrację metanu pomiędzy pokładami, wtórnie nasycając bądź odgazowując pokłady węgla, co przekłada się na metanowość podczas robót górniczych w złożu.
- Wpływ czynników górniczych na emisję metanu (koncentracji wydobycia, długości i postępu ścian, głębokości eksploatacji) nakłada się na oddziaływanie warunków naturalnych eksploatacji (czynników geologicznych).
- Projektując wyrobiska korytarzowe oraz eksploatacyjne, należy brać pod uwagę również warunki geologiczne determinujące rozkład gazonośności w złożu.

4. Źródła danych oraz metody badawcze

W celu zweryfikowania hipotez badawczych wykorzystano podział GZW na strefy gazonośne wg Kotarby i in. (1995), dzięki czemu większość stref była reprezentowana przez jedną kopalnię charakteryzującą się ciągłością eksploatacji, możliwie najwyższym rocznym wydobyciem węgla kamiennego oraz emisją metanu w całej strefie (Rys. 1). Biorąc pod uwagę wyżej wymienione czynniki, do szczegółowych badań wybrano następujące zakłady:

- Mysłowice-Wesoła (PGG S.A.) (strefa I),
- Budryk (JSW S.A.) (strefa II),
- Brzeszcze (Tauron Wydobycie) (strefa III),
- Pniówek (JSW S.A.) (strefa IV),
- Rydułtowy (PGG S.A.) (strefa VII).



Rys.1 Strefy gazonośne Górnośląskiego Zagłębia Węglowego (zmod. Kotarba i in. 1995)

Na potrzeby rozprawy doktorskiej strefa VI została połączona z VII ze względu na podobny rozkład gazonośności złóż w obu strefach oraz na stosunkowo niską metanowość oraz wydobycie KWK Marcel w strefie VI, natomiast strefa V nie jest reprezentowana przez żadną kopalnię ze względu na krótkotrwałą pracę jedynego zakładu w tej części zagłębia – KWK Morcinek. Kopalnia Brzeszcze została objęta badaniami jako zakład reprezentacyjny dla strefy III, ale ze względu na podobny model rozkładu pionowego gazonośności złoża oraz trend zmian metanowości kopalni w czasie, jak dla kopalni Mysłowice-Wesoła, postanowiono nie włączać jej do rozprawy. Szczegółowe dane dla każdej kopalni pozyskiwano indywidualnie z zakładów górniczych, korzystając z dokumentacji geologicznych oraz z zestawień działów mierniczo-geologicznych i wentylacyjnych ze szczególnym uwzględnieniem: budowy geologicznej i naturalnej gazonośności złoża, danych wentylacyjnych kopalni (metanowość), danych techniczno-ruchowych (średnie postępy wydobycia, głębokości eksploatacji, liczba ścian, itp.). Każdy zakład górniczy charakteryzuje się odmiennymi warunkami geologiczno-gazowymi oraz wartościami metanowości, co pozwala przedstawić te kopalnie jako reprezentatywne dla całego zagłębia. Dane dodatkowe, zebrane dla wszystkich kopalń wydobywających węgiel kamienny w GZW od 1994 roku, pozyskano z *Raportów rocznych o stanie podstawowych zagrożeń naturalnych i technicznych w górnictwie węgla kamiennego* (GIG, 1995-2021) Głównego Instytutu Górnictwa w Katowicach oraz *Oceny stanu bezpieczeństwa pracy, ratownictwa górniczego oraz bezpieczeństwa powszechnego w związku z działalnością górniczo-geologiczną* publikowane przez Wyższy Urząd Górniczy w Katowicach (WUG 2015-2020). Dane te oraz charakterystyka geologiczno-górnicza całego GZW pozwoliła na poglądowe rozeznanie co do m.in. metanowości oraz wielkości wydobycia węgla kamiennego, co skutkowało wyborem reprezentatywnych kopalń dla poszczególnych stref gazonośnych zagłębia.

Zebrane dane zostały szczegółowo przeanalizowane pod kątem rocznych emisji metanu z wyrobisk górniczych (metanowość całkowita, wentylacyjna oraz odmetanowanie) i zestawione z wydobyciem węgla kamiennego, głębokością robót górniczych, obecnością i zasięgiem uskoków, stratygrafii oraz litologią utworów karbońskich, jak i miąższością oraz charakterem litologicznym nadkładu.

Litologia, tektonika oraz stratygrafia złoża mają silny wpływ na rozkład ciśnienia w górotworze, co skutkuje wyższą intensywnością desorpcji metanu z węgla przy wysokim ciśnieniu oraz gazonośności złoża. Potwierdziły to analizy próbek z KWK Budryk oraz Pniówek. Badania te wykazały wzrost zarówno ciśnienia w pokładzie oraz intensywności desorpcji gazu wraz ze wzrostem gazonośności, co przy zwiększającej się głębokości prowadzonych robót górniczych może mieć istotny wpływ na wielkość emisji metanu do wyrobisk, a co za tym idzie - na bezpieczeństwo podczas prowadzonych prac eksploatacyjnych oraz przygotowawczych (Dreger, Kędzior 2021). Dyfuzyjność węgli oraz pojemność sorpcyjna określająca objętość metanu możliwą do zaadsorbowania w wewnętrznej strukturze węgla przy zmiennym ciśnieniu i temperaturze, została zbadana dla próbek węgla z KWK ROW Ruch Rydułtowy na aparacie sorpcyjnym IGA 001 należącym do Centralnego Laboratorium Pomiarowo-Badawczego sp. z o.o. w Jastrzębiu-Zdroju. Pełna izoterma sorpcji została wykonana w celu zbadania maksymalnej pojemności sorpcyjnej węgla przy ciśnieniu hydrostatycznym panującym w górotworze oraz wysyceniu węgla metanem, co pozwoliło określić stopień zapełnienia węgli gazem w warstwach porębskich oraz jaklowieckich (Kędzior, Dreger 2022).

Podczas realizowania pracy doktorskiej przeanalizowano również wpływ emisji metanu z górnośląskich kopalń węgla kamiennego do atmosfery w stosunku do całkowitej emisji gazów cieplarnianych w Polsce. Dane oraz niezbędne informacje pozyskano m.in. z Głównego Urzędu Statystycznego (GUS 2005–2020) oraz raportu przygotowanego przez Krajowy Ośrodek Bilansowania i Zarządzania Emisjami (KOBiZE 2020). Emisja gazów cieplarnianych z obszarów silnie uprzemysłowionych oraz terenów uprawnych była przedmiotem wielu badań i prac naukowych (np. Kożuchowski, Przybylak 1995; Kundziewicz 2013). Coraz większa świadomość społeczna, jak i restrukturyzacja rolnictwa oraz przemysłu ciężkiego ograniczyły emisję szkodliwych gazów. Emisja metanu do atmosfery przez sektor górniczy - wynosząca ponad 700 mln m^3 metanu rocznie - nie pozostaje jednak bez wpływu na polski bilans cieplarniany. W artykule omówiono przyczyny geologiczno – górnicze wpływające na wielkość emisji metanu w GZW oraz przyjrzano się emisji metanu oraz wybranych pozostałych gazów cieplarnianych w kraju. (Dreger 2020).

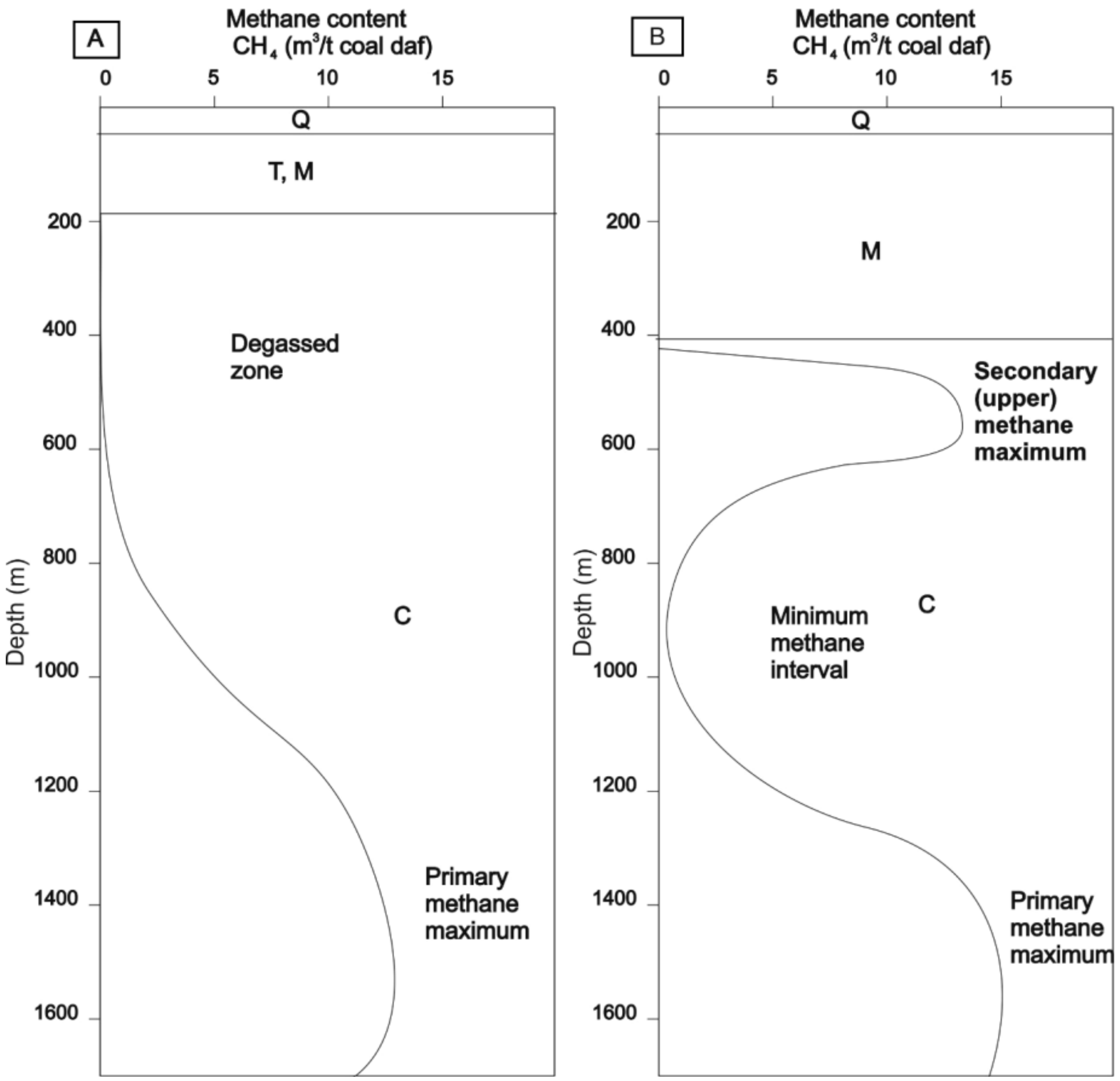
5. Wyniki badan i interpretacja

5.1 Występowanie metanu, emisje oraz zagrożenia w Górnośląskim Zagłębiu Węglowym

Kędzior S., **Dreger M.**, 2019: Methane Occurrence, Emissions and Hazards in the Upper Silesian Coal Basin, Poland, International Journal of Coal Geology, vol. 211, 103226. Lista MNiSW: 140 pkt, Impact Factor (IF): 6.3

W pracy naukowej przedstawiono trendy emisji metanu do wyrobisk górniczych oraz do atmosfery w trzech rejonach Górnośląskiego Zagłębia Węglowego na tle zróżnicowanej budowy geologicznej oraz warunków górniczych. W artykule przeanalizowano okres 1994 – 2016, który obejmuje początki transformacji w polskim górnictwie, stopniowe spowalnianie wydobycia węgla kamiennego oraz zintensyfikowanie zagrożeń naturalnych, w tym metanowego. Emisje metanu do wyrobisk górniczych można podzielić na naturalne (geologiczne) obejmujące budowę geologiczną zagłębia oraz nasycenie pokładów gazem, a także antropogeniczne (górnicze) wynikające z głębokości prowadzonych robót, sposobu eksploatacji, wielkości wydobycia węgla itp. Dodatkowe czynniki sprzyjające emisji i migracji metanu to m.in. porowate, przepuszczalne pakiety piaskowcowe, które jednocześnie w sprzyjających warunkach mogą być zbiornikiem dla gazu wolnego.

Górnośląskie Zagłębie Węglowe zostało podzielone na trzy niezależne rejony różniące się budową geologiczną (fałdowa, blokowa), charakterem litologicznym nadkładu oraz zmienną metanonośnością pionową i poziomą. **Rejon I** zlokalizowany między uskokiem jawiszowickim na południu a granicą zagłębia na północy charakteryzuje się triasowym nadkładem w części północnej (≤ 300 m). W środkowej części utwory karbońskie pojawiają się w formie wychodni lub przykryte są cienkimi utworami czwartorzędu oraz triasu (Rys. 2A). W części południowej osady miocenu (~500 m) szczelnie izolują cały górotwór karboński. **Rejon II** obejmuje część GZW na południe od uskoku jawiszowickiego do granicy zagłębia na południu, jak i wzdłuż nasunięcia orłowskiego na zachodzie. Utwory karbońskie prawie w całości przykryte są przez szczelny pakiet iłów mioceńskich o miąższości od 200 do 1000 m (Rys. 2B). Znaczne zaangażowanie tektoniczne złoża (uskoki np. Bzie-Czechowice, jawiszowicki) oraz zmienna obecność i miąższość nadkładu sprawiły, że górotwór został odgazowany w różnym stopniu, co widoczne jest w pionowym rozkładzie metanonośnym. **Rejon III** reprezentujący obszar fałdowy zagłębia znajduje się na zachód od nasunięcia orłowskiego i sięga zachodniej granicy obszaru GZW. Litologia nadkładu jest tutaj bardzo zróżnicowana, przy miąższości dochodzącej do 1000 m, występują rejony, w których utwory karbońskie odsłaniają się na powierzchni w postaci wychodni. Charakterystyczne dla tej części GZW są struktury fałdowe w formie niecki jejkowickiej oraz chwałowickiej.



Rys. 2 Pionowy rozkład metanonośności GZW– model północny (A) oraz południowy (B) (Kędzior 2012) Q – czwartorzęd, M – miocen, T – trias, C – karbon

Różnice w budowie geologicznej, wielkość wydobycia węgla oraz liczba zlokalizowanych kopalń w danym rejonie wymiernie wpływają na emisję metanu do wyrobisk górniczych, odmetanowanie i metanowość względną. Okresowe zmiany oraz fluktuacje w ogólnym wzrostowym trendzie emisji wynikają ze zmian organizacyjnych w kopalniach, spowolnienia eksploatacji lub eksploatacji partii/pokładów mniej metanowych. Biorąc pod uwagę całe Górnośląskie Zagłębie Węglowe, 750 mln m^3 metanu zostało wydzielone do wyrobisk górniczych w 1994 r., by w końcowym etapie badań zanotować metanowość na poziomie 933 mln m^3 CH_4, co oznacza wzrost o ~180 mln m^3 w ciągu 21-letniego okresu badawczego. Największe zmiany w stosunku wydobycia oraz emisji metanu widoczne są w metanowości względnej, gdzie ~6 m^3 metanu wydzieliło się z 1 tony węgla w GZW w 1994 r., podczas gdy pod koniec badanego okresu wartość ta wynosiła już 15 m^3 metanu na tonę wydobytego surowca, co pokazuje jak bardzo zwiększyło się zagrożenie metanowe w całym okresie badawczym. W przyszłości spodziewany jest dalszy wzrost metanowości relatywnej ze względu na spadające wydobycie węgla oraz eksploatację w warunkach wysokiego zagrożenia gazowego.

Głębokość eksploatacji w GZW wzrasta średnio o 8 m/rok czyniąc wydobycie coraz bardziej narażonym na oddziaływanie zagrożeń naturalnych. Średnia głębokość robót górniczych w złożu wynosząca 770 m sprawia, że kopalnie z rejonu I eksploatują węgiel w pierwotnej strefie metanowej w tzw. pierwotnym maksimum metanonośnym, co przy wydobyciu węgla z coraz głębszych pokładów skutkuje wzmożoną metanowością do wyrobisk górniczych. Wydobycie węgla w rejonie II prowadzone jest w pokładach wysoce nasyconych metanem, dlatego metanonośność pokładów nie ma pierwszorzędnego wpływu na emisję. W kopalniach zachodnich, zlokalizowanych w rejonie III, mniejsza ilość zakładów górniczych oraz eksploatacja w pokładach w większości odgazowanych skutkuje mniejszą emisją gazu do wyrobisk górniczych. Niemniej jednak, sięganie po pokłady węgla zlokalizowane na większych głębokościach, może skutkować eksploatacją w pokładach zaliczonych do wyższych kategorii zagrożenia metanowego.

Emisja metanu do wyrobisk górniczych oraz metanonośność pokładów jest różna w zależności od rejonu GZW, a co za tym idzie, od budowy geologicznej wybranej części zagłębia. Budowa geologiczna całego Górnośląskiego Zagłębia Węglowego jest bardzo zróżnicowana, dlatego ma tak wymierny wpływ na rozkład głębokościowy metanonośności pokładów węgla oraz migrację gazów i innych mediów. Północna i środowa część GZW charakteryzująca się brakiem szczelnych utworów w nadkładzie karbonu umożliwiła wymianę gazową między górotworem karbońskim a atmosferą, co przełożyło się na odgazowanie płytszych partii węglonośnych. Obecne w niektórych miejscach triasowe oraz mioceńskie utwory są pozostałościami po procesach wietrzeniowych i nie stanowiły bariery dla migrującego gazu. Głęboko wykształcona strefa metanonośna (>4.5 m^3/t_{csw}) występuje na głębokości 600 – 1400 m obejmując większość eksploatowanych obecnie pokładów węgla. Złoża zlokalizowane w południowej części GZW charakteryzują się szczelnym mioceńskim nadkładem, który uwięził migrujący metan pod miąższym pakietem iłów. Metan mikrobialny w połączeniu z termogenicznym reprezentuje strefę wtórnego nasycenia metanem. Obecność porowatych piaskowców może dodatkowo sprzyjać migracji metanu i w efekcie zwiększać emisję metanu do wyrobisk górniczych. Jednocześnie miąższe, porowate pakiety piaskowcowe znajdujące się tuż pod szczelnym nakładem mioceńskim, mogą być zbiornikiem dla migrującego gazu wolnego i być przedmiotem późniejszej eksploatacji, tak jak dzieje się to np. w przypadku piaskowców łaziskich w kopalni Silesia. Roboty górnicze oraz eksploatacja węgla w tej strefie obarczone są wysokim dopływem metanu do wyrobisk, czyniąc eksploatację na płytszych głębokościach bardzo wymagającą i obarczoną wysoką metanowością. W głębszej partii profilu głębokościowego występuje strefa obniżonych metanonośności, z których metan migrował w przeszłości geologicznej ku płytszym partiom. Głębiej natomiast, znajduje się strefa pierwotnego nasycenia metanem pokładów węgla i skał otaczających. Jednocześnie, przeszłość geologiczna, zaangażowanie tektoniczne oraz zróżnicowana litologia skutkują łączeniem się obu stref gazonośnych . Nierzadko, blisko uskoków występują strefy głęboko odgazowane, a występujący w nich gaz przemigrował do sąsiednich pokładów i skał występujących w obrębie zaburzenia.

Migracja oraz nasycenie metanem warstw w strefach wysokometanonośnych jest wynikiem zaangażowania tektonicznego złoża oraz litologii górotworu. Nieprzepuszczalne dla migrujących gazów iłowce i mułowce (seria mułowcowa) oraz miąższe pakiety piaskowcowe (górnośląska seria piaskowcowa) stanowią barierę dla metanu, w efekcie gazonośność pokładów jest wysoka (>4.5 m^3/t_{csw}). Biorąc pod uwagę tektonikę, regionalne dyslokacje (np. Bzie-Czechowice, jawiszowicki, kłodnicki) przerywające ciągłość warstw na dużym obszarze górotworu, zrzucają nasycone metanem warstwy zgodnie z kierunkiem zrzutu, jednocześnie przemieszczając całą strefę, w której zakumulowany został metan. Regionalne przemieszczenie stref jest dobrze widoczne w rejonie nasunięcia orłowskiego, gdzie zachodnia część niecki chwałowickiej charakteryzuje się niską metanonośnością (<4 m^3/t_{csw}), natomiast we wschodniej części metanonośność kształtuje się w przedziale III i IV kategorii zagrożenia metanowego.

Akumulacja znacznych ilości metanu w pokładach, zaawansowana tektonika złoża, litologia, w tym obecność porowatych piaskowców oraz czynniki górnicze w postaci zwiększającej się głębokości robót górniczych, jak i koncentracja wydobycia wymiernie wpływają na emisję metanu do wyrobisk górniczych, intensyfikując zagrożenie z roku na rok, co widoczne jest w wynikach rosnącej metanowości całkowitej oraz przede wszystkim względnej, gdzie średnio ponad 15 m^3 gazu jest uwalnianie z każdą toną wydobytego węgla. Tak wysoka emisja do wyrobisk spowodowana jest nie tylko wysoką metanonośnością pokładów, ale migracją gazu z pokładów otaczających oraz sąsiednich zrobów.

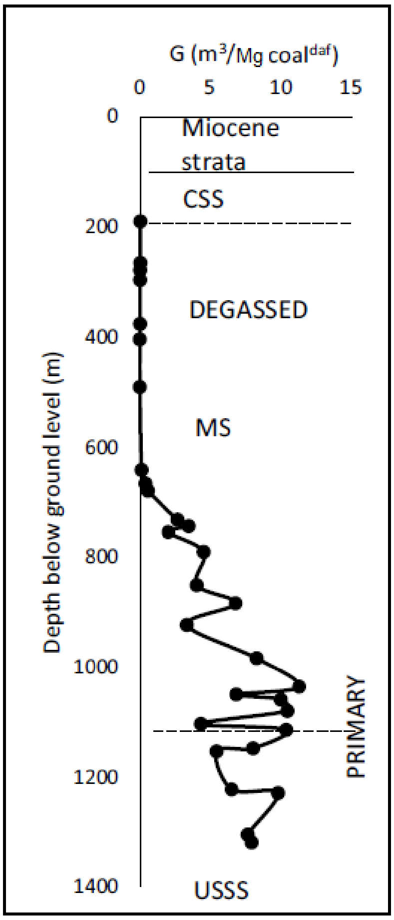
5.2 Zmiany w wydobyciu węgla kamiennego i emisji metanu w kopalni Mysłowice – Wesoła

Dreger M., 2020: Variabilities in Hard Coal Production and Methane Emission in the Mysłowice-Wesoła Mine, Journal of Mining Science, 2021, Vol. 57, No. 3, s. 421–436 Lista MNiSW: 70 pkt, Impact Factor (IF): 0.85

Kopalnia Mysłowice-Wesoła należąca do Polskiej Grupy Górniczej S.A. została wybrana jako reprezentatywna dla północnego regionu gazonośnego (strefy I wg Kotarby i in., 1995) ze względu na wysokie średnioroczne wydobycie węgla oraz najwyższą emisję metanu w porównaniu do innych zakładów. W publikacji przeanalizowano budowę geologiczną złoża, metanonośność serii węglonośnej, parametry techniczne eksploatowanych ścian oraz wydobycie węgla dla lat 1994 – 2018 i metanowość kopalni dla okresu 1974 – 2018. Szczegółowe informacje pozyskano z dokumentacji geologicznej złoża Wesoła, dokumentacji geologicznej otworów badawczych Wesoła PIG 1 oraz Wesoła PIG 2H oraz z danych Działu Wentylacji PGG S.A. KWK Mysłowice -Wesoła.

Złoże węgla kamiennego Wesoła zlokalizowane jest w północnej części Górnośląskiego Zagłębia Węglowego w obrębie niecki głównej. To wielopokładowe złoże składa się z 41 udokumentowanych pokładów węgla różniących się zarówno miąższością, jak i jakością. Podział litostratygraficzny obejmuje warstwy porębskie, siodłowe, rudzkie, orzeskie oraz łaziskie. Ponadto karbońskie utwory węglonośne są przykryte młodszymi osadami triasowymi i mioceńskimi (głównie w południowej części złoża) oraz czwartorzędowymi. Tektonika złoża Wesoła, podobnie jak całego obszaru GZW, jest bardzo zróżnicowana i wywiera znaczący wpływ na rozkład gazonośności złoża oraz na migrację gazów w jego obrębie. Główna nieciągłość tektoniczna – uskok książęcy - dzieli złoże Wesoła na dwie części – północą oraz południową. Uskok książęcy (SWW – NEE), w podobieństwie do innych dyslokacji o charakterze regionalnym występujących na obszarze GZW, zrzuca warstwy na południe (320 – 420 m). Szerokość strefy uskokowej dochodzi do 300m, natomiast na pozostałym obszarze stwierdzono wiele mniejszych nieciągłości, dzielących północą część złoża na mniejsze bloki tektoniczne. Drożny charakter opisywanego uskoku sprawił, że wysokometanowe pokłady węgla znajdujące się w bliskim sąsiedztwie zaburzonej strefy zostały odprężone i w konsekwencji odgazowane.

Wysokie zaangażowanie tektoniczne złoża Wesoła ma odzwierciedlenie w rozkładzie metanonośnym występującym po dwóch stronach uskoku książęcego. Skrzydło wyniesione charakteryzuje się odgazowanym stropem karbonu oraz strefą metanową zlokalizowaną na głębokości 400m (>2.5 m^3 CH_4/Mg), która dokumentowana jest coraz głębiej wraz ze zbliżaniem się do omawianej dyslokacji. W skrzydle zrzuconym strop strefy metanowej występuje na głębokości 900 – 1000 m w bliskim sąsiedztwie uskoku i ulega wypłycaniu wraz z oddalaniem się od uskoku w kierunku południowym ku granicom złoża, gdzie zlokalizowany jest na głębokości 400 m. W profilu otworu Lędziny-Głęboka 23 (LG-23, Rys. 3) widoczna jest pionowa zmienność metanonośności pokładów węgla południowego obszaru złoża, gdzie utwory krakowskiej serii piaskowcowej oraz większość serii mułowcowej zostały odgazowane do głębokości 600 – 700 m, po czym zawartość metanu w węglu gwałtownie rośnie do osiągnięcia maksimum (>10 m^3 CH_4/Mg) na głębokości 1100 – 1200 m. Obecność nieprzepuszczalnych utworów iłowcowo-mułowcowych oraz miąższe pakiety piaskowcowe szczelnie izolują głębokie partie górotworu, przyczyniając się do wysokiej koncentracji metanu w złożu.



Rys. 3 Pionowy rozkład metanonośności w otworze LG -23 (mod. Kędzior, Dreger 2019) CSS – krakowska seria piaskowcowa, MS – seria mułowcowa, USSS – górnośląska seria piaskowcowa

Oddział Górnośląski Państwowego Instytutu Geologicznego, Państwowego Instytutu Badawczego przeprowadził próbę przedeksploatacyjnego ujęcia metanu z pokładów 501 – 510 w złożu Wesoła w celu oceny możliwości odmetanowania pokładów na kilka lat przed planowaną eksploatacją węgla. W tym celu odwiercono otwór pionowy (Wesoła PIG – 1) oraz otwór kierunkowy (Wesoła PIG – 2H), z których dopływ gazu wynosił w początkowej fazie ok. 230 – 250 m^3/dobę. W drugim etapie pokład 510 był szczelinowany hydraulicznie, co skutkowało wysokim dopływem gazu, ale również wysokim dopływem wody złożowej wraz z drobinami węgla (Jureczka i in. 2015). Badanie przeprowadzone przez PIG udowodniło, że odmetanowanie dziewiczych złóż jest możliwe w GZW i bardzo potrzebne ze względów bezpieczeństwa (obniżenie metanonośności pokładów), natomiast skomplikowana sytuacja tektoniczna złoża oraz niska przepuszczalność górnośląskich węgli sprawiają, że takie działania są obarczone wysokim ryzykiem oraz mogą być bardzo trudne do zrealizowania w większej skali. Ponadto, oznaczenie metanonośności podczas wiercenia dwóch otworów potwierdziło wcześniejsze badania części południowej złoża, gdzie strop strefy wysokometanowej został zlokalizowany na głębokości 600 – 700 m, a pokłady 501 – 510 charakteryzowały się metanonośnością > 7 m^3 CH_4/Mg.

W artykule przeanalizowano również parametry techniczne wyrobisk eksploatacyjnych oraz wielkość produkcji węgla w latach 1994 – 1997. Największe wydobycie miało miejsce na początku badań – ok. 4 mln t/rok (1995 – 1996) i było prowadzone w pokładach stosunkowo mało metanowych, przy wysokości ścian dochodzących do 1.5 m i długości < 200 m. Wraz z kolejnymi latami (1996 – 2007) eksploatacja była prowadzona na coraz większych głębokościach (600 – 700 m) a wielkość wydobycia spadła do ok. 3 mln t/rok, przy jednoczesnym wzroście wysokości i długości ścian do odpowiednio 2.30 – 2.60 m oraz >220 m. Wejście eksploatacji w strefę wysokometanową w 2007 roku przełożyło się na gwałtowny spadek wydobycia węgla w kolejnych latach (poza kilkuletnim okresem wzrostowym), przy jednoczesnym wzroście metanowości bezwzględnej kopalni. Koncentracja wydobycia i skomplikowane warunki geologiczne złoża wydatnie ograniczają roboty górnicze w złożu oraz samą eksploatację, co przekłada się na coraz niższe wyniki w produkcji węgla. Długość i wysokość ściany oraz dobowy postęp są w większości uzależnione od warunków geologicznych panujących w danym obszarze eksploatowanego złoża. Wraz ze wzrostem zagrożenia metanowego i komplikacji sytuacji tektonicznej złoża, parametry techniczne ściany powinny być tak dobierane, aby zapewnić jednocześnie maksymalne bezpieczeństwo górnicze oraz korzyść ekonomiczną.

Metanowość kopalni Mysłowice – Wesoła została dokładnie przeanalizowana dla okresu 1974 – 2018. Eksploatacja węgla na relatywnie płytkich głębokościach (500 – 600 m) przy metanonośności pokładu < 2.5 m^3 CH_4/Mg nie skutkowała dużym uwalnianiem się metanu do wyrobisk. W miarę pogłębiania eksploatacji i wejścia do strefy o większym nasyceniu metanem gaz zaczął wydzielać się do wyrobisk z warstw otaczających z eksploatowanego węgla i ociosów oraz zaczął pojawiać się w zrobach. To zwiększyło metanowość bezwzględną kopalni do średniej wartości wynoszącej 43 mln m^3/rocznie aż do 2006 roku. Wraz z pogłębianiem się robót przygotowawczych i eksploatacyjnych metanonośność utworów węglonośnych stopniowo rosła, co przełożyło się na zwiększoną emisję metanu. Około 80% wydzielonego gazu jest usuwane przez system podziemnej wentylacji wprost do atmosfery jako VAM (*ventilation air methane*), natomiast ok. 20% jest pozyskiwane systemem podziemnego odmetanowania. Odmetanowanie wraz z gospodarczym wykorzystaniem gazu zostało wprowadzone na przełomie lat siedemdziesiątych i osiemdziesiątych w celu rozładowania naprężeń w węglu przed wejściem frontu eksploatacyjnego oraz obniżenia metanonośności pokładu. Po roku 2007 głębokość eksploatacji przekroczyła 700 m, tym samym roboty górnicze były prowadzone w strefie maksimum metanonośnego, co skutkowało m.in. wysokim dopływem gazu do wyrobisk. Metanowość bezwzględna rosła z 50 do niemal 90 mln m^3/rocznie. Metanowość względna kopalni Mysłowice-Wesoła od 2007 roku niemal stale przekraczała 20 m^3 CH_4 z 1 tony węgla, co oznacza, że gaz desorbujący z urobionego surowca odpowiada za ok. 50% wydzielonego metanu do środowiska ściany. Metan migrujący szczelinami, mniejszymi uskokami z pokładów wyżej oraz niżej ległych wydatnie zwiększa metanowość kopalni, intensyfikując zagrożenie gazowe w rejonie prowadzonych robót. Duża miąższość pokładów węgla warstw siodłowych (~13 m) sprawia, że bardzo trudno jest urobić cały węgiel znajdujący się w obrysie ściany, w związku z czym węgiel pozostawiony w zrobach zwiększa nie tylko zagrożenie metanowe, ale również i pożarowe. W ostatnich latach badań (2016 – 2018) ok. 40 m^3 metanu wydzieliło się z jednej tony węgla, co pokazuje, że eksploatacja prowadzona w strefie coraz wyższych koncentracji metanu w połączeniu ze szczelnymi utworami otaczającymi (m.in. mułowce, piaskowce) i migracją gazu strefami uskokowymi do środowiska ściany, przyczynia się do wzrostu zagrożenia metanowego i coraz wyższej metanowości bezwzględnej kopalni, która w kolejnych latach powinna utrzymywać się na równie wysokim poziomie.

Złoże węgla kamiennego Wesoła, będące w eksploatacji przez kopalnię Mysłowice – Wesoła, charakteryzuje się skomplikowaną budową tektoniczną, w tym obecnością regionalnej strefy uskokowej (uskok książęcy), która kształtuje pionowy rozkład metanonośności złoża. Zrzucone na południe, wysoko metanowe pokłady znajdujące w otoczeniu miąższych i słabo przepuszczalnych utworów, m.in. górnośląskiej serii piaskowcowej są przedmiotem eksploatacji od kilku lat, co skutkuje wysokim dopływem metanu z urabianego węgla, pokładów otaczających oraz zrobów do środowiska wyrobisk eksploatacyjnych.

5.3 Emisja metanu w kopalniach Budryk i Pniówek na tle warunków geologiczno – górniczych

Dreger M., Kędzior S., 2021: Methane emissions against the background of natural and mining conditions in the Budryk and Pniowek mines in the Upper Silesian Coal Basin (Poland), Environmental Earth Sciences, 80:746. Lista MEiN: 70 pkt, Impact Factor (IF): 2.78

Kopalnie Budryk i Pniówek wchodzące w skład Jastrzębskiej Spółki Węglowej S.A. przez długi czas charakteryzowały się największą metanowością całkowitą spośród wszystkich kopalń zlokalizowanych w GZW. Odmienne warunki geologiczno-gazowe panujące w tych dwóch złożach w różnym stopniu wpływały na przyczyny i wielkość emisji metanu do wyrobisk górniczych.

Kopalnia Budryk, zlokalizowana w północnej części zagłębia, na północno-zachodnim skrzydle niecki głównej między dwoma uskokami – kłodnickim i bełckim (II strefa gazonośna GZW wg Kotarby i in., 1995), charakteryzuje się niezgodnie leżącymi utworami triasu, neogenu oraz czwartorzędu, które zostały zdeponowane na zerodowanej powierzchni karbonu. Utwory te cechuje niewielka miąższość oraz przepuszczalny charakter, co wraz z zaawansowaniem tektonicznym złoża skutkowało odgazowaniem płytszych warstw górotworu karbońskiego do głębokości 400 – 600 m. Głębiej metanonośność gwałtownie rośnie, osiągając maksimum (15 m^3CH_4/Mg) na poziomie 1000 – 1200 m w obrębie pierwotnej strefy metanowej.

Kopalnia Pniówek natomiast, znajduje się w południowej części GZW, na południowo -zachodnim skrzydle niecki głównej, równocześnie granicząc ze strefą uskokową Bzie-Czechowice od południa (IV strefa gazonośna wg Kotarby i in. 1995). Budowa nadkładu, mająca wymierny wpływ na pionowy rozkład metanonośności złoża, jest w południowej części zagłębia zupełnie inna niż w rejonie północnym. Mioceńskie iły, iłowce, piaskowce oraz zlepieńce charakteryzujące się dużą miąższością, szczelnie przykryły zwietrzałą powierzchnię karbonu produktywnego, osiągając maksymalną miąższość (220-1000 m) w rejonie skrzydła zrzuconego strefy uskokowej Bzie-Czechowice. Zaangażowanie tektoniczne złoża sprawiło, że metan wraz z innymi gazami migrował szczelinami uskokowymi ku płytszym partiom złoża wtórnie akumulując wraz z metanem wolnym pod szczelnymi utworami nadkładu. Porowate i zwietrzałe utwory karbonu produktywnego (tzw. utwory pstre) znajdujące się tuż pod mioceńskim nadkładem stały się zbiornikiem dla migrującego i zakumulowanego gazu, którego ciśnienie dochodzi do 6 – 7 MPa, a sama metanonośność pokładów oscyluje w okolicach 10 m^3CH_4/Mg będąc najwyższą w całym profilu głębokościowym złoża Pniówek.

Na potrzeby badań przyjrzano się dokładnie danym dotyczącym ciśnienia panującego w złożu oraz metanonośności pokładów węgla. Porównano zależność współczynnika intensywności desorpcji metanu oraz metanonośności. Intensywność desorpcji metanu w polskim górnictwie jest badana przy pomocny desorbometru cieczowego DMC-2, natomiast metanonośność za pomocą metody zwiercinowej bądź kawałkowej - przy użyciu hermetycznych stalowych pojemników. Dane zebrane przez Tarnowskiego (1971) wskazują, że ciśnienie gazu w węglu jest powiązane wprost proporcjonalnie z metanonośnością pokładu. Potwierdzeniem badań może być wysoka gazonośność stropowej części górotworu karbońskiego w złożu Pniówek, gdzie wysokie ciśnienie gazu (6 – 7 MPa) objawia się najwyższą zbadaną metanonośnością. Metanonośność oraz intensywność desoprcji metanu dla okresu 2018 – 2020 zostały dokładnie przeanalizowane dla kopalni Budryk oraz Pniówek dzięki danym udostępnionym przez Centralne Laboratorium Pomiarowo Badawcze Sp. z o.o. Zebrane dane potwierdzają zależność przedstawioną w badaniach Tarnowskiego (1971), gdzie ciśnienie gazu w węglu wyrażone jako intensywność desorpcji metanu jest wprost proporcjonalne do metanonośności pokładów węgla.

Wysokie ciśnienie gazu w złożu powiązane z wysoką metanonośnością skutkowało najwyższym wydzielaniem się metanu do wyrobisk górniczych w kopalni Pniówek na początku okresu objętego badaniami (1986 – 1991). Eksploatacja tuż pod szczelnym mioceńskim nadkładem przełożyła się na najwyższą metanowość rzędu 160 – 180 mln m^3/rok, przy jednoczesnym najwyższym wydobyciu węgla (3 – 4 mln Mg/rok). W kolejnych latach metanowość całkowita kopalni spadła do około 120 mln m^3/rok, będąc jednocześnie najwyższą w całym GZW. Eksploatacja pokładów w strefie obniżonych metanonośności (400 – 800 m) skutkowała mniejszym, ale wciąż wysokim, dopływem gazu do wyrobisk bezpośrednio z urabianego węgla. Zmiana rozkładu ciśnień i odprężenie górotworu wskutek bieżącej eksploatacji sprawiły jednak, że metan migrował z pokładów sąsiednich siecią szczelin i spękań do rejonu prowadzonych robót górniczych utrzymując wysoką metanowość kopalni przez cały okres badawczy (1986 – 2018).

Kopalnia Budryk, będąca jednym z najmłodszych zakładów górniczych w GZW, rozpoczęła eksploatację w 1994 roku, wydobywając węgiel z warstw płytkich (500 – 600 m), w większości odgazowanych poprzez erozję i zmiany hydrodynamiczne w górotworze, co objawiło się stosunkowo niską metanowością kopalni do 1998 roku (< 20 mln m^3 CH_4/rok). Wraz z eksploatacją głębszych pokładów, gdzie ciśnienie i gazonośność złoża w obrębie niecki głównej gwałtownie rosną, metanowość wzrosła do około 40 mln m^3 CH_4/rok (do 2012). Roboty górnicze prowadzone w złożu na głębokości > 600 m, w pierwotnej strefie metanowej, która charakteryzuje się wysokim wzrostem metanonośności pokładów z głębokością ich zalegania oraz wysokim ciśnieniem panującym w złożu, skutkowały gwałtownym wzrostem metanowości kopalni od 2013 roku do końca okresu badawczego w 2018r. Metanowość wzrosła z niecałych 60 do ponad 140 mln m^3 CH_4/rok. Wykazano, że intensywność emisji metanu z węgla do wyrobisk górniczych z pokładów wysokometanowych jest dużo większa, co przy dodatkowej migracji gazu szczelinami i spękaniami z pokładów wyżej oraz niżej ległych zwiększa metanowość kopalni i bezpośrednią emisję metanu do środowiska ściany. Dodatkowo, urozmaicona budowa tektoniczna złoża umożliwia migrację metanu z głębszych, bardziej nasyconych gazem pokładów do warstw płytszych, potęgując zagrożenie metanowe oraz wzrost metanowości bezwzględnej i względnej kopalni.

Kopalnie Budryk i Pniówek charakteryzują się odmienną budową geologiczną, a tym samym metanowość obu kopalń zmienia się w czasie w sposób odmienny, a jej zmiany odnoszą się głównie do czynników geologicznych, takich jak zaangażowanie tektoniczne złoża, obecność i miąższość nadkładu oraz pionowy rozkład metanonośności, w tym obecność stref o zwiększonej koncentracji metanu. Ponadto, strefy wysokometanowe charakteryzują się występowaniem metanu pod wysokim ciśnieniem, co przy wysokiej desorpcji wzmaga emisję CH_4 do wyrobisk, czego dobrym przykładem jest strefa wtórnego nasycenia metanem tuż pod szczelnym nadkładem mioceńskim w kopalni Pniówek. Dodatkowo oddziałujące czynniki, takie jak głębokość eksploatacji, koncentracja wydobycia węgla oraz migracja metanu z warstw i zrobów otaczających daną ścianę wydobywczą, wzmagają wzrost metanowości kopalni.

5.4 Geologiczne i górnicze czynniki wpływające na warunki metanowe zachodniej części Górnośląskiego Zagłębia Węglowego – na przykładzie kopalni PGG S.A. ROW Ruch Rydułtowy

Kędzior S., **Dreger M.**, 2022: Geological and Mining Factors Controlling the Current Methane Conditions in the Rydułtowy Coal Mine (Upper Silesian Coal Basin, Poland) Energies, 2022, 15, 6364. Lista MEiN: 140 pkt, Impact Factor (IF): 3.252

Praca naukowa przedstawia zachodnią, fałdowo-uskokową część GZW, która została zaprezentowana na przykładzie kopalni PGG S.A. Ruch Rydułtowy, eksploatującej złoże Rydułtowy 1 (VII strefa gazonośna GZW). Zachodnia część Górnośląskiego Zagłębia Węglowego jest zróżnicowana pod względem budowy geologicznej. Najmłodsze utwory nadkładu w niektórych miejscach zostały wykształcone w postaci miąższych i szczelnych iłów, piasków i mułków, natomiast w niektórych rejonach utwory mioceńskie i czwartorzędowe zostały zerodowane, co objawia się wychodniami karbonu produktywnego. Złoże Rydułtowy 1 znajduje się na skrzydle wyniesionym regionalnej dyslokacji – nasunięcia michałowicko-rybnickiego o zrzucie 750 – 1500 m. Dodatkowo, złoże zlokalizowane jest w północno-zachodniej oraz środkowej części niecki jejkowickiej, której oś zapada na północny-wschód, a nachylenie warstw wzrasta wraz ze zbliżaniem się do granicy nasunięcia. W związku ze zróżnicowaną i zaawansowaną tektoniką złoża, zmiennością litologiczną utworów karbonu oraz nadkładu, jak i zmiennym nasyceniem węgla metanem, kopalnia Rydułtowy do 2000 r. eksploatowała węgiel w warunkach względnie nie metanowych niewielkiego zagrożenia metanowego. Płytsze partie górotworu zostały w większości odgazowane na skutek braku szczelnego nadkładu powstrzymującego migrujący metan z głębszych warstw. Odgazowana strefa występuje do głębokości ok. 600 m, natomiast w głębszych partiach metanonośność węgla wzrasta do > 14 m^3/Mg csw. Rozpoznając litologię złoża Rydułtowy 1, zauważono, że udział porowatych piaskowców mógł przyczynić się migracji metanu i odgazowania fragmentów złoża, natomiast nieprzepuszczalne utwory ilaste blokowały migrację gazu. Warstwy porębskie charakteryzują się większym udziałem utworów piaskowcowych w porównaniu do głębszych warstw jaklowieckich (35 do 29%), jednocześnie starsze, głębiej zdeponowane utwory mogą charakteryzować się większą szczelnością na skutek dużego udziału skał ilastych w profilu. Potwierdzeniem odgazowania płytszych warstw na skutek obecności porowatych piaskowców może być obecność stropu warstw metanonośnych (>4.5 m^3/Mg) zlokalizowana niemal dokładnie na granicy warstw jaklowieckich i porębskich.

Rozpoczęcie eksploatacji wysokometanowych pokładów (>4.5 m^3/Mg) na początku XXI wieku skutkowało wysokim dopływem gazu do wyrobisk i w efekcie wysoką metanowością bezwzględną kopalni. Wysoka emisja CH_4 łącznie z kilkoma fluktuacjami kontynuowała się przez cały okres objęty badaniami – do 2020r. Eksploatacja warstw jaklowieckich z roku na rok na coraz większych głębokościach, była obarczona wysokim wydzielaniem się metanu do środowiska ściany nie tylko z rozkruszonego węgla, ale również z warstw otaczających, gazu migrującego ze zrobów oraz pokładów wyżej i niżej ległych. Stosunkowo wysoka zwięzłość węgla (f=0.81) oraz niska intensywność desorpcji gazu (k=0.70 kPa) przekładają się na względnie łagodną emisję CH_4 z odsłoniętej calizny, niemniej jednak, zgodnie z prawem Langmuira, najwięcej gazu jest uwalniane w pierwszych minutach tuż po urobieniu węgla, co przy wysokiej gazonośności pokładu skutkuje wysoką emisją metanu do wyrobisk.

Eksploatacja głębszych pokładów węgla związana jest z wyższym ciśnieniem panującym w górotworze oraz ograniczoną pojemnością sorpcyjną węgli. Wzrost temperatury ogranicza możliwości sorpcyjne, podczas gdy wyższe ciśnienie wywierane przez skały nadkładu jest pozytywnie skorelowane z większą akumulacją CH_4 w węglu (np. Lamberson, Bustin 1993; Laxminarayana, Crosdale 1999; Crosdale i in. 2008; Mangi i in. 2022). W Górnośląskim Zagłębiu Węglowym, optimum metanonośne, sprzyjające akumulacji metanu, występuje na głębokościach 800 – 1500 m z możliwością wahań, natomiast w złożu Rydułtowy 1 największa stwierdzona metanonośność zlokalizowana jest na głębokości 1100m (14 – 15 m^3/Mg). Aby zbadać możliwości sorpcyjne węgli ze złoża z kopalni Rydułtowy oraz wysycenie pokładów metanem, próbki węgli z głębokości 1000 – 1200 m zostały zbadane na analizatorze sorpcji gazów – IGA 001, poprzez nasycenie węgli metanem w ciśnieniu do 20 MPa w temperaturze równej złożowej (36 – 40^{o}C). W wyniku przeprowadzonych badań, maksymalna pojemność sorpcyjna węgli z kopalni Rydułtowy obliczona z izotermy sorpcji Langmuira wynosi 15 – 16 m^3/tonę na głębokości 1000 m. Biorąc pod uwagę metanonośności oznaczone na głębokościach 1000 – 1200m (14 – 15 m^3/Mg), można stwierdzić, że węgle są wysycone metanem w 95%. Metanonośność węgli kopalni Rydułtowy generalnie wzrasta wraz z głębokością, dlatego płytsze pokłady są nasycone metanem w dużo mniejszym stopniu – od 30 do 78%. Badania przeprowadzone na rydułtowskich węglach potwierdzają również ograniczoną sorpcję wraz ze wzrostem temperatury, w tym przypadku pojemność sorpcyjna spada o 0.05 m^3 CH_4 na 1^{o}C, co potwierdza badania innych naukowców (Wierzbicki 2013). Wraz ze wzrostem temperatury zwiększa się również dyfuzyjność węgli o około 0.2 x 10^{-10} cm^2/s przy wzroście o 1°C. Średnia zbadana dyfuzyjność wynosi natomiast D= 4 x 10^{-10} cm^2/s.

Czynniki górnicze, takie jak głębokość wydobycia węgla oraz odprężenie i odgazowywanie górotworu bieżącą eksploatacją oraz odmetanowaniem pokładów, przyczyniają się do wzmożonej desorpcji i migracji metanu, jak i zmiany pierwotnej metanonośności w profilu. Metanowość względna podczas okresu badawczego (2000-2020) wynosiła momentami >15 m^3 CH_4/tonę, co świadczy o emisji metanu do wyrobisk nie tylko z urabianego węgla, ale także z pokładów otaczających oraz zrobów. Strefa odprężenia uzależniona jest od parametrów technicznych ściany oraz zmienności litologicznej górotworu karbońskiego.

Nieciągłości tektoniczne, charakter litologiczny oraz stratygrafia złoża wraz z coraz głębszą eksploatacją oraz towarzyszącymi czynnikami górniczymi mają zasadniczy wpływ na wysoką emisję metanu do wyrobisk kopalni Rydułtowy. Coraz trudniejsze warunki geologiczno-górnicze, w tym rosnąca głębokość prowadzonych robót, eksploatacja w strefie wysokich metanonośności pokładów (od 2000r) mają wymierny wpływ na wzrost metanowości bezwzględnej. Badania sorpcyjne węgli z kopalni Rydułtowy pokazują, że przy maksymalnej pojemności sorpcyjnej w okolicach 15 – 16 m^3/tonę, pokłady na głębokości >1000 m są w 95% wysycone metanem, co przekłada się na wysoką metanowość podczas prac wydobywczych.

5.5 Emisja metanu i wydobycie węgla kamiennego w Górnośląskim Zagłębiu Węglowym w nawiązaniu do wzrostu efektu cieplarnianego w Polsce w latach 1994 – 2018.

Dreger M., 2021: Methane emissions and hard coal production in the Upper Silesian Coal Basin in relations to the greenhouse effect increase in Poland in 1994-2018, Mining Science, vol. 28, 2021, s 59–76. Lista MEiN: 70 pkt, Impact Factor (IF): 0.46

Wzrost efektu cieplarnianego nierozerwalnie jest związany z wysoką emisją CO_2 i CH_4 oraz innych niebezpiecznych gazów wprost do atmosfery. Obecność m.in. metanu ogranicza odpływ ciepła przy relatywnie swobodnym jego dopływie, potęgując efekt szklarniowy, tym samym doprowadzając do stopniowego ogrzewania się Ziemi (np. Etminam i in. 2016). Metan, jako gaz cieplarniany silniejszy nawet 30 – krotnie od dwutlenku węgla został dokładnie przeanalizowany zarówno dla Górnośląskiego Zagłębia Węglowego, jak i dla całego kraju. Polska, tak jak wiele innych europejskich i światowych krajów, zobligowały się do redukcji emisji gazów cieplarnianych wymienionych w Protokole z Kioto i uznanych za najbardziej szkodliwe o średnio 5.2% w stosunku do okresu referencyjnego, który został określony dla każdego kraju indywidualnie. Kolejnym krokiem było podpisanie światowego porozumienia na Szczycie Klimatycznym w Paryżu w 2015, którego głównym założeniem było powstrzymanie wzrostu globalnej temperatury o 1.5 – 2^{o}C w odniesieniu do epoki przedprzemysłowej. Polityczne i techniczne decyzje zostały ustalone trzy lata później na konferencji COP 24 w Katowicach. W badaniach zauważono, że kraje Unii Europejskiej są odpowiedzialne za zaledwie kilkanaście procent emisji szkodliwych gazów do atmosfery, natomiast główni emitenci – Chiny, USA oraz Indie nie są zobligowani żadnym dokumentem do obniżenia emisji. Bez wspólnych, zdecydowanych działań plan redukcji wzrostu globalnej temperatury może się nie powieść.

Emisja metanu w Górnośląskim Zagłębiu Węglowym prawie w całości jest pochodzenia kopalnianego. Gaz uwalniany do wyrobisk w trakcie robót górniczych jest usuwany systemem wentylacji na zewnątrz kopalni, aby zapewnić bezpieczne warunki pracy. Dodatkowo, w celu obniżenia ciśnienia złożowego oraz redukcji metanonośności pokładu, metan usuwany jest z węgla przy pomocy odmetanowania. Pozyskany gaz jest wykorzystywany jako paliwo do silników generujących prąd, ciepło, chłód lub zostaje sprzedawany odbiorcom zewnętrznym. Jednakże, niewykorzystany gospodarczo gaz jest uwalniany do atmosfery w postaci tzw. wydmuchu. Te dwa główne źródła emisji metanu mają największy wpływ na cały bilans emisyjny CH_4 w GZW.

Biorąc pod uwagę dane Głównego Urzędu Statystycznego, Raport KOBIZE z 2020r oraz dane zawarte w Raportach rocznych o stanie podstawowych zagrożeń naturalnych i technicznych, w górnictwie węgla kamiennego (GIG 1995-2021; GUS 2005-2020; KOBiZE 2020) zbadano trendy emisji metanu i wszystkich gazów cieplarnianych w Polsce oraz emisję CH_4 w zagłębiu i odniesiono ją do wyników dla całego kraju. W okresie objętym badaniami (1994 – 2018) emisja metanu w GZW przyjmuje ogólny trend wzrostowy, co jest związane z eksploatacją głębokich pokładów, wysoko nasyconych metanem. Pokłady niemetanowe zostały w większości wyeksploatowane w północnej części zagłębia, natomiast obecnie większość zakładów prowadzi roboty w pokładach węgla przynależnych do III i IV kategorii zagrożenia metanowego, co przekłada się na wysoką emisję metanu do wyrobisk. Wysokie ciśnienie złożowe, wysoka metanonośność oraz migracja CH_4 z nieeksploatowanych pokładów sąsiadujących, skał płonnych oraz zrobów przekłada się na coraz wyższą emisję metanu do atmosfery, pomimo malejącego wydobycia węgla kamiennego. W 1994 kopalnie

GZW wypuściły do atmosfery 440 tys. Mg CH_4, aby pod koniec okresu badawczego w latach 2015 – 2018 emisja utrzymywała się na stałym poziomie powyżej 500 tys. Mg CH_4.

W Polsce, główna emisja metanu pochodzi z trzech sektorów gospodarki (KOBiZE 2020):

a) emisja z paliw – 47%,
b) rolnictwo – 30%,
c) odpady – 23%.

W polskiej gospodarce najwięcej metanu wydzieliło się na początku okresu badawczego (2.42 Mg CH_4), by z każdym rokiem emisja stopniowo spadała do wartości 1.95 Mg CH_4 w 2018 r. Większa odpowiedzialność społeczna, restrukturyzacja przemysłu oraz lepsze zarządzanie w rolnictwie czy przemyśle ciężkim skutkowały 19% spadkiem emisji metanu w całym okresie badawczym.

Biorąc, jednak pod uwagę emisję wszystkich gazów cieplarnianych, największy udział ma dwutlenek węgla – 81.8%, którego większość pochodzi ze spalania paliw oraz przemysłu ciężkiego. Podobnie jak w poprzednich badaniach, największa emisja gazów szklarniowych miała miejsce na początku okresu badawczego, gdzie ze względu na ożywienie gospodarcze wydzieliło się ponad 430 mln Mg ekwiwalentu [ek] CO_2 (KOBiZE 2020) Kolejne lata charakteryzowały się stopniowymi, kilkuletnimi spadkami oraz wzrostami emisyjności. Od 2014, ze względu na ponowne ożywienie krajowej gospodarki, emisja wzrosła z 383 do 402 mln Mg [ek] CO_2.

Górnośląskie Zagłębie Węglowe jako najbardziej uprzemysłowiony region w kraju odpowiada za znaczną ilość wydzielonego metanu do atmosfery – prawie w całości z górnictwa węgla kamiennego. Uwzględniając emisję wentylacyjną oraz wydmuch niewykorzystanego metanu ze stacji odmetanowania, ustalono, że CH_4 z kopalń w całym okresie badawczym (1994 – 2018) odpowiadał za 18 – 27% całkowitej emisji tego gazu w Polsce oraz za jedyne 3%, biorąc pod uwagę emisję metanu z GZW do emisji wszystkich gazów szklarniowych.

Emisje metanu oraz innych gazów cieplarnianych do atmosfery są tematem wielu badań oraz rozważań naukowych. Polskie górnictwo węgla kamiennego, sięgając po głębsze, bardziej metanowe pokłady, emituje coraz więcej tego gazu do atmosfery. Metan jako gaz o wysokiej kaloryczności jest wykorzystywany przez wiele zakładów górniczych do produkcji energii, ograniczając jednocześnie bezpośredni wydmuch gazu do atmosfery. Wizja opłat ekologicznych nakładanych za każdą wyemitowaną tonę CH_4 (liczoną według ekwiwalentu CO_2) każe się zastanowić, nad jak najlepszym zagospodarowaniem tego surowca, który w wielu przypadkach traktowany jest jako kopalina towarzysząca i może być gospodarczo wykorzystany. Coraz trudniejsze warunki metanowe oraz geologiczno-górnicze będą skutkowały utrzymywaniem się emisji CH_4 do wyrobisk na wysokim poziomie lub mogą wzrosnąć wraz z eksploatacją prowadzoną na coraz głębszych poziomach, gdzie nasycenie węgla metanem będzie coraz wyższe, a sam gaz będzie dopływał do wyrobisk nie tylko z urabianego węgla, ale także z pokładów otaczających, ociosów, skał płonnych oraz zrobów.

6. Wnioski

Przeprowadzone badania zrealizowane na potrzeby rozprawy doktorskiej pozwoliły na uzyskanie następujących wniosków:

- ❖ Budowa geologiczna nadkładu wywiera wpływ na rozkład gazonośności w złożu i w konsekwencji na wielkość emisji metanu.
- ❖ W złożach węgla, w których w górniej partii obecna jest strefa odgazowana, jest raptowny wzrost metanowości bezwzględnej z chwilą wejścia eksploatacji do strefy wysokometanowej na głębokości większej niż 600-700 m (strefy gazonośne GZW I, II, III i VII).
- ❖ W IV strefie gazonośnej GZW, w której metan obecny jest w całym profilu złoża, ze zmienną, ale wysoką metanowością bezwzględną, mamy do czynienia od początku istnienia kopalni do teraźniejszości (KWK Pniówek).
- ❖ Głębokie, bardziej nasycone metanem pokłady są głównym źródłem wydzielania się tego gazu, który migruje do środowiska ściany również z pokładów nadbieranych, podbieranych, zrobów oraz skał płonnych.
- ❖ Przykład kopalni Rydułtowy pokazuje, że pokłady na głębokości >1000 m są w wysokim procencie wysycone metanem, co przekłada się na wysoką metanowość podczas prac wydobywczych na skutek ograniczonej pojemności sorpcyjnej węgli na tak dużych głębokościach.
- ❖ Uskoki kształtują metanonośność oraz metanowość złóż, będąc źródłem wtórnego nasycenia lub odgazowania pokładów. Węgle w rejonie stref uskokowych mogą charakteryzować się osłabioną zwięzłością, co przekłada się na silniejszą emisję metanu do wyrobisk oraz może przyczynić się do wzrostu zagrożenia wyrzutami gazów i skał.

- Wtórne nasycenie lub odgazowanie pokładu może mieć również związek z drożnymi dla gazu porowatymi i przepuszczalnymi piaskowcami (np. piaskowce łaziskie, siodłowe).
- Szczelny (izolujący) charakter nieciągłości kumuluje metan w jej obrębie, co przy naruszeniu uskoku robotami górniczymi może objawić się wysoką metanowością.
- Duże ciśnienie gazu w węglu jest wprost proporcjonalne do wysokiej metanonośności pokładów, co skutkuje wzmożonym wydzielaniem się metanu do wyrobisk w trakcie eksploatacji.
- Spadek ilości wydobytego węgla nie spowalnia emisji metanu do wyrobisk korytarzowych i eksploatacyjnych.
- Czynniki górnicze (np. głębokość eksploatacji oraz koncentracja wydobycia węgla) nakładają się na warunki naturalne i na ogół w istotny sposób przyczyniają się do wzrostu metanowości bezwzględnej badanych kopalń.
- Metan wyemitowany przez kopalnie GZW odpowiada za ~3% emisji gazów cieplarnianych w Polsce oraz ~27% ogólnej emisji metanu.

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- przygotowanie i opracowanie danych wyjściowych dotyczących metanowości bezwzględnej kopalń oraz wielkości wydobycia węgla w Górnośląskim Zagłębiu Węglowym (GZW)
- obliczenie metanowości względnej kopalń i opracowanie wyników
- interpretacja wyników dotyczących metanowości kopalń oraz wydobycia węgla
- autorstwo rozdziałów 4.1, 4.2.3. i 5
- współautorstwo rozdziałów 1, 2, 3 i 6

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- przygotowanie, opracowanie i interpretacja danych wyjściowych dotyczących metanonośności pokładów węgla badanych regionów GZW
- autorstwo rozdziałów 4.2.1 i 4.2.2.
- współautorstwo rozdziałów 1, 2, 3 i 6
- edycja i porządkowanie całości tekstu artykułu, rysunków i tabel
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Udział doktoranta:
- przygotowanie, opracowanie i interpretacja danych na temat emisji metanu oraz wydobycia węgla
- zebranie i interpretacja danych na temat sorpcji metanu, ciśnienia gazu w pokładzie w porównaniu z metanonośnością pokładu
- opracowanie graficzne danych w postaci wykresów na fig. 5 – 11
- opis budowy geologicznej złóż, autorstwo tabel 1 – 3
- opracowanie konkluzji, udział w przygotowaniu tabeli 4
- opracowanie rozdziału na temat aspektu środowiskowego emisji metanu z badanych kopalń
- kontakt z redakcją (autor korespondencyjny)

Udział współautora:
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- autorstwo figur 1 – 4
- udział w opracowaniu konkluzji końcowych, udział w opracowaniu tabeli 4
- koncepcja podziału treści artykułu i zawartości poszczególnych rozdziałów

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Udział doktoranta:

- przygotowanie, opracowanie i interpretacja danych na temat emisji metanu oraz wydobycia węgla
- wykonanie analizy sorpcji metanu w pokładzie węgla kopalni Rydułtowy – opracowanie izotermy sorpcji oraz zmienności nasycenia pokładów metanem na poszczególnych poziomach
- opracowanie rozdziałów: 2 (fragmentarycznie), 4.2., 4.3.4 oraz 4.4.
- opracowanie figur 2, 4, 5, 8, 9, 10
- opracowanie tabeli 1
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- interpretacja zmienności metanonośności pokładów węgla w kontekście uwarunkowań geologicznych i rozwoju geologicznego zagłębia
- opracowanie rozdziałów 1, 2 (fragmentarycznie), 4.1., 4.3.1., 4.3.2., 4.3.3.
- opracowanie figur 3 i 7
- opracowanie tabeli 2
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Methane occurrence, emissions and hazards in the Upper Silesian Coal Basin, Poland

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ABSTRACT

The paper presents the variability of methane emissions into mining excavations and the atmosphere in the Upper Silesian Coal Basin (USCB) (Poland) against the background of natural and mining factors. Emissions of methane from exploited coal seams have become a serious problem in the USCB due to the growing methane hazard in coal mines and emissions of methane into the atmosphere. In the mid-nineties 753 million m^3 of methane was emitted annually from the USCB mines. Despite a significant drop in coal production over the next 20 years, methane emissions have not decreased sharply; on the contrary, in recent years they have begun to grow, and, in 2016, reached the level of 933 million m^3 per year. This represents an increase of 180 million m^3 per year since the mid-nineties. One of the important reasons for this phenomenon is the constantly increasing depth of coal exploitation, which in many mines now exceeds 1000 m; this is the depth corresponding to the deep methane zone, where the volume of accumulated methane in the coal seams is particularly high. Factors influencing the volume of methane emissions in relation to mine workings can be divided roughly into two groups: natural (geological) and anthropogenic (mining-related). Natural factors include methane content in coal seams, gas pressure, the presence of free gas in fault zones, related fissures and porous sandstone, the migration of methane through faults and fissures, and the presence of a continuous and impermeable Miocene overburden. Mining factors include the depth of exploitation and the concentration of coal production as expressed in terms of the length, height, and advance of walls. The interdependence of these factors means that, despite the decline in coal production, methane emissions, both total and specific, are increasing. This problem cannot be neglected, especially since it may grow worse in future. One measure to prevent the growth of methane emissions and the associated hazard may be the intensification of mine methane drainage and the economic use of captured mining gas, which is already done in the USCB.

1. Introduction

This study is an attempt to connect the question of methane emissions and hazards in coal mines in the Polish part of the Upper Silesian Coal Basin with the methods of coal mining and the occurrence of methane in the context of the geological structure of the basin. Therefore, it is a combination of geological and mining issues in order to thoroughly analyze the temporal changes in methane emissions in the study area.

Methane accompanying coal-bearing formations causes fire and explosion hazards in mines. The gas occurs both in coal seams and surrounding rocks at a pressure equilibrium. Disruption of the pressure equilibrium, e.g. through disturbance of a rock mass due to mining exploitation, causes the liberation of methane from the beds and its emission into mining excavations (e.g. Krause and Smoliński, 2013). All methane released during and after mining operations is called coal mine methane (CMM; Karacan et al., 2011). An increase in the concentration of methane in mine air threatens its ignition and/or explosion. A methane/air mixture is explosive when the methane content in the air ranges between 5 and 15% with oxygen content above 12%. Ignition of the mixture occurs at temperatures above 650 °C (e.g. Kozłowski and Grębski, 1982). Therefore, a frequent cause of methane ignition is sparking of rock (e.g. sandstone, which is prone to sparking and igniting methane when mined; Krause and Smoliński, 2013) due to friction caused by a mining tool.

Methane is also a greenhouse gas and a strong absorber of infrared heat, and contributes to global warming. Among greenhouse gases, it is listed in second place, but its radiative power is 21–25 times higher than that of first-place carbon dioxide (e.g. Warmuziński, 2008; Kędzior, 2015). Methane is responsible for 17–18% of the greenhouse

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effect (e.g. Adler, 1994). Coal mining accounts for about 6% of global methane emissions (Best Practice Guidance, 2010).

The Upper Silesian Coal Basin (USCB) is the largest coal basin in Poland and one of the largest in Europe. It covers an area of ca 7500 km^2, of which 5600 km^2 belongs to Poland (Silesia and Małopolska provinces) and the rest to the Czech Republic. The number of hard coal mines in the Polish USCB has changed over time, from 65 mines in the early 1990s to 22 in 2016. The decline in the number of working mines was caused by restructuring processes and the mergers of several working mines into large mining enterprises. However, especially in the northern and south-western parts of the USCB, mines have been closed, because shallow-lying and easily-extracted coal reserves had been depleted, or because difficult natural and technical conditions prevented further operation.

Coal output, from the beginning of the political transformation in Poland (early 1990s) to the present, has been significantly reduced. > 130 million tonnes of coal was extracted in 1997 compared to about 60 million tonnes in 2016, more than a twofold decrease. However, hard coal is being extracted in the USCB from deeper and deeper coal seams every year. In 2000, the average depth of coal production was 600 m; in 2010, 700 m; in 2016, 770 m below ground level (Annual Report, 1995-2017). The maximum depth of exploitation in many mines exceeds 1000 m, and in some approaches 1300 m. From one year to the next, mines located in the USCB need to extract coal from deeper coal seams to maintain profitability and provide security for thousands of jobs (Dreger and Kędzior, 2019). The exploitation of deeper coal seams leads to the exacerbation of methane-related danger (Kędzior, 2015; Dreger and Kędzior, 2019), one of the most dangerous natural hazards in the Polish underground mining industry. Methane emissions from USCB coal mines increased from ca 750 million m^3 in 1994 to > 930 million m^3 in 2016 (Annual Report, 1995-2017).

Thus the aim of the present paper is to study how methane emissions changed throughout the Polish part of the USCB and in three selected areas therein during the period 1994–2016. The factors influencing changes in methane emissions were also studied. The research period, constituting the period from 1994 to 2016, was chosen due to reorganisation processes, i.e. mergers of several small mines into one, the closing of coal mines, and the exploitation of coal seams at greater depths, where methane content is higher and methane-related danger is greater. We wish to examine how these changes are influencing methane emissions in the USCB.

Methane emissions in coal basins are governed by many factors, which can be generally divided into natural (geological) and anthropogenic (mining-related). The former group includes the geological setting of coal basins and gas occurrence. Research carried out in various coal basins in the world reveal that gas content in coal was formed as a result of many processes, such as coalification (coal rank), which depends mainly on temperature, and maceral composition (coal type), which results from primary plant matter (e.g. Teichmüller, 1989; Kotarba, 2001; Kędzior, 2015). The current volume of methane is influenced by the sorption capacity of coal, which exhibits a negative dependence on temperature, moisture, and ash content and a positive dependence on pressure, coal rank, and maceral composition (vitrinite occurrence) (e.g. Lamberson and Bustin, 1993; Laxminarayana and Crosdale, 1999; Scott, 2002; Crosdale et al., 2008; Mastalerz et al., 2008; Weniger et al., 2012). Methane content may be repeatedly modified by sorption and desorption processes caused by changes in hydrostatic pressure which facilitate methane migration and its subsequent accumulation in suitable conditions (in coal seams, which are capable of adsorbing and holding certain quantities of gas; e.g. Scott, 2002; Kędzior, 2009; Moore, 2012). Tests carried out on American coal showed that the presence of micropores in the inner structure of coal is a decisive factor (Mastalerz et al., 2008).

Coal mining involves the emission of methane and contributes to changes in the primary methane content in coal (e.g. Kędzior, 2015). The area from which methane is expelled includes the exploited coal seam as well as the overlying and underlying strata (e.g. Lunarzewski, 1998; Karacan et al., 2011; Krause, 2005; Patyńska, 2013). Therefore, the volume of methane emissions is higher than the in situ gas content in the coal seam itself (Karacan et al., 2011). Faults and rock breaks that facilitate gas flow from adjacent mined coal beds often serve as natural pathways for migrating methane. Other factors influencing methane migration include the occurrence of permeable sandstone, the localisation of shearing coal zones which enable changes in coal permeability, and folding structures. These features have been identified in many coal basins (e.g. Noack, 1998; Pashin, 1998; Thielemann et al., 2000; Li, 2001; Coolen, 2003; Li et al., 2003; Karacan et al., 2008, 2011).

Mining factors also influence methane emissions from coal mines. The most important are the depth of exploitation (due to increased methane content with depth; e.g. Kędzior, 2009, 2015; Moore, 2012), exploitation system (longwall), and concentration (rate) of coal extraction, i.e. the number of tonnes of coal extracted from one wall per day.

Due to the large number of factors affecting the amount of emitted methane, the estimation and prediction of methane emission in individual coal deposits and basins is a difficult task and often requires the application of computer modelling with the use of several variables (e.g. Karacan, 2009; Karacan et al., 2011; Ju et al., 2016; Duda and Krzemień, 2018).

2. Methods

This paper is based on the archival data of methane content defined as the volume of methane included in a mass unit of coal in a dry ash-free state (daf), as well as of methane emissions from coal mines, understood as total methane emissions (including both ventilation air methane VAM, and methane captured CMM) measured in the course of a year (absolute methane emissions) and specific methane emissions, i.e. total methane emissions per ton of extracted coal, calculated to compare the total methane emissions between individual regions in different time periods (years) taking into account how many tonnes of coal were extracted. Data concerning methane content are now archived in the National Geological Archive, whereas data on methane emissions are published for each mine every year in the *Annual Report on the State of Basic Natural and Technical Hazards in the Hard Coal Mining Industry* (Annual Report, 1995-2017) drawn up by the Central Mining Institute in Katowice, Poland. The obtained data include information on hard coal production and total (absolute) methane emissions as well as on methane captured by methane drainage systems and utilised during the period 1994–2016.

Methane content is measured in coal samples in hermetic containers by means of vacuum degasification, followed by calculation of methane content (Kotas, 1994; Kędzior, 2009). These measurements are carried out both in mine workings, where coal samples are collected from boreholes drilled in the side walls, and from mine and surface boreholes. Polish health and safety regulations require sampling for methane content at intervals of 200 m in a drifted excavation.

Measurements of methane emissions from mines are made from two emission sources: ventilation shafts and underground drainage systems (Patyńska, 2013). Measurements of methane emitted from ventilation shafts include the rate of air flow in the ventilation duct of a given shaft and the concentration of methane in this air, measured with a methane detector (Gawlik and Grzybek, 2002). The volume of emitted methane is calculated using the following formula:

$$Q = \frac{vSC}{100}$$

where Q is the volume of emitted methane (m^3/s), S is the cross-sectional area of the ventilation duct (m^2), v is air-flow rate (m/s), and C is methane concentration in ventilation air (%).

Measurement of methane from underground in seam drainage systems is carried out with the use of industrial gas meters and methane detectors that record the concentration of methane in captured gas (Gawlik and Grzybek, 2002).

Total (absolute) methane emissions are the sum of methane emissions from mine shafts and methane captured by the underground drainage system; methane emitted into the atmosphere is the difference between total methane emissions and the quantity of methane captured and used for energy purposes or sold to consumers.

Based on annual coal production and annual total methane emissions, specific methane emissions were calculated using the following formula:

$$Esp = \frac{Et}{Pc}$$

where E*sp* is specific methane emissions (m^3/t), Et is total methane emissions (m^3 per year) and Pc is annual coal production (output) (t). In this study, specific methane emissions were calculated solely to compare total methane emissions with the amount of coal extracted.

The study area comprises the entire USCB (Polish part). Due to the variability of geological and methane-bearing conditions, the USCB was divided into three regions which differ in terms of geological structure, methane spatial distribution, and methane emissions (Fig. 1): (i) region 1 – north and central, (ii) region 2 – southern, and (iii) region 3 – western parts of the USCB. The basic criteria for this division were the presence or absence of overburden strata of the Carboniferous coal bearing series, the tectonic type of the area (folding or disjunctive), and methane distribution (number of methane peaks in the profile and distribution of methane contents). The boundaries of these regions are formed by large tectonic USCB fault zones or overthrusts (Fig. 1). Analysis of methane emissions was carried out separately in each individual region, and for comparison in aggregate for the entire USCB.

3. Study area

The study area, on a regional scale, is the Upper Silesian Coal Basin, which represents the foreland of a Variscan fold belt filled with Carboniferous coal-bearing molasses (Kotas, 1990). The Carboniferous coal-bearing series, which attains a thickness up to several thousand metres, is divided into four lithostratigraphic series which differ from one another in terms of the lithological character of rocks, ratio of coarse-grained sandstone to fine-grained claystone, and number and thickness of coal seams (Table 1). The overburden of the Carboniferous coal-bearing series includes Permian, Triassic, Jurassic, and Miocene deposits; however, in some places, the Carboniferous strata lie directly below Quaternary sediments.

In terms of tectonics, the dominant elements are regional faults trending NW-SE with lengths of approximately 40 km and displacements ranging from several hundred to > 1000 m to the south. In addition, folded structures such as depressions and overthrusts are found in the western part of the basin. The central and northern parts are dominated by flat folding structures such as the Main Syncline, Main Anticline, and Bytom Syncline (Fig. 1).

The gaseous conditions of the basin are complicated. The methane content in coal seams is variable, both vertically and horizontally. The vertical profile includes several zones of methane maxima. The areas bearing the most gas are the central, southern, and western parts of the basin; towards the north and east, the gas-bearing capacity of coal seams in the basin clearly decreases (Kotas, 1994).

As already mentioned, due to the differences in geological structure and gas-bearing conditions, the USCB was divided into three regions: 1 – northern and central, 2 – southern, and 3 – western.

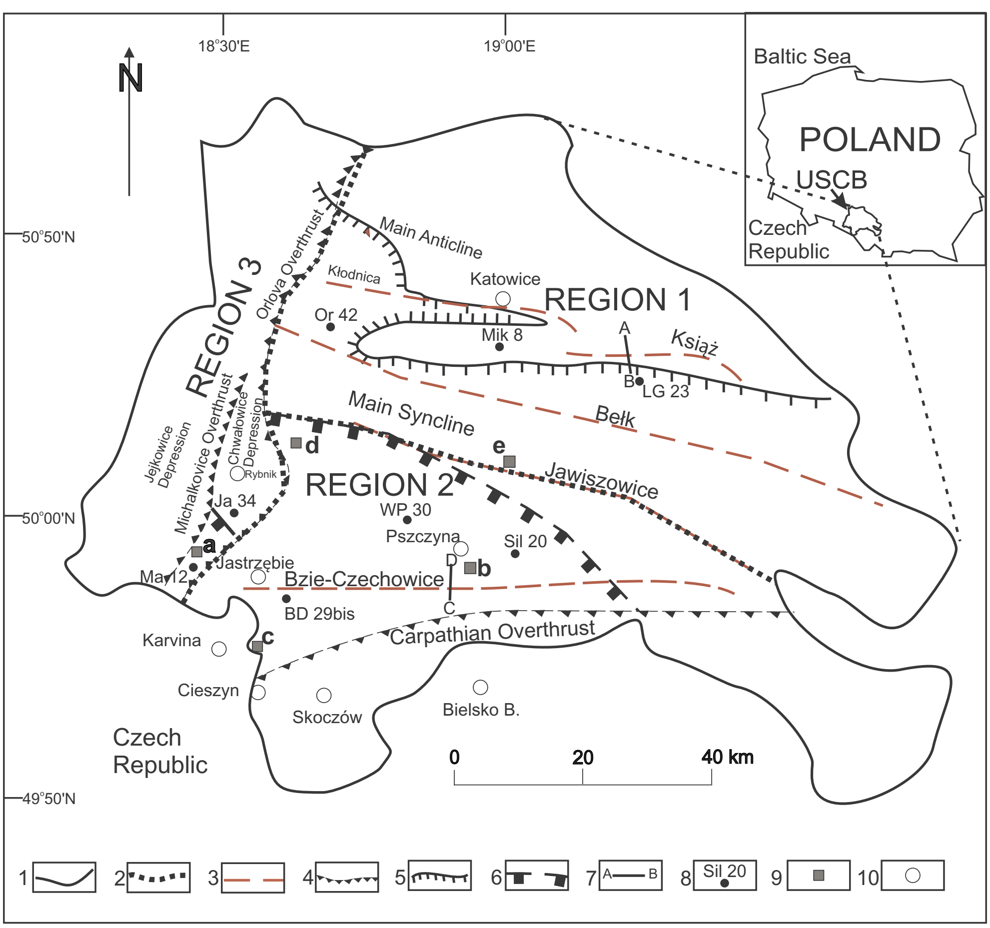

Fig. 1. Tectonic sketch of the Upper Silesian Coal Basin (modified after Kędzior, 2012).
1 – the boundaries of the Polish part of the USCB, 2 – the boundaries between the regions 1, 2 and 3, 3 – important fault zones, 4 – overthrusts, 5 – the range of the continuous Miocene cover, 6 – the range of the secondary methane zone (ticks point the direction inside the areas of ranges), 7 – cross-section lines on Fig. 7 and 8, 8 – location of bore-holes with profiles shown in Fig. 2-4, 9 – location of: a – Marklowice free gas accumulation, b – Silesia free gas accumulation, c – accumulation of gas in goaf of abandoned Morcinek Mine, d – accumulation of gas in goaf of abandoned Żory Mine, e – test of pre-mining gas drainage by surface bore-holes in Gilowice, 10 – important towns.

Table 1
Summarised lithostratigraphical division of Carboniferous coal-bearing strata in the Upper Silesian Coal Basin. Series description after Kotas (1994).

Stratigraphy		Lithostratigraphical Unit	Description	Thickness (m)
Pennsylvanian	Moscovian	Cracow Sandstone Series	Predominance of coarse-grained channel sandstones (up to 90%) over fine-grained sediments. The economic coal seams thickness reaches 6–7 m	Up to 1640
	Bashkirian	Mudstone Series	Typified by cyclically alternating coals, clays, mudstones and sandstones; sandstones makes only up to 20% of the series. Numerous but thin and irregular coal seams	From 100 to 2000
	Bashkirian	Upper Silesia Sandstone Series	Major economical coal-bearing unit in the basin, thick coal seams with average thickness in the range of 4 to 8 m in common. Predominance of coarse-grained sediments	1100 in total, it pinches out in the eastern part of the basin
Mississippian	Serpukhovian	Paralic Series	A cyclic alteration of coals and fine, and coarse clastic sediments deposited in marine, deltaic and fluvial environments. Horizons with marine fauna. Numerous of coal seams with varied thickness	From 200 to 3780

3.1. Region 1 – northern and central parts of the USCB

This region is located between the northern boundary of the basin and the Jawiszowice fault zone in the south (Fig. 1). As of the end of 2016, it contained 18 coal mines. Carboniferous coal-bearing units are covered by Triassic sediments up to 300 m thick in the north; in the middle, outcrops of Carboniferous rocks occur on the surface or are overlain by relatively thin Quaternary or Triassic deposition; in the south the underlying Carboniferous is covered with tight and impermeable Miocene clays with thicknesses up to 500 m.

Methane content in coal seams increases with depth, with two distinct gas-bearing zones evident. First, there is an upper naturally degassed zone with modest methane content (up to 2.5 m^3/t $coal^{daf}$); below this zone, an abrupt increase in methane content along with depth is noted, followed by a zone of maximum methane content (over 10 m^3/t $coal^{daf}$) (Kędzior, 2015) (Fig. 2). The depth range of this zone has not been precisely determined by drillings. Below a depth of 2000 m, methane content probably tends to decrease along with depth. The lack of a seal for gases in overburden rocks facilitated methane migration into the atmosphere in the geological past; consequently, an degassed zone is present in the uppermost part of the Carboniferous coal-bearing strata (e.g. Kotarba, 2001).

3.2. Region 2 – southern part of the USCB

This region, containing 3 coal mines, stretches between the Jawiszowice fault zone in the north and the boundary of the USCB in the south. From the west it is limited by the Orlova Overthrust (Fig. 1). Among important tectonic elements in the area are two fault zones, Jawiszowice in the north and Bzie-Czechowice in the south. Carboniferous coal-bearing units are almost entirely covered with a thick package of Miocene clays, with an average thickness of 400–500 m (ranging from 200 to a maximum of over 1000 m). In the southernmost part, Carpathian flysch is found overthrusted on Miocene and Carboniferous formations.

Methane in coal is present nearly throughout the Carboniferous profile. Two vertical zones of methane content can be distinguished (Fig. 3; Kotas, 1994; Kędzior, 2009). The secondary methane zone, with methane content amounting to 8–10 and locally even to 20 m^3/t $coal^{daf}$, is located directly below the sealing Miocene cover (e.g. Kotarba, 2001; Kędzior et al., 2013). At greater depths, the primary methane zone occurs, with methane content reaching 16–18 m^3/t $coal^{daf}$ at depths of 1000–1200 m; however, average methane content ranges between 6 and 10 m^3/t $coal^{daf}$. The maximum depth of this zone has not been determined in detail by the current drilling prospection. The two methane zones are separated by an interval characterised by lower methane content. Towards the east, the secondary methane zone becomes more and more limited, or vanishes completely, due to a thick pack of porous Łaziska sandstone, which contributes to local natural degassing of the coal seams belonging to the Cracow Sandstone Series (e.g. Kotas, 1994; Kędzior et al., 2013).

Adsorbed methane predominates in coal, but free methane also occurs in sandstone, fault zones, and breaks, in some areas under elevated pressure, which can cause methane and rock outbursts. In this case the Miocene cover acts as a trap for free and adsorbed methane derived from the deeper parts of the Carboniferous series and mixed with microbial methane, which occupies the uppermost part of the coal-bearing strata (Kotarba, 2001; Kotarba and Pluta, 2009). The largest accumulation of free methane in Carboniferous formations in region 2 is found in the Silesia gas field within the Silesia Mine (Fig. 1), in which the reservoir rocks are porous and permeable Łaziska sandstone, which has formed a dome underneath a sealing Miocene clays (Kędzior et al., 2013). The gas has been exploited several times in small amounts from the 1960s to the present time. The gas reserves are constantly supplemented with methane flowing in from the deeper part of the mine due to mining degasification (Kędzior et al., 2013).

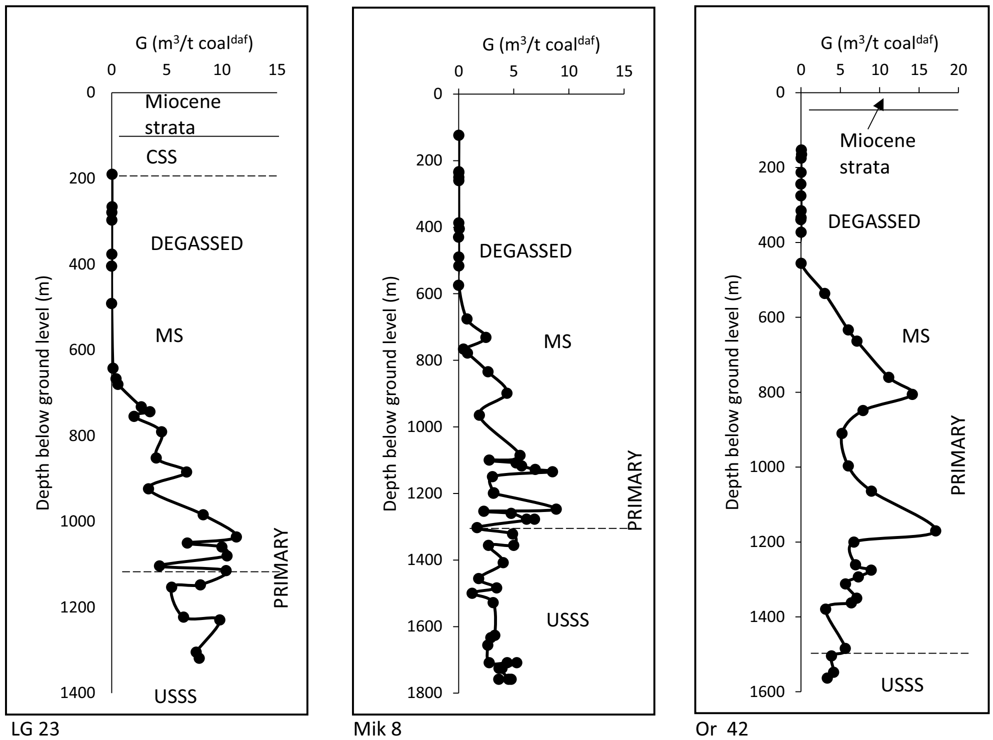

Fig. 2. Depth distribution of methane content (G) in selected boreholes in relation to stratigraphy in region 1.
Legend for Figures 2-4: Carboniferous series: CSS – Cracow Sandstone Series, MS – Mudstone Series, USSS – Upper Silesia Sandstone Series, PS – Paralic Series. Series description in Table 1. SECONDARY – the secondary methane zone in coal seams lying in the uppermost part of the Carboniferous strata, DEGASSED – naturally degassed zone, PRIMARY – the primary methane zone in coal seams lying beneath the degassed zone or secondary methane zone.

3.3. Region 3 – western part of the USCB

This region encompasses the USCB fold zone, including the Chwałowice and Jejkowice depressions (Fig. 1). In 2016, coal was mined here in 1 mine ROW created from the merger of four mines (Marcel, Chwałowice, Jankowice and Rydułtowy). The western boundary of this region is formed by a range of coal-bearing strata, the eastern by the Orlova Overthrust. The thickness of the Miocene cover varies, ranging between 0 and 1000 m. The depth distribution of the methane content includes both secondary and primary methane zones, separated by an interval of reduced methane content (Fig. 4).

Worthy of note is the historical presence of considerable volumes of free gas in sandstone and adsorbed methane in coal seams directly under the Miocene cover. The Marklowice methane deposit (Fig. 1) proved very dangerous during attempts to drill mine shafts in the 1920s. It was necessary to exploit this gas with the use of surface

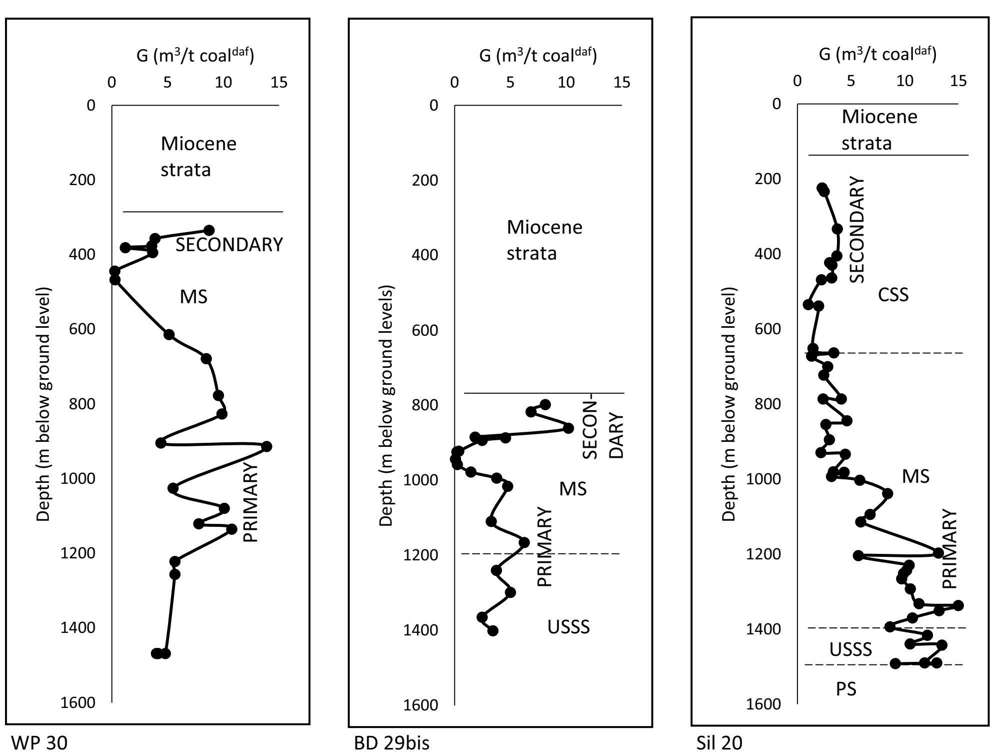

Fig. 3. Depth distribution of methane content (G) in selected boreholes in relation to stratigraphy in region 2.
Legend for Figures 2-4: Carboniferous series: CSS – Cracow Sandstone Series, MS – Mudstone Series, USSS – Upper Silesia Sandstone Series, PS – Paralic Series. Series description in Table 1. SECONDARY – the secondary methane zone in coal seams lying in the uppermost part of the Carboniferous strata, DEGASSED – naturally degassed zone, PRIMARY – the primary methane zone in coal seams lying beneath the degassed zone or secondary methane zone.

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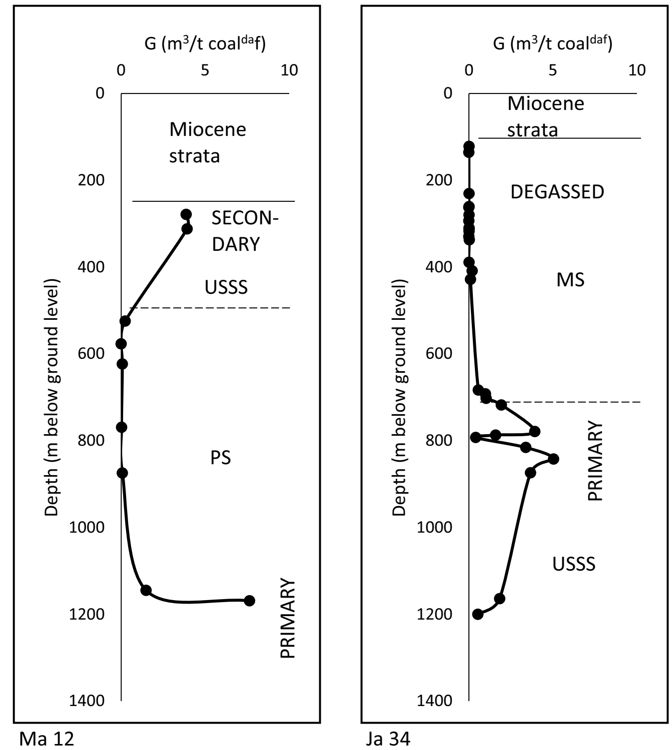

Fig. 4. Depth distribution of methane content (G) in selected boreholes in relation to stratigraphy in region 3.
Legend for Figures 2-4: Carboniferous series: CSS – Cracow Sandstone Series, MS – Mudstone Series, USSS – Upper Silesia Sandstone Series, PS – Paralic Series. Series description in Table 1. SECONDARY – the secondary methane zone in coal seams lying in the uppermost part of the Carboniferous strata, DEGASSED – naturally degassed zone, PRIMARY – the primary methane zone in coal seams lying beneath the degassed zone or secondary methane zone.

Table 2
Methane hazard categories in Polish underground coal mining (modified after the Regulation of the Minister of Interior and Administration of June 14, 2002 on natural hazards in mining plants).

Category	Methane content (m^3 CH_4/t $coal^{daf}$)
Non methane	< 0.1
1	0.1–2.5
2	$> 2.5 \leq 4.5$
3	$> 4.5 \leq 8$
4	> 8

boreholes for methane drainage, as well as to make economical use of the captured gas. The exploitation of this gas started in 1949. In the years 1949–74, approximately 330 million m^3 of gas was extracted through ca 30 boreholes. In addition, approximately 330 million m^3 of gas had been separated from the mining shaft during previous 22 years. In total, as a result of 47 years of methane drainage, the methane content in the coal was reduced by half, i.e. to about 5 m^3/t $coal^{daf}$, which corresponds to the lower limit of 3 category of methane hazard (Table 2), so further methane drainage was not necessary (Kozłowski and Grębski, 1982; Kędzior, 2009).

Within the primary methane zone, an increase is evident in the gas content of the seams from the edges (ca 5 m^3/t $coal^{daf}$) to the centre ($>$ 10 m^3/t $coal^{daf}$) of the Chwałowice Trough (Kędzior, 2009). Towards the north of the western region, the distribution of methane content is similar to that of the northern and central regions due to the absence of both a secondary methane zone and the thick and continuous Miocene cover (Fig. 4). A similar situation is found in the westernmost part of the region, where the Miocene clays have been proven not to be sealing for migrated gases.

4. Results and discussion

4.1. Methane emissions

4.1.1. Number of coal mines and categories of methane hazard

Methane occurrence is one of the most dangerous natural hazards in Polish underground hard-coal mining (e.g. Krause and Smoliński, 2013). To describe the danger connected with this gas, four categories (1–4) of CH_4 hazard are used in Polish mining (Table 2). Each category specifies the volume in m^3 of methane included in one tonne of coal (methane content) exclusive of ash and moisture (m^3 CH_4/t $coal^{daf}$) or the volume of methane emitted into the mine workings per minute.

Polish coal mines are classified as methane (gas) and non-methane (non-gas) mines. When at least one of the coal seams being exploited is within the range of methane (minimum, or category 1 of methane hazard), the working mine is classified as a methane (gas) mine. In 1994, of all 65 mines, 47 were classified as methane, 18 as non-methane (Table 3). With every succeeding year, the number of both methane and non-methane mines decreased as a result of the closures and mergers of mines throughout the USCB. In the period 1994–2016, 30 methane mines were closed. In 2015–16, seven more mines were lost due to the merger of neighbouring mines or closure. This represented the biggest difference within this two-year studied period. The number of non-methane mines decreased at a slower rate. From 1994 to 1999, non-methane mines numbered between 14 and 18. It was not until 2000 that the number of mines decreased by 6, from 14 to 7. In the following years, the number of non-methane mines remained more or less stable. In 2016, of all 22 mines, only 5 mines were classified as non-methane (Annual Report, 1995-2017; Table 3).

4.1.2. Variations in total (absolute) and specific methane emissions in 1994–2016

Total methane emissions in three selected areas are presented separately (Fig. 5a). The greatest volume of methane was emitted from mines in region 1 (Fig. 5a); in 1994, these mines released 373.5 million m^3 of methane into coal workings. An increasing trend is evident throughout the studied period, with several short-term fluctuations; in 2016, methane emissions totalled 603 million m^3.

All mines located in region 2 emitted in total of an annual average of 263.5 million m^3 of CH_4 throughout the research period. The largest volume of methane emissions was noted in 1994: 310.5 million m^3 of CH_4. Subsequently, emissions declined gradually; however, from 1999 to 2002 a significant reduction took place, as emissions of methane decreased from 270.6 to 235 million m^3. In the succeeding years, emissions increased until 2007, when 290 million m^3 was emitted. Subsequently, methane emissions declined consistently; the research period closed with 242 million m^3 of emitted methane in 2016 (Fig. 5a).

In region 3, the smallest volumes of methane in the entire studied period were emitted. The annual quantity of methane released into coal workings was usually lower than 100 million m^3. Only in 2004, 2012, and 2015 were methane emissions higher. Until 1999, release of methane into coal workings was significantly low. A period of higher emissions began in 2000, when average annual CH_4 emissions (2000–16) equalled 86.9 million m^3 of gas Fig. 5a).

In 1994, 750 million m^3 of CH_4 was emitted into coal workings in the entire USCB (Fig. 5b). In the ensuing years (1995–2001), absolute methane emissions fluctuated, with an average value at the level of 742.5 million m^3. Starting in 2002, methane emissions consistently increased to 880 million m^3 of CH_4 in 2008. A four-year period of decline was noted in 2009–12, by the end of which absolute methane emissions had fallen to

828 million m^3. The final period of the research (2013–16) is characterised by a rapid increase in methane emissions when mines in

Table 3
Number of mines, coal production, total methane emissions, methane captured and utilised in the USCB in 1994–2016 (Annual Report, 1995-2017).

Year	Number of mines		Coal output (million t)	Total (absolute) methane emissions (million m^3)	Methane captured (million m^3)	Methane used (million m^3)
	Methane	Non-methane				
1994	48	17	124.65	764.53	204.45	136.26
1995	44	16	130.61	745.31	198.29	137.09
1996	41	15	132.94	737.95	195.87	142.58
1997	39	14	133.02	790.86	205.24	140.40
1998	39	14	112.43	733.63	196.37	136.33
1999	39	14	104.93	764.81	218.02	131.66
2000	39	7	97.91	772.65	226.02	123.97
2001	37	6	98.25	756.99	219.72	131.80
2002	37	3	97.20	765.06	208.02	122.29
2003	35	5	96.24	798.28	227.11	128.10
2004	33	6	93.69	825.88	250.88	106.06
2005	28	4	91.78	851.12	255.26	144.80
2006	28	4	86.74	870.30	289.50	158.30
2007	26	4	81.71	878.91	268.75	165.72
2008	26	4	76.74	880.90	274.20	156.50
2009	26	4	72.02	855.91	259.80	159.50
2010	25	4	70.34	834.86	255.90	161.10
2011	23	4	69.67	828.82	233.85	166.29
2012	25	5	71.16	828.24	257.70	178.60
2013	24	5	68.11	847.79	259.00	187.66
2014	23	6	63.32	891.20	300.73	211.43
2015	24	6	63.74	933.20	338.98	197.09
2016	17	5	61.31	933.76	342.08	195.00

the USCB released 933 million m^3 of CH_4 into coal workings (Fig. 5b). Apart from several fluctuations, methane emissions are exhibiting a tendency to increase over time, with a difference of over 180 million m^3 between the beginning and the end of the research period.

Specific methane emissions differ from absolute methane emissions. Mines from region 2 release the most methane per tonne of extracted

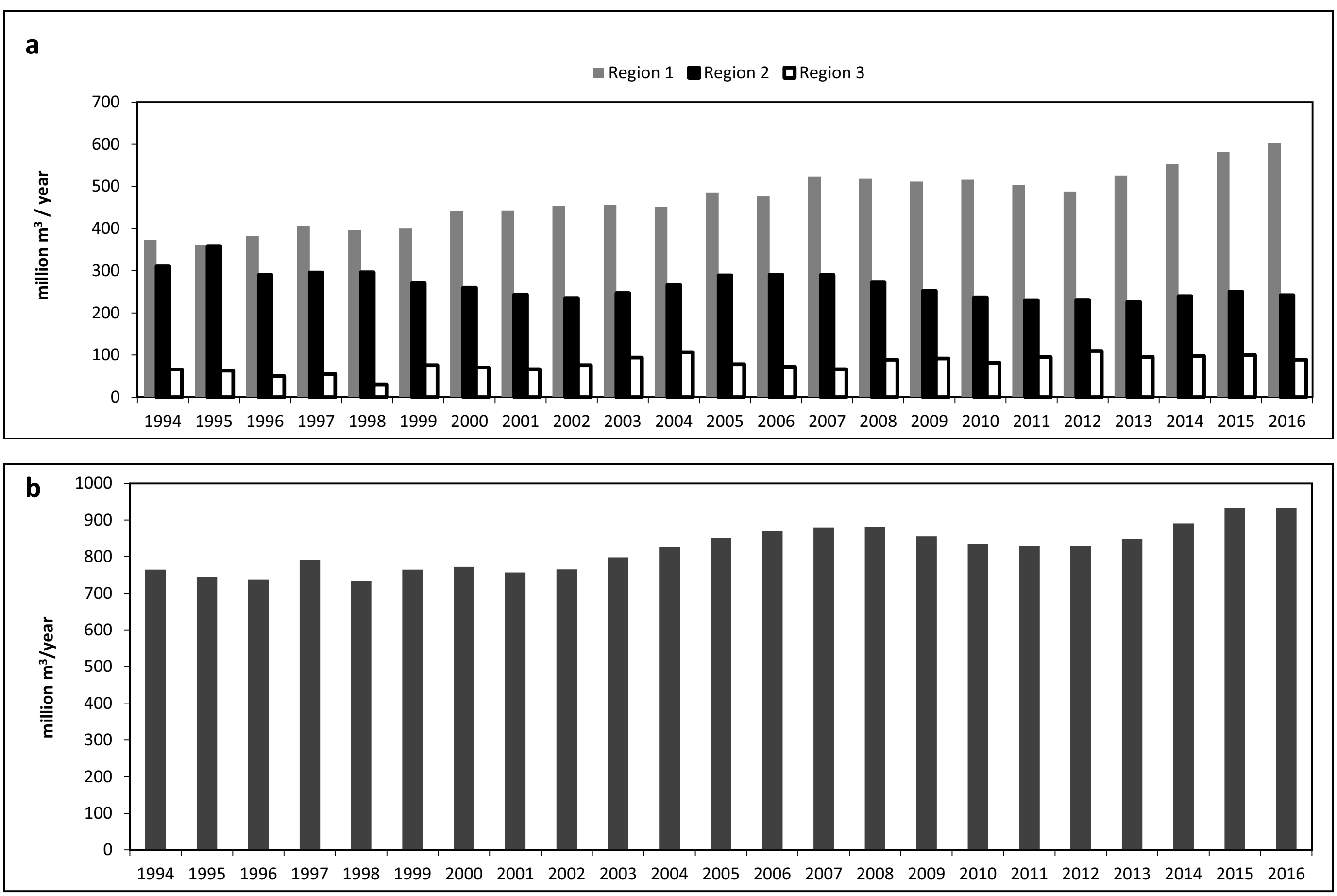

Fig. 5. Total (absolute) methane emissions in three USCB regions (a) and in the USCB as a whole (b).

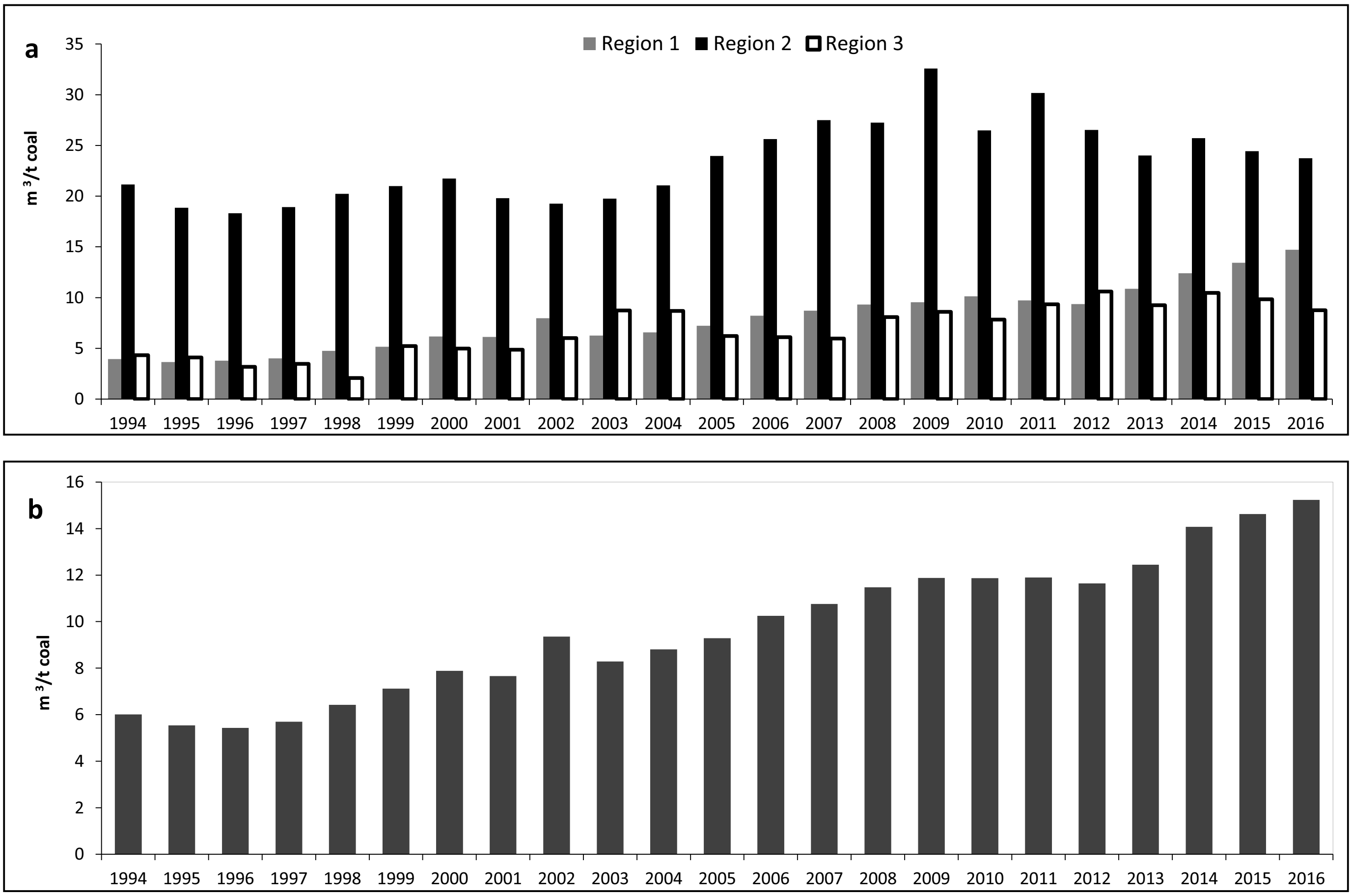

Fig. 6. Specific methane emissions in three USCB regions (a) and in the USCB as a whole (b).

coal (Fig. 6a). From 1994 to 2003, specific methane emissions fluctuated from 18.31 to 21.73 m^3 CH_4/t. As of 2003, specific methane emission increased, until 2009, when > 30 m^3 of methane was released with every single tonne of extracted coal. This represented the highest level of emissions in this region and in the entire USCB. The reason for such a high specific methane emissions in 2009 was a sharp decrease in coal production in the region (by 2.3 million tonnes compared to 2008) with only a minimal decrease in total methane emissions (only by 21 million m^3). Then, until the end of the study period, specific methane emissions decreased, with fluctuations, with 23.74 m^3/t released in 2016. Levels of specific methane emissions from regions 1 and 3 fluctuated over time. In both areas, specific CH_4 emissions fluctuated around 4 m^3/t in 1994. Subsequently, specific methane emissions steadily increased, with a slight decrease in 2003, reaching 14.71 m^3/t in 2016 (Fig. 6a). In region 3, methane emissions exhibited a variable trend. In the initial period (1994–98), approximately 2 m^3/t was emitted. In the following years, this amount increased and, in 2012, reached 10 m^3/t. Subsequently a slight decrease in specific methane emissions was recorded, and in the years 2015–16 slightly < 10 m^3/t of emitted gas was noted (Fig. 6a).

Throughout the basin, specific methane emissions have steadily increased in the period 1994–2016. In terms of extreme values, the minimum equalled 6 m^3/t of extracted coal in 1994 compared to a maximum of approximately 15 m^3/t in 2016 (Fig. 6b).

4.2. Factors influencing methane emissions

Fluctuations over time and the volume of methane liberated from coal mines in individual regions and in the USCB as a whole, presented in Section 4.1., are the result of various factors which can be classified into the following groups: (i) methane content, (ii) geological structure of the basin, and (iii) coal exploitation.

4.2.1. Methane content

Methane content includes gas lost during coal sampling, desorbed gas, and residual gas (Mc Lennan et al., 1995; Kędzior, 2009). Desorbed gas is spontaneously released from coal due to the lowering of pressure; thus it is crucial in terms of the volume of methane emitted in mine workings. The residual gas remaining in coal under environmental levels of pressure is not liberated rapidly from the coal substance; rather, its liberation is slowly conditioned by diffusion processes.

The distribution of methane content in the USCB is described as following two patterns (e.g. Kotas, 1994; Kędzior, 2009), i.e. the northern and southern patterns. The northern pattern, associated with the northern region of the USCB (Section 3.1., Fig. 2), is characterised by the occurrence of naturally degassed coal seams to depths of 400–600 m, or even greater in some areas (Fig. 7). With increasing depth (≥ 500 m), methane content increases rapidly until it reaches the primary methane maximum, after which it tends to decrease at depths of 1200–1400 m.

The southern pattern is distinguished by two maxima of methane content (Sections 3.2 and 3.3., Figs. 3 and 4). The first includes secondary methane accumulation in coal seams beneath the thick impermeable cover of the Miocene Formation. The primary methane maximum lies deeper, at the depth of the prospected limit. Both methane zones are interrupted by intervals of reduced methane content (methane minimum) which may grow thinner or totally vanish. The southern pattern corresponds to region 2 and the southern part of region 3 (Section 3.2 and 3.3., Figs. 3 and 4).

The depth of coal exploitation is greater every year, increasing by an

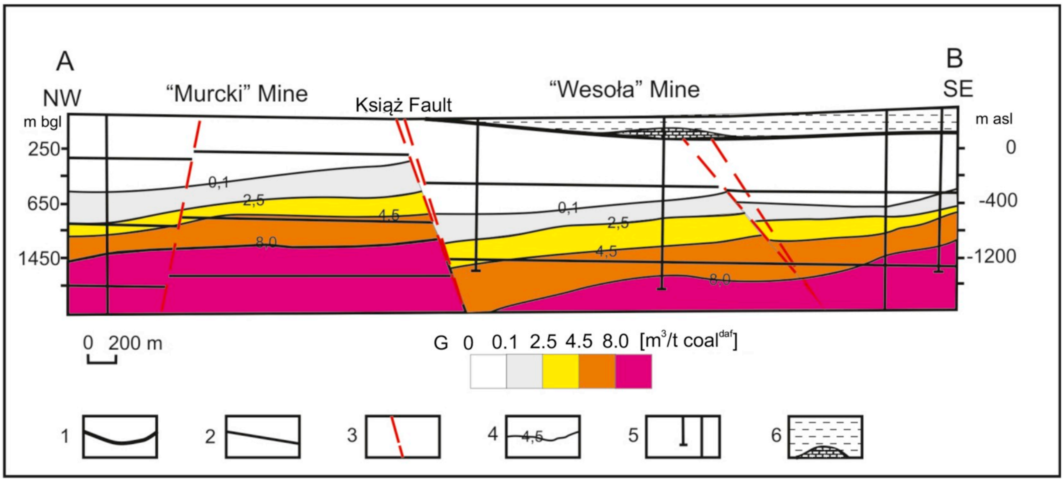

Fig. 7. Cross-section of region 1. The degassed zone (G < 4.5 m^3/t coal^{daf}) reaches a depth of 600–1400 m below ground level. The methane zone (G > 4.5 m^3/t coal^{daf}) occurring below that depth is displaced by the Książ fault.
1 – stratigraphic boundary, 2 – coal seam, 3 – fault zone, 4 – line of methane content G (m^3/t coal^{daf}), 5 – borehole, 6 – Triassic and Miocene strata.

average of 8 m per year. In 2016, mining depths reached a maximum over 1200 m and an average over

770 m, signifying that, in the northern region, coal is exploited in the primary methane zone from seams belonging to categories 3 and 4 of methane hazard (Table 2). The consistently growing methane emissions from year to year in the northern region result from the gradual relocation of coal exploitation from the degassed (upper) to the primary deep methane zone. In particular, this concerns the Budryk mine, which in the period 2005–15 recorded an annual increase in methane emissions from 56 to 88 million m^3 per year (Annual Report, 1995-2017).

In coal mines located in region 2, coal is exploited almost exclusively from seams with high methane content (> 2.5 m^3/coal^{daf}), which is associated with the presence of methane nearly throughout the Carboniferous profile (categories 3 and 4 of methane hazard). Thus, the depth of exploitation is of secondary importance here, as specific methane emissions fluctuate over time along with local minimum and maximum values (Fig. 6a).

In region 3, the volume of liberated methane is lower. This may result from the lower methane content in coal, as well as from the comparatively smaller number of coal mines with the highest category (4) of methane hazard in comparison to region 2 (Figs. 2–4, 6a).

4.2.2. Geological structure of the basin

The variations in methane content and emissions in the various regions of the basin result mostly from the diversified geological structure of individual parts of the USCB. The northern and central region (the Main Saddle and northern flank of the Main Syncline) can be described as a region with an 'open' structure for transport of media (gas and water) (Figs. 2 and 7). The term 'open' refers to the absence of a gas-tight cover in coal-bearing series, enabling the free flow of media between the Upper Carboniferous strata and the surface. Given the present low values of thickness, Triassic or Miocene cover is not a gas-tight barrier. In this situation the coal-bearing Carboniferous strata were affected by hypergenic factors, both in the geological past (during the Mesozoic and Cenozoic) and in modern times. The progressive erosion of the Upper Carboniferous, due to various weathering factors, including meteoric waters, caused considerable natural degasification of methane-saturated coal beds as well as surrounding rocks, followed by the consequent migration of released methane into the atmosphere (e.g. Kotarba, 2001). Degassing of the upper part of the Carboniferous section resulted in the formation of the two zones described in Section 4.2.1: an upper naturally degassed zone and a lower methane zone, which has probably retained gas since the time of methane generation in coal-bearing series in the Late Carboniferous period (Kotarba, 2001). The upper boundary of the deep methane zone is an isoline of methane content of 4.5 m^3/t coal^{daf} (category 3 of methane hazard), which occurs at various depths (600–1400 m), determining the so-called high methane zone top (Fig. 7).

Within the area of the deep methane zone, the variability of methane content is chiefly influenced by the lithology of Carboniferous rocks, reflected in the occurrence of gas-tight siltstone and mudstone of the Mudstone Series as well as compact and thick sandstone of the Upper Silesian Sandstone Series. These rocks provide a tight seal for beds; therefore, their methane content is high (Fig. 2). The effect of fault tectonics is reflected in the broken continuity of the zone of methane content and its shift towards the direction of fault throw (e.g. the Kłodnica or Książ fault; Fig. 7). The same phenomenon was observed in the southern part of the basin (Fig. 8) as well as in the case of the Orlova Overthrust, on which western side, in the Chwałowice Trough, methane content in coal seams is much lower (2–4 m^3/t coal^{daf}) than on its eastern side (often > 8 m^3/t coal^{daf}). Shifts of the zone of methane content resulted in a considerable difference in methane volume within one level; a zone of high methane content adjoins a non-methane zone through the fault zone (Kędzior, 2009). As described in Sections 4.1 and 4.2.1, an increasing trend in time of both total and specific methane emissions in region 1 clearly coincides with the increasing depth of coal exploitation, which has already reached levels with high methane content. At such great depths, dynamic free methane liberation has been observed, occurring under elevated pressure in the zones of tectonic breaks (faults, fissures) (Annual Report, 1995-2017). Similar observations have been made elsewhere (e.g. Thielemann et al., 2001; Karacan et al., 2011).

Region 2 and part of region 3 are located within a sealing Miocene overburden which covers the Carboniferous coal-bearing strata (Fig. 1). Secondary methane accumulations have developed here in coal beds located immediately under the Miocene-Carboniferous contact (Section 4.2.1., Figs. 3 and 4). The methane-saturated zone near the top of Carboniferous strata, ca 100–200 m thick, is separated from the deep gas-bearing zone by a low-methane interval, or else directly overlaps the deep zone, in which case the entire profile is methane-bearing.

The important element of geological structure providing the basis for developing this methane distribution is the diversified morphology of the pre-Miocene erosional surface of the Carboniferous sediments. Subsequent methane migration led to entrapment of the gas in morfologically high areas in the Carboniferous strata where the Miocene sediments cover and seal the entire coal bearing series (resulting in noticeable absence of Carboniferous outcrops). This gas entrapping system is observed to the south of the Bzie-Czechowice dislocation in the area

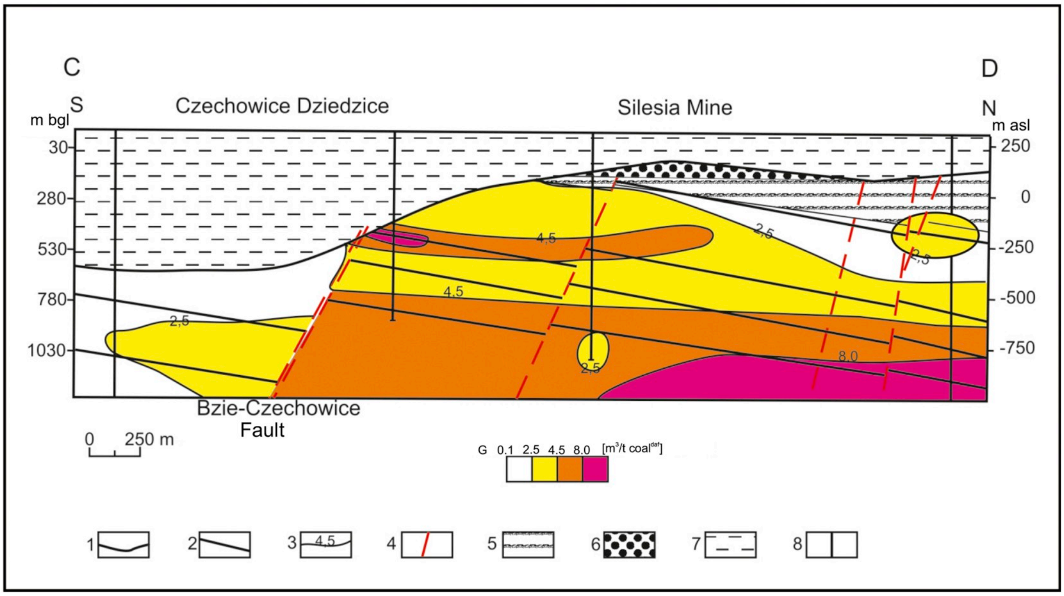

Fig. 8. Cross-section of region 2. The methane zone (G > 4.5 m^3/t $coal^{daf}$) occurs to the north of the Bzie-Czechowice fault, that influences the broken continuity of the zone of methane content. The accumulation of free methane is evident within the erosional elevation of the Carboniferous strata.
1 - stratigraphic boundary, 2 – coal seam, 3 – line of methane content (m^3/t $coal^{daf}$), 4 – fault zone, 5 – Łaziska sandstone, 6 – accumulation of free methane in Łaziska sandstone, 7 –Miocene strata, 8 – borehole.

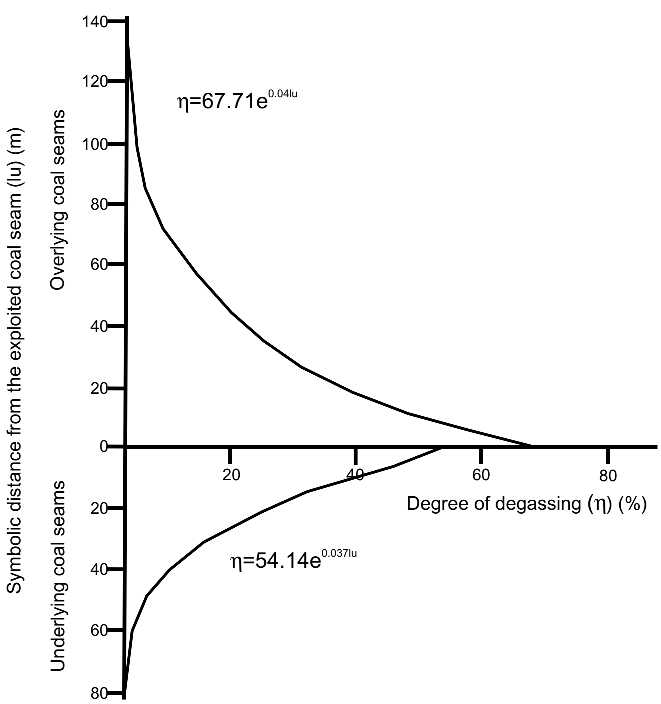

Fig. 9. Degassing of over- and underlying beds in Experimental Mine Barbara, Mikołów, Poland (modified after Krause, 2005).

of the former Morcinek coal mine and in the unmined (prospective) regions of Zebrzydowice and Bzie-Dębina. Differences in paleotopography of erosional surface of the Carboniferous contact with the Miocene are also present in coal mines such as Marcel, Borynia-Zofiówka-Jastrzębie, Pniówek and Silesia. The principle of variability of methane content is based on the occurrence of increased quantities of methane in beds located in paleoerosional highs in the upper contact of the Carboniferous series, whereas in the area of erosional depressions, the quantity of accumulated methane near the Carboniferous contact is lower, or methane does not occur at all (Kędzior, 2009; Fig. 8).

The southern USCB region (region 2) is characterised by an abundance of adsorbed and free methane in the coal-bearing series as well as its considerable accumulation in uppermost Carboniferous strata. Another characteristic feature is accumulations of free methane, forming economic concentrations, in Carboniferous sandstone (Section 3.2.) which is discordantly covered with a stratigraphically younger, impermeable Miocene cover (Fig. 8). This manner of methane accumulation may be compared to natural, conventional gas accumulations in classic secondary stratigraphic natural gas traps (e.g. Selley, 1998), formed chiefly as the result of discordant arrangements of rock strata.

As mentioned in Section 4.2.2, total methane emissions fluctuate over time, but the largest emissions were noted in Pniówek (116 million m^3/year) and Krupiński (75 million m^3/year). Both of these mines are adjacent to large regional faults, Bzie-Czechowice and Jawiszowice, respectively. Additionally, the Bzie-Czechowice fault is characterised by the presence of so-called ‘gas pockets’, i.e. relaxed zones capable of releasing significant quantities of free gas in a short time. In this fault zone, gas outbursts have occurred (e.g. Zofiówka Mine in 2005), claiming several fatalities. Fault zones facilitate gas migration due to the increased permeability of coal seams and surrounding rocks (e.g. Noack, 1998; Gentzis et al., 2007; Karacan et al., 2008; Alsaab et al., 2009).

Cao et al. (2001) evaluated the occurrence of gas outbursts along reverse faults in selected Chinese coal basins and revealed that these disasters were more frequent in footwalls than in hanging walls. They explained that the tectonic deformations to which the footwalls were subjected caused alterations in the primary inner structure of coal consisting in the formation of cataclastic coal, granular coal and mylonitic coal, which favours the accumulation of gas under high pressure and as a consequence gas outbursts. In the USCB, gas and rock outbursts occur mainly in the Bzie-Czechowice fault zone (Pniówek and Zofiówka mines) and are associated with zones of structurally altered coal, e.g. mylonitic coal zone in the Zofiówka mine. Therefore, tectonic deformations of coal may also apply to normal faults, i.e. the Bzie-Czechowice fault zone.

Some faults in the USCB may also have gas-tightness. Geochemical studies carried out in the near-surface zone (Sechman et al., 2019) showed a lower methane anomaly in the soil gas over the Jawiszowice fault than in the area of the Bzie-Czechowice fault, which may indicate

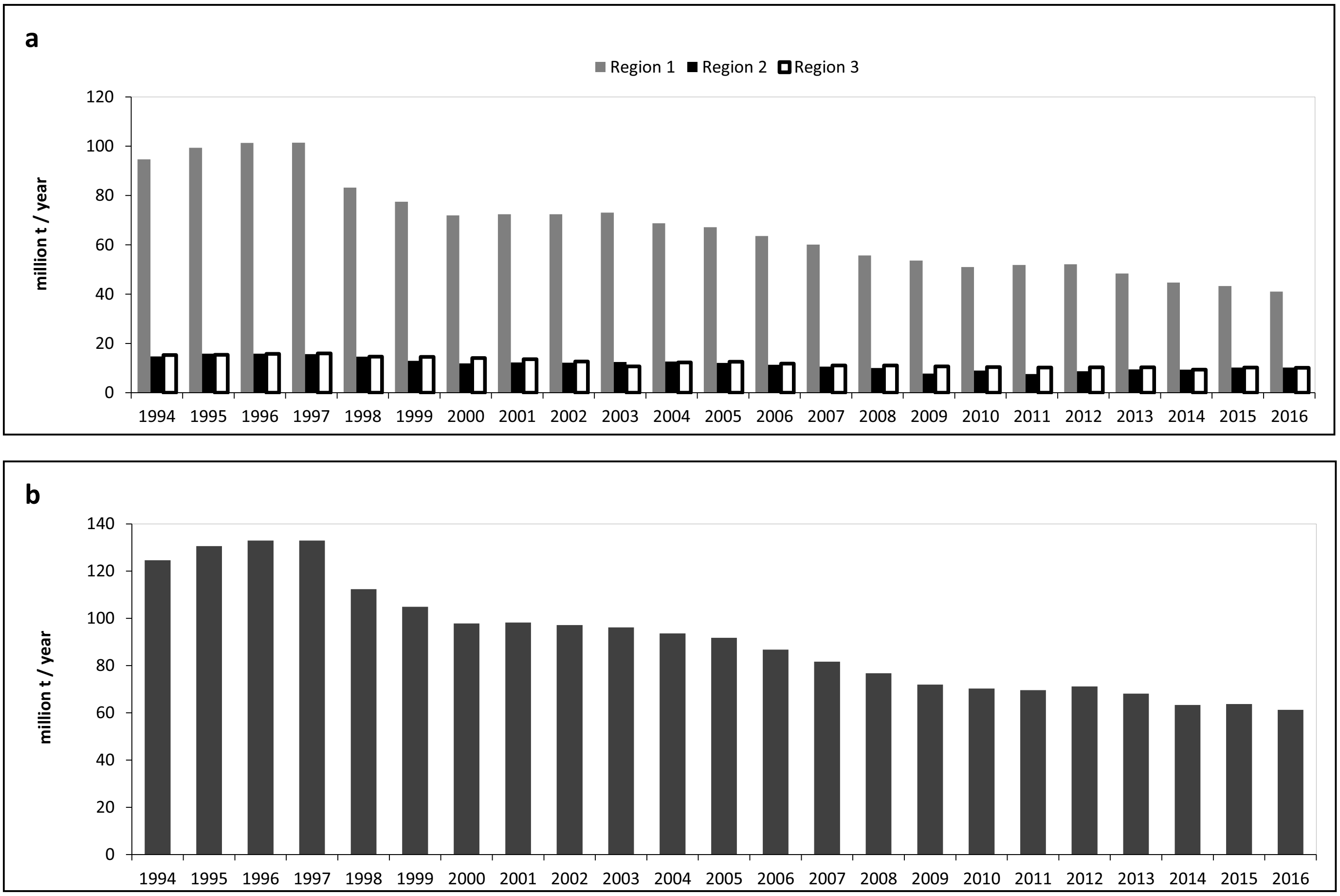

Fig. 10. Coal production in three USCB regions (a) and in the USCB as a whole (b).

the gas-tight nature of the Jawiszowice dislocation in contrast to the Bzie-Czechowice fault. In this context, the high methane emissions in the Krupiński mine may result from the high gas content of the coal seams that are additionally sealed with the gas-tight Jawiszowice fault or with the concentration of coal mining (see Section 4.2.3).

Cap rocks such as the Miocene cover constitute an effective seal for migrating gases and thus enable their accumulation under increased pressure.

In the southern region, the largest specific methane emission in any of the described regions (> 20 m^3/t extracted coal, see Section 4.1.2, Fig. 6a) merits attention, as it is 2 to 4 times higher than methane content in coal seams.

This clearly proves that the sources of methane emissions are not only extracted coal seams, but also the zones surrounding them. Global research has shown that a degassed zone can cover a distance of up to 200 m above and up to 100 m below the coal seam being exploited (Lunarzewski, 1998; Krause, 2005; Karacan et al., 2011; Ju et al., 2016; Duda and Krzemień, 2018; Fig. 9). Other sources of methane emissions include sandstone with accumulated free methane and fault zones filled with methane. The geological structure of the southern part of the USCB (region 2 and the southern part of region 3), distinguished by the presence of a sealed Miocene overburden, erosive elevations built of porous sandstone, and gas-pathway fault zones, allows methane to be accumulated in various forms (adsorbed and/or free) and then released during coal exploitation. Therefore, this region has always been regarded as one of the most dangerous in Polish mining due to methane emissions and gas hazards.

4.2.3. Coal exploitation

There are three sources of methane emissions from Polish hard coal mines (Patyńska, 2013). The first consists of areas of mined longwalls involving both the coal seam being currently exploited and under- and overlying seams which have decompressed due to mining (Section 4.2.2., Fig. 9); the second comprises post-mining goaf isolated from active excavations by explosion-proof dams; the third consists of drilled development excavations. Of the listed sources of methane emissions, the first two are of substantial importance, accounting for 90% of total emissions.

During the 23-year period 1994–2016, the number of hard coal mines in the USCB was reduced from 65 to 22, while coal output decreased from over 130 to approximately 60 million tonnes per year (Sections 1 and 4.1.1) (Fig. 10). Hard coal in the Upper Silesia region is almost exclusively exploited by means of a longwall system with the use of heading machines. One characteristic trend in Polish mining during the economic transformation has been the prevalence of coal mining involving increased coal production from one wall (about 2.5–3 thousand tonnes per day). As a result, thick coal seams (> 1.5 m in thickness) are preferred for mining, as they allow for e.g. greater wall heights, which, since 1990, average between 2 and 3 m (Turek, 2007). The share of thick and very thick coal seams (> 1.5 m in thickness) in developed reserves of coal in the USCB is over 80%. The height of the wall is in fact a factor strongly influencing the volume of gases released from the currently extracted coal seam with a heading machine, as well as from underlying and overlying seams and mining goaf and, in the case of close-lying seams, from longwall excavation (Krause, 2005).

The concentration nature of coal extraction also involves extension of the lengths of walls. This affects the volume of methane emissions, because the length of a wall affects the extent of the relaxed zone around the bed being exploited. As a result of extending the length of the wall, the range of relaxation of the bed from top to bottom increases, as does the volume of gases released from the under- and overlying seams (Krause, 2005). Thus, designing walls over 200 m in length contributes to a significant increase in methane emissions due to the concomitant increase in the volume of decompressed deposit. In fact, 100% more methane is released from a wall 300 m long than from one 200 m long. Therefore, it is important to consider the length of the walls in coal seams with a high category of methane hazard (E. Krause, oral information).

Another factor affecting the amount of methane emitted is wall advance. On average, this value ranges from several to 15 m per day in the USCB. Acceleration of the rate of wall advance causes relaxation and unsealing of the rock mass in the zone in front of, above, and under the wall frontage. Breaks created in this way serve as pathways of methane flow to the wall goaf. The decompressed zone of rock mass in front of the wall frontage can reach > 100 m given a wall advance of 6 m per day (Krause, 2005).

Coal exploitation at ever greater depths where the methane content of the coal seams is high (Section 3.1), given the current high level of concentration of coal mining, causes a constant increase in gas hazard; thus methane emissions follow an increasing trend in the basin's mines despite the decline in coal extraction. This is evidenced by the constantly increasing specific methane emissions of the USCB mines, which reached a record 15.05 m^3/t of extracted coal in 2016 (Fig. 6b). Of the 63 million tonnes of coal extracted in 2015, 88.5% came from methane seams, the remaining 11.5% from non-methane seams (Annual Report, 1995-2017). In 2015, 933.02 million m^3 of methane was released from the rock mass covered by mining exploitation, which means that, on average, 1773.15 m^3 of methane was released per minute (Annual Report, 1995-2017). This equates to a nearly 5% increase compared to the previous year. Methane emissions were similar in the following year (Fig. 5b).

Another problem which cannot be neglected involves methane emissions from abandoned mines into the goaf, because methane emission does not cease with the cessation of coal mining. Estimates following the model enabling the estimations of the volume of methane emitted into longwall goafs from relaxed coal seams for the abandoned Anna Mine (Duda and Krzemień, 2018) revealed that emissions can continue for > 10 years following mine closure (with a decreasing trend from year to year), and predicted that during this time (2017–23) a total of 7.9 million m^3 of methane will be liberated into the mine goaf. It should be noted that approximately 30 methane mines have been closed in the Upper Silesia region since 1994 and that gas accumulated in those goafs can be exploited as fuel (see Section 5).

5. Methane utilisation

The results presented in Section 4.1. show that methane emissions in the USCB during the period 1994–2016 display an increasing trend in spite of the reduction in coal output, while in individual USCB regions this trend is variable and depends mainly on the distribution of methane content, number of active coal mines, and relevant geological structure. In 2016 > 930 million m^3 of methane was emitted from the entire basin, of which 68% derived from the northern and central region, 26% from the southern region, and the remaining 6% from the western region (Annual Report, 1995-2017; Fig. 5a). The increased depth of coal exploitation in the USCB, which has reached the zone of high methane content and pressure, results in a high level of methane emissions notwithstanding the reduced coal output at present. This problem cannot be neglected, especially since it may grow worse in future.

The factor preventing ventilation emissions and methane hazards in mines is methane drainage from the rock mass, in association with economic use of the captured gas (e.g. Karacan, 2009; Karacan et al., 2011; Patyńska, 2013; Kędzior, 2015). Gas (methane) drainage (degasification) is carried out prior to coal exploitation (pre-mine methane drainage), during coal extraction, and from abandoned mine workings (post-mining goaf). Fig. 11 shows changes in the total (absolute) methane emissions, methane captured and utilised in the USCB throughout the entire research period. In 2015, almost 339 million m^3 of methane was output by drainage mining systems in the USCB, of which 328 million m^3 was intended for use. The greatest volumes of gas were collected from mining excavations (during coal exploitation) (66%); in second place were those collected from goaf (32%). Pre-mining degasification was marginal (only 2%) (Annual Report, 1995-2017; Fig. 12). Capture (drainage) efficiency, defined as the ratio of methane captured by underground gas systems to total methane emissions (including ventilation shafts), amounted in 2015 to approximately 36%. Of 328 million m^3 of methane intended for utilisation, only 197 million m^3 was actually used (ca 60%) (Annual Report, 1995-2017; Table 3; Fig. 11). The rest of the captured methane was emitted into the atmosphere as so-called 'discharge'. The fact that the volumes of gas captured and used are both systematically growing from year to year (Table 3; Fig. 11) is a positive development. In 2005, 255 million m^3 of methane was collected, of which 145 million m^3 was used; in 2015, these values were 327 and 197 million m^3, respectively. The existing degasification stations are being expanded and new ones are being built; however, there are frequent problems with the sale of the captured gas, which is, in fact, a methane-air mixture characterised by unstable composition, in which the share of methane fluctuates between 40 and 60%. Such gas can be combusted only in specially dedicated installations and cannot be transferred into the high-methane gas distribution network. Another problem is the inability to store gas surpluses during periods of lower demand (in spring and summer months) due to the lack of gas storage in mines. Thus mining gas is used by mines for energetic purposes,

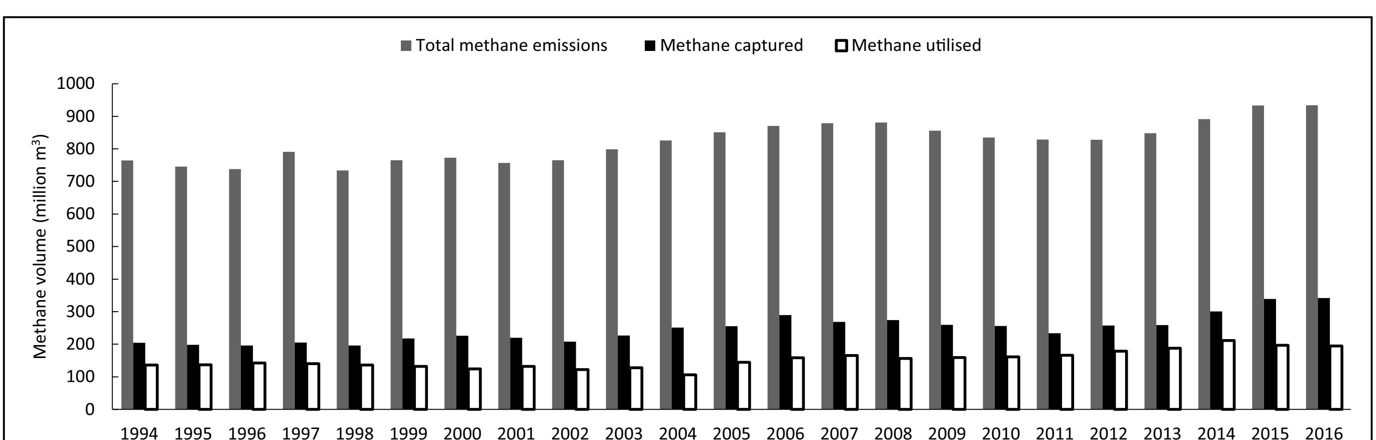

Fig. 11. Total (absolute) methane emissions, methane captured and utilised in the USCB in 1994–2016.

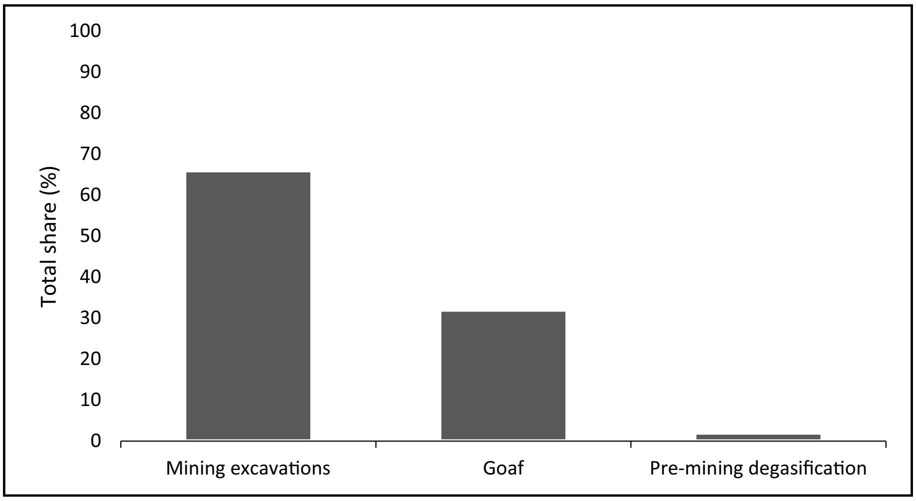

Fig. 12. Sources of methane emissions in the USCB in 2015.

including heat and electricity generation, and sometimes cooling (as part of tricogeneration). Mining methane is also used by external consumers, i.e. local heat and power stations, municipalities, schools, etc.

Gas from abandoned workings (goaf) is characterised by a more favourable composition (almost 90% methane), and thus can be sold and used for any purpose. Therefore, several contractors, having acquired operating licences for methane exploitation from abandoned goaf, exploit it using surface boreholes. The greatest volumes of this gas are extracted from the abandoned Żory Mine (located on the boundary between regions 1 and 2; Fig. 1) at a level of approximately 3.2 million m^3 per year.

Pre-mine drainage was limited in the USCB (Fig. 12) due to the low level of efficiency resulting from the poor permeability of coal seams untouched by mining; however, for some time, coal seams have been tested in the Upper Silesia basin by means of a surface-to-inseam borehole doublet, consisting of a vertical borehole intersected by a horizontal borehole in a coal seam. Tests of gas operation are performed several years before coal extraction begins in a given region, with the goal of reducing the methane content of the coal seam and thereby reducing future gas hazards. In order to increase capture efficiency, hydraulic fracturing is used to increase coal permeability. The results of the tests carried out so far by the Polish Oil and Gas Company (PGNiG) and the Polish Geological Institute (PGI) in the area of Gilowice on the boundary between regions 1 and 2 (Fig. 1) are promising. Similarly, tests conducted in mine workings have also yielded positive results.

The extraction and economic use of methane from coal mines in the USCB is extremely important from the viewpoints of the reduction of methane emissions into the atmosphere, the safety of miners at work, and the energy balance of the Upper Silesian region.

6. Conclusions

In the analysed period covering the years 1994–2016 in the USCB, coal production was reduced more than twofold, from 130 to approximately 60 million tonnes per year, while absolute methane emissions from coal seams covered by mining exploitation increased from 750 to over 930 million m^3 yearly within the same period.

Of the three analysed regions, the largest volume of absolute methane emissions was recorded in region 1, comprising the northern and central part of the basin, due to its having the greatest number of mines and to the increasing depth of exploitation to a point at which the volume of methane in coal seams is greater due to the presence of a primary (deep) methane zone at a depth below 400–600 m.

The highest level of specific methane emissions was found in region 2, in which high methane content occurs almost throughout the Carboniferous profile due to the occurrence of a sealing Miocene cover that blocked the escape of methane into the atmosphere in the geological past. In addition, the presence of free methane under high pressure in the relaxed parts of the rock mass (faults, rock fissures) is the cause of sudden methane and rock outbursts into mining excavations.

Our observations revealed that changes in methane emissions over time vary between different individual regions as well as throughout the USCB. This is due to the diverse geological structure of the basin and various natural (geological) and mining factors affecting the volume of methane emissions.

The most important natural factors include methane content in coal seams formed by geological factors such as the presence of sealed Miocene deposits, the lithology of Carboniferous strata, and tectonics, expressed by the presence of faults and relaxed zones in the rock mass, that allow migration and accumulation of gases.

Important mining factors are the constantly increasing depth of coal exploitation, along with the growing amount of methane accumulated in the rock mass, the progressive concentration of coal output as manifested in increases in the length and height of the walls and in wall advance, which, taken together, contribute to the increase in methane emissions into mine excavations.

An activity that may counteract the increase in methane emissions from year to year is the intake of released gas by underground methane drainage systems. The progressively increasing volumes of both captured and used methane in the USCB should have a positive effect on the reduction of methane emissions, the work safety of miners, and the energy balance of the Upper Silesia region.

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MINERAL MINING TECHNOLOGY

Variabilities in Hard Coal Production and Methane Emission in the Mysłowice–Wesoła Mine

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Abstract—Hard coal production is a strategic branch of the Polish economy. The exploitation processes at greater depths encounter natural hazards, such as methane hazard. The Mysłowice–Wesoła mine is located in the largest coal basin in Poland—the Upper Silesian Coal Basin (USCB). Methane concentration increases with depth in this area of the studied basin. During the period of gas research, the volume of emitted methane increased over 5 times. This large increase in methane liberation to the mining faces was caused by many factors, including complex tectonic characteristics of the area, permeable nature of the Książ Fault, varied geological structure, higher concentration of coal extraction. The overall study of coal output for the years 1994–2018 follows the entire Polish hard coal production trend, namely, slow, yet constant coal extraction decrease. The total coal output in the Mysłowice–Wesoła mine decreased more than twice with simultaneous increased methane emission.

Keywords: The Upper Silesian Coal Basin, methane emissions, Mysłowice–Wesoła mine, Polish Mining Group, hard coal output.

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INTRODUCTION

Hard coal has been one of the most important energy sources for the Polish economy, power and heat generation for many decades [1, 2]. Poland is the prime hard coal producer in the European Union with 95% market share, the rest of the output (5%) originates from the Czech part of the Upper Silesian Coal Basin (Karvina region) [3, 4]. The Polish Mining Group (PMG) is the largest coal mining enterprise in Poland and in Europe. It pools 14 mines which provide 47% of hard coal output in the country [3, 5]. One of the most important members of PMG is the Mysłowice–Wesoła Mine located in the northern part of the Upper Silesian Coal Basin—the largest coal basin in Poland. The Mysłowice–Wesoła Mine is characterized by the highest methane hazard among all mines of PMG. However, it produces the highest amounts of the energetic coal in the Group, becoming the representative mine showing changes in methane emissions (1974–2018) and hard coal production (1994–2018). Hard coal production in Poland decreases every year. Political and economic changes connected with easily extracted, shallow lying coal seams which were depleted in the past caused that mining enterprises had to reach for the deeper lying and, at the same time, methane-rich coal beds. Such activities involve higher costs and greater natural hazards. Polish coal mines produced over 100 million t/year till the end of the 20th century. During the following years the overall output was gradually but constantly decreasing and dropped to 63 million ton of extracted coal in 2018 [1–3]. The complex geological structure, disturbed tectonic characteristics and overburden are the cause of the inhomogeneous methane-containing structure. The absolute methane emission in the Upper Silesian Coal Basin has been changing in time. Until 2003, the total recorded CH_4 emission was under

800 million m^3 per annum. In 2004, methane emission from all USCB mines exceeded 800 million m^3 and in 2015 it was over 900 million m^3. The entire emission values fluctuated from year to year, but the emission trend is increasing [1, 6]. Similar, rising emissions were recorded in other coal basins worldwide e.g. [7]. The paper presents changes in methane emission in the years 1974–2018 and coal production in the years 1994–2018. This time period overlaps with coal production entering to high methane coal seams in the Mysłowice–Wesoła mine (1974–2018). The coal output values show the last 25 years (1994–2018) as the background for CH_4 emission changes.

1. MATERIALS AND METHODOLOGY

Official data used in the research (geological structure of coal deposits, stratigraphy, lithology, tectonics, methane emissions, methane content and overall hard coal output, longwall technical parameters) were obtained from official geological documentation [8] prepared specially for the Mysłowice Mine, member of the Polish Mining Group. Supplementary data were obtained from Annual Reports (for the years 1994–2018) on the state of basic natural and technical hazards in the hard coal mining industry [3] published annually by the Central Mining Institute (GIG) in Katowice and from Accident Statistics [5] published by the State Mining Authority in Katowice.

The natural *methane concentration (content)* in coal is measured using the vacuum degassing method. The coal samples (collected from the mine, side walls and surface boreholes) placed in a hermetic container are completely degassed by the created vacuum and the result is given as cubic meters of CH_4/ton of coal *daf* (*daf*—dry and ash free coal substance)—m^3/t *daf* [8–10]. Polish health and safety regulations based on the regulation of the Ministry of the Environment and the Ministry of Energy impose sampling for methane concentration measures at 200 m intervals in a drifted excavation and classify the coal seam group to one of the four categories of methane hazard [11, 12]:

Category	Methane content, m^3/t *daf*
Methane-free	< 0.1
I	0.1–2.5
II	$> 2.5 \leq 4.5$
III	$> 4.5 \leq 8.0$
IV	> 8.0

In the paper, the total (absolute) methane emission is presented as a sum of the average yearly ventilation methane emission (VAM) Q_{vam} and CH_4 captured by underground drainage system (outgassing) Q_o: $Q_{total} = Q_{vam} + Q_o$. The outgassing Q_o refers to the volume of captured methane in the underground methane drainage network and is measured constantly by gas/methane detectors. The specific CH_4 emission Q_{sp} refers to methane emission calculated per single extracted ton of coal [13]:

$$Q_{vam} = \frac{VSC_m}{100},$$

where S is the cross sectional area of the ventilation duct, m^2; V is the air flow rate; C_m is the methane concentration in ventilation air, %.

The specific methane emission per 1 t of coal produced:

$$Q_{sp} = \frac{Q_{total}}{P_c},$$

P_c is the hard coal output, t/yr.

2. OUTLINE OF GEOLOGICAL STRUCTURE

The Wesoła coal deposit is located in the northern part of the Main Trough in the Upper Silesian Coal Basin. This a multilayer deposit consisting of 41 documented seams with various thicknesses and qualities of the beds. The geological structure of the coal deposit is composed of Carboniferous, Triassic, Miocene and Quaternary deposits with complex tectonic characteristics.

The lithostratigraphic division of Carboniferous strata proposed by Doktorowicz–Hrebnicki and Bocheński was applied [8, 14]:

• *Namurian A–Poruba layers* (coal seams group 600) are the bottom part of the Carboniferous strata in the Wesoła coal deposit. There are no many coal seams found in the Poruba layers. Only one, the 610 coal seam, was studied and documented but it has not been mined yet. Other coal seams are too thin and constitute anticipated subeconomic resources. The Poruba layers were developed as dark grey siltstones, mudstones (with marine fauna) and fine to medium-grained sandstones;

• *Namurian B–Saddle layers* (coal seams group 500). The most important coal seam present in the Saddle layers and in general is the 510 coal seam. The total thickness of the 510 seam, which is the most economic coal seam, is around 13 meters. This seam is found at a depth of between 480 m below the ground level in the northern part of the deposit and 800 metres north of the Książ Fault. In the southern area, the 510 seam occurs at 940 to 1000 m below the ground level Furthermore, in the northern area of the Wesoła deposit a 501 seam is found with has a thickness of 4.4 m;

• *Westphalian A–Ruda layers* (coal seams group 400) are characterized by different lithological composition and have been divided into upper and lower Ruda layers. Upper Ruda layers are composed of mudstones, claystones and sandstones with numerous inserts of coal seams. Lower Ruda layers are built of different type of deposits. The predominant rock type is medium-grained sandstone with less numerous coal seam inserts. In the entire group 11 coal seams were found and seam 416 is now being mined;

• *Westphalian B–Orzesze layers* (coal seams group 300) occur over the entire studied area and were developed as the youngest Carboniferous strata in the northern part of the deposit. The thickness varies from 600 m (north) to 800 m (south). The Orzesze layers are built of alternately deposited sand claystones, claystones and sandstones and numerous coal seams. There are 22 coal seams numbered from 301 to 364;

• *Westphalian C–Łaziska layers* (coal seams group 200) are found in the southern area of the deposit. In the northern area of the Wesoła coal deposit almost all Łaziska layers were eroded or occur as small patches in the western part. The entire profile thickness varies from 85 to 260 metres and it is composed of thick sandstone – conglomerate complex with claystone inserts. Three coal seams were found in Łaziska layers located only in the southern part of the deposit, and characterized by small thickness.

Triassic deposits are found in the southern area of the coal deposit and are represented by limestones, marls and sand-silt deposits and they are 3–125 m thick. There is lack of Triassic formations close to the Książ Fault. Miocene formation is represented by loams, shales, sands, silt, sandstones and conglomerates. The overall thickness varies from 7 to 216 m. The highest thickness occurs in the southern part of the deposit, close to the Książ Fault. North of the Książ Fault, Miocene deposits are found locally in eroded parts of the Carboniferous deposits. Quaternary formation was deposited over almost all of the studied area. Pleistocene and Holocene deposits were developed as clays, sands, gravels and cobbles. The thickness varies from 0.1 to almost 60 m. The overall thickness of the Carboniferous overburden varies from 0.1 to over 200 m.

The Wesoła coal deposit is characterized by the occurrence of numerous faults. The main tectonic dislocation is the Książ Fault, which divides the coal deposit into two major areas/parts: the northern (main area/part) and the southern area/part. In the northern area, the dip of deposits is 4–6° southwards. In the southern area the dip is 2–8°, closer to the Książ Fault it rises to 8–14°, but in the direct proximity (100 m width zone) the dip rises twice, to 16–28°. The maximum depression occurs 300 m from the Książ Fault, in next phase, the Carboniferous deposits gently rise up in the southern direction forming an anticline in the central and south-eastern part of the coal deposit. The main dislocation is the Książ Fault (SWW–NEE direction) which throws the deposits from 320 to 420 m to the South and the width of dislocation zone is about 300 m (Fig. 1). In the Wesoła coal deposit many other faults occur, dividing the deposit into smaller areas/parts.

3. METHANE OCCURRENCE AND HAZARD IN THE UPPER SILESIAN COAL BASIN

Methane hazard is one of the most dangerous and unpredictable natural threats in the Polish and global underground coal mining industry [6]. Methane is an undetectable gas for human senses. It is lighter than air, displaces oxygen from the mining air, making it non-breathable [16]. Unfortunately, methane is characterized by high explosivity, when its concentration in the air mixture reaches 5–15%. An open fire (previous explosion, cigarette smoking) or a single spark (e.g. roadheader works in sparking sandstones) can start the ignition and explosion [9, 16]. Moreover, methane presence in the mining air substantially increases the power of a coal dust explosion [17].

Methane is a potent greenhouse gas that contributes to global warming, and it can arise from both human activities and natural emissions [18, 19]. CH_4 sustains for from 9 to 15 years in the atmosphere while carbon dioxide can persist for around 100 years and it is a heat absorbent 25 to 30 times stronger than CO_2. The main global emitters of CH_4 are peatlands, livestock, rice fields, thermokarst lakes and industry [20, 21]. The European Union's International Energy Agency attempts to include methane gas in the European Emissions Trading System (ETS). If this happens, CH_4 will be treated as a 30 times stronger heat absorbent than CO_2. Mining industries will have to pay huge sums for every tone of methane emitted directly into the atmosphere. It is estimated that after including CH_4 in the EU ETS, the coal production costs will increase in Poland by 1 billion Euro a year [21, 22]. In Poland, over 900 million m^3 of methane was emitted from coal and surrounding rocks to the mining excavations in recent years (2015–2018). More than 70% of the emitted gas (on the average) goes directly into the atmospheric air via ventilation shafts [1, 3, 5, 6].

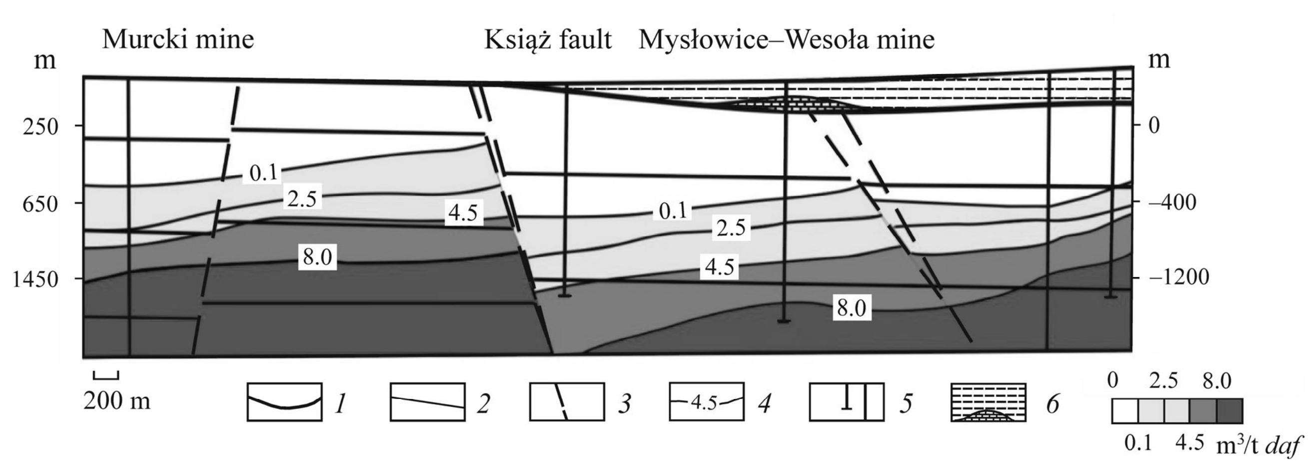

Fig. 1. Cross-section of Mysłowice–Wesoła mine region: *1*—stratigraphic boundary; *2*—coal seam; *3*—fault zone; *4*—line of methane content G (m^3/t *daf*); *5*—borehole; *6*—Triassic and Miocene strata.

Methane factors and methane occurrence. Methane gas was formed during coalification processes of organic substance and is present in Carboniferous coal bearing strata in free and adsorbed state. In sorbed state methane is combined with coal physically and chemically, but in the free state methane fills voids, cracks and pores in coal and surroundings rocks [23–28]. The maximum amount of methane produced during coalification processes was 255 m^3 from 1 t of coal [29]. Methane occurs in coal bearing strata in a pressure balance. During mining activities, such as excavation drifting, the sorption balance is disturbed and methane is released into coal workings. The most intense gas inflow takes place after an exposure of a new surface/wall, afterwards the emission decreases in time as a result of pressure and thermodynamics equalization [30–32]. In addition to that, methane migrates to coal excavations also from overmined and undermined strata, from goafs and directly from extracting a coal face by crushing coal [23, 33, 34]. In unmined areas, normal faults regularly act as CH_4 conduits for surface emissions into the atmospheric air from deep coal formations. The concentration of coal production is also one of the factors which increases methane emission. Longwall technical parameters, such as its length, height and daily extraction progress, determine the coal output concentration. In recent years the average longwall length increased by 41% and other parameters like coal output concentration, the average daily output from one longwall and finally, the absolute methane emission have also risen [3, 33]. In the Polish underground coal mining in the years 1990–2008 the average longwall height increased from 2.28 to 2.59 m, the longwall length increased from 159 to 223 m and the daily advance rate increased from 2.04 to 3.83 m/day. On the other hand, the average daily advance rate of development works decreased from 6.46 to 4.51 m per day [33]. Every breakdown, unexpected stoppage and slowdown can increase CH_4 emission to the excavation from new coal face, crushed coal, breaks, overlying and underlying strata due to constant methane liberation to the coal workings. The technical parameters like longwall run and height have to be designed considering the natural hazards like methane.

During the entire coal production research period (1994–2018) for the Mysłowice–Wesoła mine, 11 coal seams were operated/extracted: 308, 318, 349, 401, 416, 418, 501, 510, 405/1, 405/2, 405/5. The technical longwall parameters at the Mysłowice–Wesoła mine were studied in the period 1995–May 2020. In 1995 only one longwall was operating with a height of 1.40 m. In succeeding years (1996–2001) the number of operating walls increased to 7 (2001). During the same period, the average longwall heights also increased: to over 2.30 m on each longwall.

The highest number of operating walls was studied in the years 2004–2006 and 2013: 9 longwalls. In general, since 2009 till the end of the research period (May 2020), the number of operating longwalls fluctuated from 6 to 9, with two periods, 2018 and 2020, when 5 and 3 walls were operated, respectively. The average longwall height had an increasing value, from less than 2 m in 1995/1996; between 2.30 and 3.0 m in 1997–2005, to over 3 m from 2006 to the end of the research period. In the Upper Silesian Coal Basin, the average depth of coal extraction increased from 700 m in 2010 to 788 m in 2018. Every year, the extraction depth increased by 8–10 m [3]. In the Mysłowice–Wesoła mine the average depth of extraction was constantly increasing (with few fluctuations) during the period 1995–May 2020 (Fig. 2). Between 1995 and 2002 the depth of coal production was in the range of 485–606 m. Since 2002 coal was extracted from gradually greater depths. In 2002 the depth of production exceeded 600 m. The level of seven hundred metres was exceeded in 2008 and coal production from more than 800 m started in 2015.

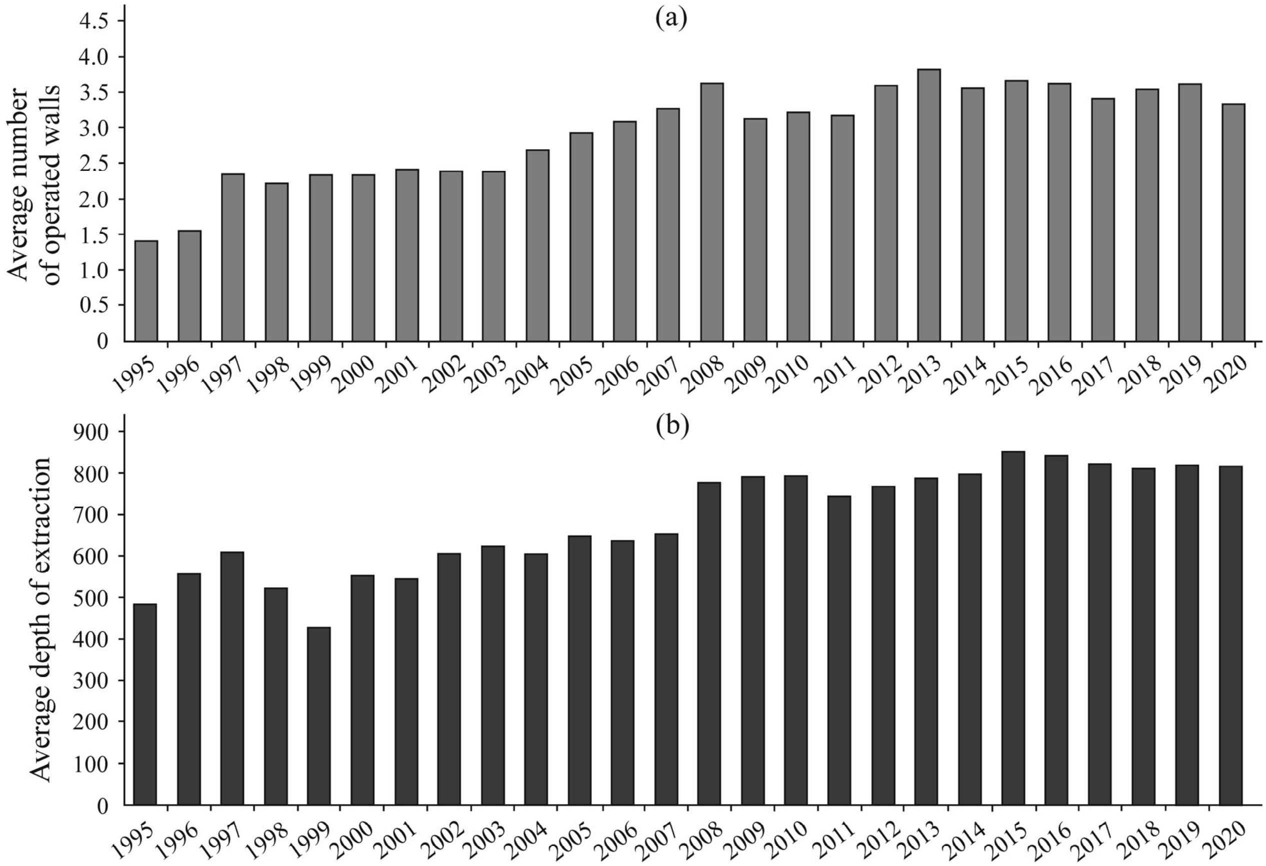

Fig. 2. (a) Average number of operated walls and (b) depths of extraction.

These depths are the average figures from each year, but the deepest coal production in the Mysłowice–Wesoła mine took place from 2012–2016 at 900–955 m below the ground level [8]. These depths correspond with high methane concentration zone, when methane content exceeds 5 m^3/t *daf* (Fig. 3).

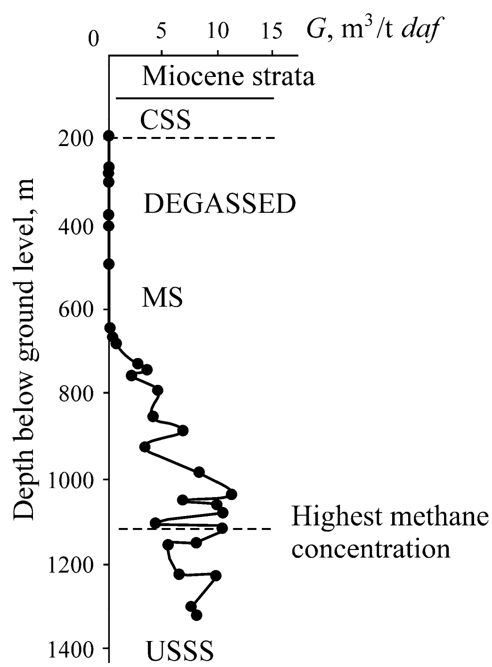

Fig. 3. Methane distribution in the LG-23 borehole: CSS—Cracow sandstone series; MS—mudstone series; USSS—Upper Silesia Sandstone Series.

Methane hazard in the Upper Silesian Coal Basin. In the Upper Silesian Coal Basin mines, over 700 million m^3 of methane per year was emitted during the period between 1994 and 2003. The volume of CH_4 liberated into coal workings increased to over 800 million m^3 annually in the years 2004– 2014. In 2014–2018 the absolute methane emission amounted to more than 900 million m^3 per year on the average [1, 2]. Hazardous methane conditions in deeper coal seams force mining enterprises to utilise methane for internal mining purposes in opposite to releasing the gas directly into the atmosphere and enhancing thereby the greenhouse effect and putting at additional costs in the near future.

The Polish methane resources found in coal bearing strata are estimated at 170 billion m^3 [35]. The CMM drainage combined with coal production allows for coal extraction under much safer conditions. A reasonable drainage process should enable coal production from the main bed and gas output from other coal beds [36].

Geological discontinuities are an important consideration in evaluating the gas drainage potential of coal seams using vertical or horizontal drainage. Faults, fissures and other anomalies can be a serious problem for gas control in the mining industry due to their potential of enhancing gas inflows into mining excavations [26]. In the USCB, two big CBM projects were conducted. The Geo-Methane project's main goal was to study the possibilities of gas production with high methane content from the 510 coal seam using hydraulic fracturing processes. The Geo-Methane project proved successful: the gas from the 510 seam supplies a 0.9 MW generator delivering energy to settlements in the Pszczyna county in the Upper Silesian region [37].

The Upper Silesian division of the Polish Geological Institute—National Research Institute studied the possibilities of pre-industrial outgassing in the 501–510 coal seams using hydraulic fracturing. It was the first CBM research project conducted in a working mine in Europe, and probably the first in the world [35]. Additionally, the methane concentration, lithostratigraphy and permeability of the 501–510 seams were also studied. For this purpose, two boreholes were drilled from the surface in the western area of the Part A in the main area of the Wesoła coal deposit: the Wesoła PIG-1 was a vertical 1000 m borehole (with drill cores retrieved from the depth between 591.0 and 1000.0 m) connected with a horizontal (no cores retrieved) borehole named Wesoła PIG2-H of 1918 m total length (Fig. 4). Both boreholes were drilled down to the 501–510 coal seams. In the first phase, in both boreholes production tests of methane yield were made. The gas obtained was rich in methane (>95% CH_4) with 230–250 m^3 daily output. In the second phase, the 510 coal seam was fractured and methane outflow was faster but with a high content of reservoir water [35].

The results of the Mysłowice–Wesoła CBM research project proved that methane drainage from virgin coal seams is possible and desirable in the Polish underground coal mining. It reduces the overall methane concentration in coal seams, making future exploitation much safer as regards methane conditions. Moreover, methane concentration in the collected gas mixture is >90% and the gas can be used for e.g. power production. However, the complex tectonic structure and low coal permeability, which have not been studied extensively over the entire USCB area, significantly impede using virgin coal bed methane drainage on a larger scale. In the near future the methane drainage on a larger scale will be required due to increasing coal production depth and consequent rising methane emissions [35].

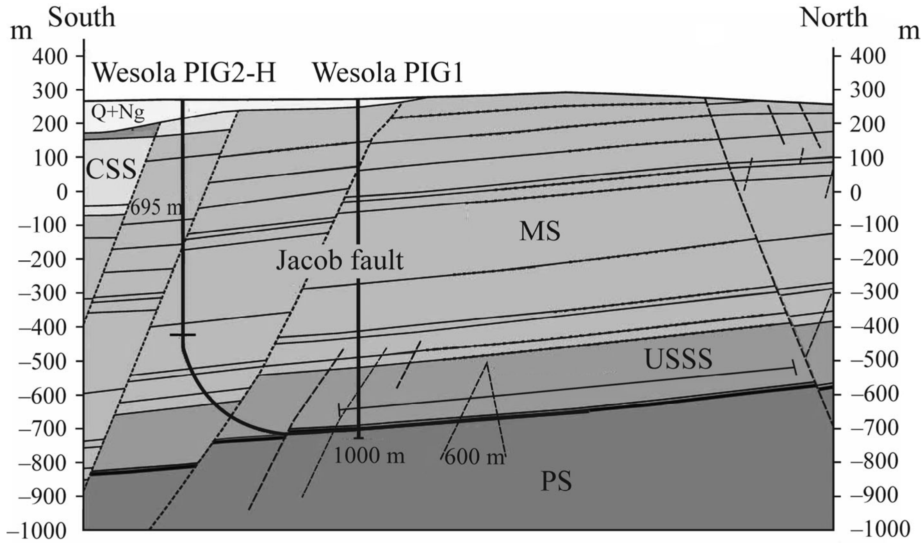

Fig. 4. Boreholes drilled to the 501–510 coal seams: CSS—Cracow sandstone series; MS—mudstone series; PS—paralic series; USSS—Upper Silesia sandstone series.

The Mysłowice–Wesoła mine is located in the northern gassy region of the Upper Silesian Coal Basin [9]. In this area methane concentration in coal seams increases with depth. In the geological past, shallow lying coal seams were naturally degassed. Lack of hermetic and impermeable Miocene cover combined with the presence of the permeable Książ Fault zone helped to liberate methane and other gases from coal seams and surrounding rocks in the geological past. Dislocation zones are important since displacements can weaken the seam bedrocks due to creation of weakness zones and making them permeable [36]. Faults and associated weakness zones can also be responsible for high methane contents liberated during mining and can diversify vertical and horizontal methane content in the whole Carboniferous profile, which is seen in many coal basins [38]. In the Upper Silesian Sandstone Series (USSS) and Mudstone Series (MS) the zones of increased gas concentration are situated in the upthrown sides of the fault [39]. The permeable character of the main dislocation was studied by the occurrence of methane zone (>2.5 m^3/t *daf*) top. In the main (northern) part of the Wesoła deposit the top of the methane zone is 400 metres below ground level (eastern area) and is found on greater depths close to the Książ Fault where the top was located 800–850 m below ground level [2, 8]. In the southern part of the Wesoła deposit, coal seams close to the Książ Fault with CH_4 concentration >2.5 m^3/t *daf* occur 900–1000 m below ground level. The top of the methane zone is getting shallower with increasing distance from the fault. In southern areas, close to the deposit boundary, the CH_4 zone is found 400 m below ground level [8]. The permeability of the Książ Fault helped methane to migrate from greater depths to the ground levels and be naturally released into the atmosphere in the past. Coal seams and surrounding rocks further from the main dislocation were also naturally degassed due to the presence of many smaller faults. The Książ Fault shifts the methane rich deposits in accordance with fault throw direction. The southern part of the Wesoła coal deposit is the downthrown side of the Książ Fault, where the methane concentration ceiling occurs deeper than in the upthrown side of the fault (main area). This main dislocation in the Wesoła deposit, shaped the methane zone occurrence on both sides of the fault line. These are the common effects in the shape of the methane zone structure close to the extensive regional faults like the Książ Fault, Kłodnica Fault, Jawiszowice Fault or Bzie-Czechowice Fault zone [2, 40].

Table 1. Methane content of the Mysłowice–Wesoła coal deposit parts, m^3/t *daf*

Part	Minimum	Maximum	Average
A	0.00	14.11	5.68
A1	0.01	10.58	5.82
B	0.00	11.80	3.35
C	0.65	15.10	6.35
D	0.00	7.40	2.68
D1	0.50	7.93	3.44
S, southern area	0.00	19.12	2.49

The Książ Fault divides the coal deposit into two areas: the main (northern) area and the southern area, but in the northern part the smaller faults divide the coal deposit into parts: A, A1, B, C, D, D1. Each of the separated parts is characterized by different methane content (Table 1) [8].

In the years 1988–1991 six boreholes were drilled (1358–1574 m deep) to recognise and identify e.g. methane content and tectonics in the Ruda and Saddle layers in the southern part of the Wesoła deposit [35]. The vertical distribution of methane can be seen in the Lędziny–Głęboka 23 borehole (LG-23). The shallower deposits were naturally degassed in the geological past, thus the degassed zone, free of methane occurs at 0–700 m.

The methane concentration in the coal seams and surrounding rocks increases at the depth of ~700 m, reaching the primary maximum between 1000 and 1200 m. The occurrence of gas-tight deposits of mudstone series (compact siltstones and mudstones) and thick sandstones of the Upper Silesian sandstone series provide thick seal for the beds, in effect the methane concentration is high [2].

In the Mysłowice–Wesoła coal mine five coal production levels were studied (465, 665, 865, 1000, 1230/1250 m). In three most representative parts of the coal deposits, where a large number of tests were made, the methane content increases with depth [8]. In the largest area, the southern part, methane concentrations in shallower coal production levels (465 and 665) were around 0 m^3/t *daf*. At 865 m the CH_4 concentration increases to 2.5 m^3/t *daf* (I category of methane hazard).

At deeper levels, the gas content exceeds 4.5 m^3/t *daf* (level 1000) and 9.6 m^3/t *daf* (level 1250) and correlates with II, III and IV category of CH_4 hazard. In the northern area in part A, close to the Książ Fault, in the 665, 865 and 1000 levels, tests were made and results of maximum CH_4 concentration measurements were: 3.16; 5.40 and 6.59 m^3/t *daf*, respectively. In part D, located further from the Książ Fault to the north, three shallower lying production levels were studied. The results trend is similar to previous tests: 0.38 (465 m); 2.13 (665 m) and 3.08 m^3/t *daf* (865 m).

The data collected in the Mysłowice–Wesoła mine geological report [8] show that methane increases with depth and coal seams with surrounding rocks closer to the Książ Fault are less methane rich than those located further from it. The most recent research on vertical methane distribution in the Wesoła coal deposit was made during the Polish Geological Institute pilot program in the Wesoła PIG-1 borehole (Table 2) [35].

Table 2. Methane content in selected coal seams in the Wesoła PIG-1 borehole

Coal seam	Depth, m		Methane content, m^3/t *daf*		
	Top	Bottom	Average	Minimum	Maximum
361	660.55	661.66	0.29	0.29	0.29
364	672.30	673.26	2.17	1.88	2.47
401	681.25	682.93	2.11	2.08	2.13
404/1	701.40	702.52	2.09	1.84	2.33
Not correlated	704.10	705.40	2.71	2.07	3.36
404/5	752.55	756.60	3.02	2.02	4.16
Not correlated	772.95	774.10	3.57	3.53	3.61
405/2	786.22	788.00	4.80	4.26	5.35
407/1	801.86	803.42	4.28	3.26	5.30
414	873.55	874.95	4.68	3.89	5.57
416	889.90	892.95	5.34	3.67	7.00
Not correlated	947.47	948.50	5.80	5.29	6.32
501	962.05	965.70	6.72	5.37	7.98
510	966.05	977.10	6.17	5.11	7.29

4. RESULTS AND DISCUSSION

Hard coal extracted from the Polish mines is the main fuel for heat and power production in the country. The study period for hard coal output was 1994–2018 when 11 coal seams were operated (308, 318, 349, 401, 416, 418, 501, 510, 405/1, 405/2, 405/5). The overall coal output in the Mysłowice–Wesoła mine has been decreasing; during the same period coal production in the USCB dropped from 124 to 54.4 Mt [1, 3]. In the Mysłowice–Wesoła mine the largest amounts of coal were produced at the beginning of the research period (1994–1995) when over 3.80 Mt of coal was produced per annum (Fig. 5) [3, 8]. In the following years (1996–1998), the total output dropped to 2.51 Mt, but in the next period (1999–2006) coal production increased and remained at a stable level around 3 Mt annually with a 3.26 Mt peak in 2005. During the next three years (2007–2009) a large decrease in production took place. On the other hand in 2008, the lowest amount of extracted coal was reported: only 1.83 Mt. From 2009 to 2013 an output revival was evident which is indicated by the extraction of 3.08 Mt of coal (2013).

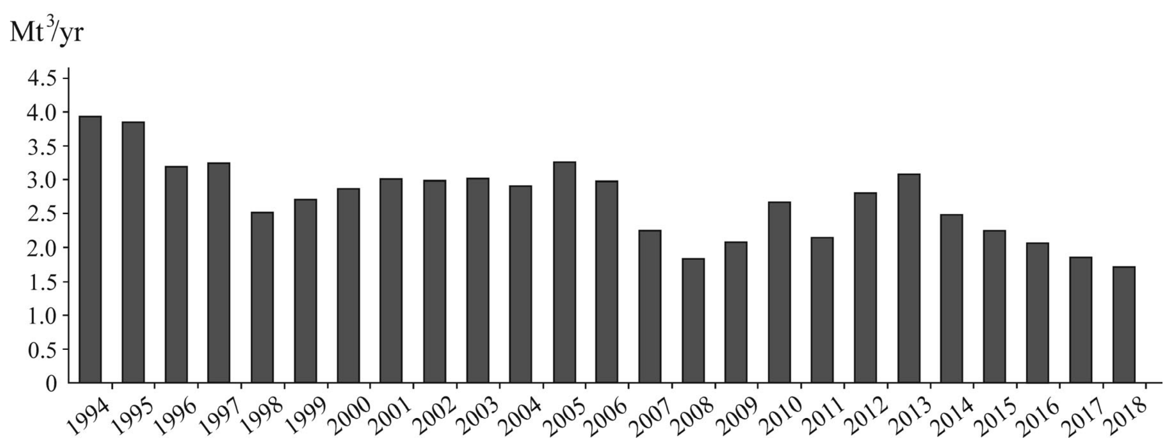

Fig. 5. Bar chart of coal production in the research period.

Coal in the Mysłowice–Wesoła mine has been extracted from increasingly deep seams every year, with longwall height increasing at the same time. Due to in the mining of deeper seams, with higher methane content and reduction in number of working longwalls from 8–9 (2012–2013) to 6 (since 2014) hard coal production was decreasing slightly but continuously from 2.48 Mt (2014) to 1.71 Mt in the last year of the study (2018). Currently, two coal seams, 416 and 510, and three longwalls are in operation [8]. The most "coal-rich" seam is 510, which has been incessantly extracted since 1997. These seams are highly methane rich, the average CH_4 content determined in the Wesoła PIG-1 borehole exceeded 5 m^3/t *daf* for these seams.

The total (absolute) methane emission, outgassing and VAM emission values were studied for the period of the last 45 years (1974–2018) (Fig. 6). In that long period of time the main trends and emission changes are clearly visible. The lowest total methane emissions to coal excavations, between 10.35 and 13.40 million m^3 in a year, were recorded in the first 4 years of the study (1974–1977). During the next three years CH_4 emission increased to 43.05 million m^3 (1980). During the next 27 years (1980–2006) methane emission was on a stable level with slight fluctuations, the average emission being around 43 million m^3 every year.

After mining the deeper and more methane-rich coal seams, the average CH_4 releases to coal workings started to increase from year to year. In 2007 the emission exceeded 55 million m^3 and in succeeding years it did not drop below 50 million m^3. From 2012 methane emission was increasing (with one periodic drop in 2013) from 61 million m^3 to the highest volume in 2016, when almost 90 million m^3 of methane were emitted to coal excavations. During the last two years of the research period (2017–2018) CH_4 emission was close to 70 million m^3 per year. From 2013–2014 a large increase in methane emission was noticed which coincided with a large decrease in coal output at the same time. The tough mining and geological factors had an effect on the decrease in coal production and methane emission increase at the same time. In the coming years coal will be extracted at the same or even deeper underground levels, and consequently methane emission can increase or remain on the very high level of 70–90 million m^3 of emitted gas every year.

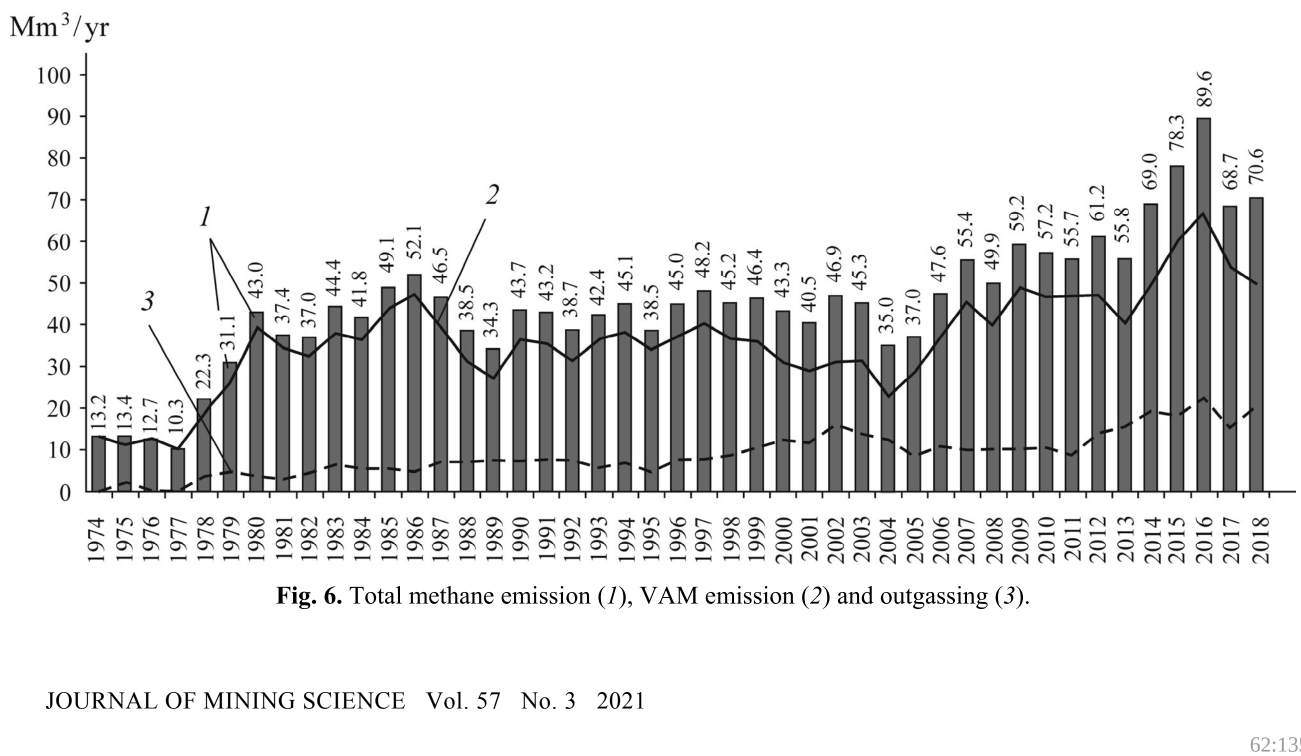

Fig. 6. Total methane emission (*1*), VAM emission (*2*) and outgassing (*3*).

The ventilation air methane (VAM) emission is the result of the simplest and the most common solution to drag used, heated air with ca. 1% methane content out of the mine and keep coal workings as safe as possible [19]. On the other hand, every ton of methane emitted to the atmosphere enhances the greenhouse effect [6]. During the first 4 years of the study (1974–1977) all emitted methane was removed by ventilation shafts directly into the atmosphere. In 1975 only 16% of the liberated CH_4 was captured by methane drainage systems, the rest was released to the atmosphere. The VAM emission chart course is similar to absolute methane emissions. These two emission figures are closely connected, because ~80% of the total emitted methane is moved out of the mine by ventilation shafts (VAM emission). From 1978 to 1980 the VAM emission increased twice, from 18 to over 39 million m^3. That rapid increase was caused by mining more methane-rich seams, in previous years almost all produced coal came from methane-free seams. One year later the emission dropped to 34.43 million m^3 but with each subsequent year it increased steadily, reaching the highest value of VAM emission in the 20th century: over 47 million m^3 in 1986. The volume of CH_4 emitted to the atmosphere by underground ventilation systems was gradually decreasing from 39.74 million m^3 (1987) to 26.75 million m^3 two years later. In the following 15-year period (1989–2003) the VAM emission was fluctuating from 30 to 40 million m^3, but the emission trend was stable. In 2004 the total CH_4 emission to coal workings was low, in effect the volume of removed methane was low too, just 22.65 million m^3. In the next years (2005–2009), the average number of m^3 of CH_4 liberated into excavations and VAM emission increased simultaneously. Coal extraction under tough geological and mining conditions necessitates more effective underground ventilation to move outside the mine the air mixture containing CH_4 (1%) and other gases. From 2009 to the end of the study (2018) VAM emission exceeded 40 million m^3 every year, during the last 4 years of the study it exceeded 50 million m^3. The highest volume of ventilation air methane was reported in 2015 and 2016—60 and 67 million m^3, respectively.

Outgassing is the second most effective and common way to keep mining excavations as free of CH_4 as possible. Underground methane capturing supports the VAM emission to maintain the lowest methane accumulation possible. In 1974–1977 almost all emitted methane was released directly to the air, with no CH_4 capturing in 1974, 1976 and 1977 (Fig. 6). In contrast to absolute and VAM emissions, the overall outgassing trend is increasing, with a few periodic drops. From 1978 to 1994 outgassing was on a stable level, with a small increasing trend. The volume of captured gas fluctuated from ~ 3 to over 7.5 million m^3 in a year. A one year drop was recorded in 1995 (4.52 million m^3), but during the next seven years (1996–2002) the largest increase in outgassing research history was recorded. In that 7-year period, the volume of captured gas rose more than twice, from 7.61 to 16.03 million m^3. After the large increase, a drop period in outgassing took place, when the volume of gathered gas dropped from almost 14 million m^3 in 2003 to 8.34 million m^3 two years later. Years 2005–2011 were a stable period, outgassing values fluctuated from over 8 to almost 11 million m^3 annually. In 2012, a revival in CH_4 capturing took place. From that year to 2016, the largest volumes of methane were gathered by underground systems. In 2012, over 14 million m^3 was captured and 4 years later (2016) the largest outgassing emission was reported—over 22.5 million m^3 in a year. Absolute methane emission, VAM and outgassing recorded the highest volumes in CH_4 emission in 2016, when a one-year peak was noticed. A large increase in total CH_4 was also recorded between 2007 and the end of the study, which coincided with mining on greater depths, where methane concentration in coal seams and surrounding rocks is higher than in shallower beds degassed in the geological past. Outgassing should remain on a high level and be the main part of methane safety practice. The European Union idea of including CH_4 in the ETS will force more efficient outgassing processes and technology to avoid high fees and to use the captured methane for energy generation or for sale.

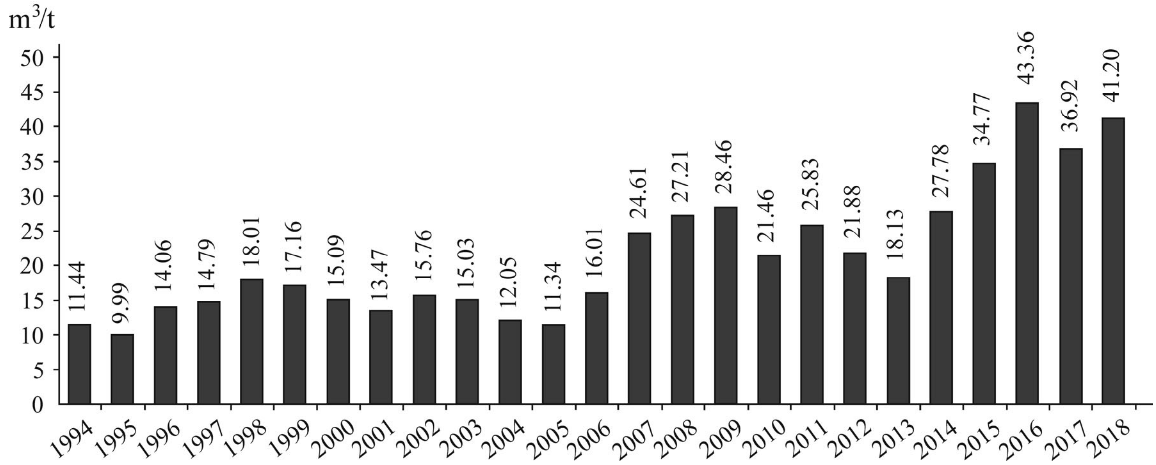

Fig. 7. Specific methane emission.

5. SPECIFIC METHANE EMISSION

The most illustrative methane hazard can be seen in specific methane emission. This value shows the real danger, describing how many m^3 of CH_4 is emitted with every single t of extracted coal. The specific CH_4 emission was calculated for the same period as hard coal output (1994–2018). During the first 13 years of the research (1994 – 2006) the volume of emitted gas per one t of coal was stable with slight fluctuations and was in the range of from 10 to 18 m^3 CH_4/Mg (Fig. 7). In next three years (2007 – 2009) specific methane emission increased from 24.61 to 28.46 m^3 CH_4/t annually. From 2007 to the end of the study (except 2013) the average annual volume of CH_4 released per one Mg of coal was higher than 20 m^3 CH_4/t and higher than 30 m^3 CH_4/t since 2015 when the highest volumes were recorded in 2016. In the coming years the highest volumes of CH_4 emitted directly to the excavations can be expected in the Mysłowice–Wesoła mine. Therefore, if the overall yearly coal output does not increase, the specific methane emission values will be greater with every year and can exceed 40 m^3 CH_4/t like in the last year of the research (2018).

CONCLUSIONS

Hard coal production is one of the most dangerous but essential branches of the Polish economy. The Mysłowice–Wesoła mine is a member of the largest mining company in Europe—the Polish Mining Group. The Wesoła coal deposit is characterized by diverse geological structure and methane distribution. The biggest dislocation in the area—the Książ Fault divides the deposit into two areas—the northern (main) area and the southern area. The Książ Fault was the most important factor shaping the methane content structure at both sides of the fault and across the entire coal deposit in the Carboniferous period. The vertical distribution of methane content in the coal seams is reduced near the Książ Fault zone. The top of the zone of methane concentration (over 2.5 m^3/t *daf*) occurs at increasingly shallow depths with increasing distance from the fault zone. The deposits at the depth of 800–1000 m below ground level in the area of the Książ Fault were mostly degassed in the geological past. Thus, in the deposit discussed to a depth of several hundred metres, there is a natural degassed zone, in which the methane content in the seams does not exceed 1 m^3/t *daf*, and beneath it there is a methane zone, in which we observe a rapid increase in methane content with increasing depth up to the maximum of >8 m^3/t *daf*. Since 2006–2008 coal has been extracted systematically from the depths of more than 700–800 m and deeper. Methane concentration at these depths is higher, and methane also flows into the coal workings from under- and overlying seams and also from goafs. These natural and mining factors caused that absolute CH_4 emission was increasing from 2006–2008 systematically exceeding 50 million m^3 of emitted CH_4 in a year. The overall hard coal output decreased twice. A large decrease in coal output took place in 2013, which coincided with an increase in methane emission and the start of mining coal seams of higher methane content.

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ORIGINAL ARTICLE

Methane emissions against the background of natural and mining conditions in the Budryk and Pniówek mines in the Upper Silesian Coal Basin (Poland)

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Abstract
The paper presents the variability of hard coal output, methane content and methane emissions into coal workings and into the atmosphere from the two most methane-gassy coal mines in Poland. The Budryk mine is one of the youngest mines in Poland, but it is the most methane-gassy as well. In 2016, the total CH_4 emissions exceed 140 million of m^3. This large increase in methane emissions to mine workings is primarily related to the increase in the depth of coal extraction (up to 1290 m) and, consequently, the rapid increase in the methane content in coal seams (up to 10–12 m^3/Mg $coal^{daf}$). On the other hand, in the Pniówek mine, methane emission was the highest at the beginning of the study period (1986–1991). During the following years, emission decreased to the values of less than 140 million of m^3, which were still one of the largest amounts of emitted methane in the entire Upper Silesian Coal Basin. The coexistence of natural factors, such as the geological structure and gas distribution, as well as mining-related factors, i.e. the depth of mining, the intensity of coal extraction determines the temporal variability of methane emissions in the studied mines.

Keywords Methane emissions · The Upper Silesian Coal Basin · Budryk mine · Pniówek mine · Hard coal output

Introduction

The Upper Silesian Coal Basin (USCB) (Fig. 1) is the most industrialised region in Poland, providing bituminous coal for heat and power generation, as well as coking coal for coke production. Reaching deeper deposited coal seams carries a high methane risk, a risk of underground tremors, and intensification of temperature hazards. The increase of methane emission is one of the most dangerous problems in modern mining activity and entails work suspension, evacuations and even fatalities after methane explosions (Trenczek 2016; Duda and Krzemień 2018; Dreger and Kędzior 2019). Two mines from the USCB, Budryk and Pniówek—members of the Jastrzębska Spółka Węglowa SA, were chosen to identify and study variations in methane emissions. These two mines are characterised by the highest CH_4 emission in the entire coal basin in Poland. Methane emissions to coal workings in the studied mines are often more than 100% higher than in other mines in the basin (GIG 1995–2019). The total methane emission in the USCB has been changing with time. In 2004, methane emission from all mines amounted to more than 800 million m^3 and in 2015 exceeded 900 million m^3. The entire emission values fluctuated from year to year, but the overall emission trend is increasing. A similar trend was observed in other coal basins, where coal was extracted from deeper levels every year e.g. (Ju et al. 2016; Wang et al. 2019; Karacan and Warwick 2019). On the other hand, the hard coal output in Poland has been constantly decreasing from over 100 million Mg at the end of the twentieth century to around 60 million Mg in 2016–2018. Methane (CH_4) is the second-most important greenhouse gas after the notorious carbon dioxide (CO_2) and plays a potent role in atmospheric chemistry and radiation balance (Warmuziński 2008; Ghosh et al. 2015; Kędzior 2015; Tutak and Brodny 2019; Swolkień 2020; Dreger 2021).

The amount of methane emission from a coal deposit is strictly dependent on many factors, which can be roughly divided into natural factors related to the geological structure

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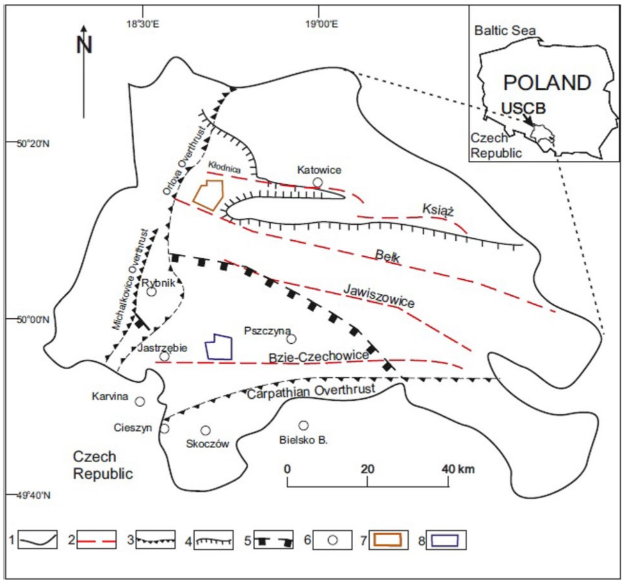


Fig. 1 Map of the Upper Silesian Coal Basin (modified after Kędzior 2012) 1—the boundaries of the Polish part of the USCB, 2—important fault zones, 3—overthrusts, 4—the range of the continuous Miocene cover, 5—the range of the secondary methane zone (ticks point the direction inside the areas of ranges), 6—important cities, 7—the Budryk mine boundary, 8—the Pniówek mine boundary

of the deposit and its natural gas content and pressure, as well as anthropogenic causes resulting from mining activities and the method of deposit exploitation e.g. (Karacan et al. 2011; Krause and Smoliński 2013; Kędzior and Dreger 2019; Dreger 2020). Therefore, the interrelationship of available results regarding the gas content of the deposit, volume and intensity of coal extraction with the data on the quantity of methane emissions should make us aware of how strongly the described factors affect the phenomenon of emissions and, therefore, how to counteract it.

Accordingly, the main purpose of this article is to show how the dependencies and causes of methane emission and hard coal output have changed with time (1986–2018) in the two most methane-gassy coal mines in Poland. The Pniówek coal mine is characterised by the one of the highest methane emissions in Poland. In the Budryk mine, methane emission has been increasing rapidly since 2013 and now it is the highest in the country.

Data sources

All the data were obtained from officially accepted geological documentation from the Budryk and Pniówek mines belonging to the Jastrzębska Spółka Węglowa SA (JSW—internal reports). In addition data from the Annual Report (for the years 1994–2018) on the state of basic natural and technical hazards in the hard coal mining industry published by the Central Mining Institute (GIG) in Katowice (GIG 1995–2019) were taken for calculations and analyses.

The most important data taken into research are the methane emission from two selected underground coal mines—Budryk and Pniówek. The total methane emission (CMM—coal mine methane) refers to methane liberated from the coal and surrounding rock strata due to mining activities. It is a combination of ventilation air methane (VAM) and methane coming from coal seam drainage (degassing). Ventilation air methane and degassing were also studied for these two coal mines. The VAM is commonly determined by measuring the pure methane concentration in the air stream by hand-held anemometer and by taking air samples to the laboratory tests. The air velocity measurements are important to determine the methane concentration in the return airways (e.g. Karacan et al. 2011; Gawlik and Grzybek 2002). The specific CH_4 emission was investigated as well. This feature describes how many methane is emitted to the mining atmosphere with every extracted Mg of coal and it shows the real methane danger during mining activities. To measure the amount of adsorbed CH_4 in coal, we use the term methane content, which describes the volume of gas in one Mg of coal^{daf} (daf is the pure coal substance, without moisture and ash, dry ash free coal substance) (Wierzbicki and Skoczylas 2014; Honysz 2015).

Moreover, to study relations between methane content and coal seam pressure (methane desorption), the data collected by Tarnowski (1971) and CLP-B Sp. z o.o. Laboratory in Jastrzębie-Zdrój were also considered and carefully analysed. After the analysis of all collected data, the multi-criteria geology and mining evaluation were set up.

Coal mines under study

Budryk mine

The Budryk coal deposit is located in the northern part of the basin (Fig. 1) at the north-western flank of the Main Trough between two dislocations: the Kłodnica Fault in the north and the Bełk Fault in the south. The Budryk deposit is composed of 43 documented coal seams (from 325 to 407/3), all of which are found in the Orzesze, Załęże and Ruda beds. The deposit has a diverse geological structure, sediment disorders, and large tectonic variability (Table 1, Fig. 2). Carboniferous top surface varies in depth from + 60 m in the north to + 300 m above sea level in the south-east. The dip of the beds is varied, from almost horizontal to incline at 15° angle.

The largest dislocations in the USCB, such as the Kłodnica, Książ or Bełk faults, have nearly latitudinal orientation and displace layers to the south (Kędzior et al. 2013; Dreger and Kędzior 2019).

Table 1 Characteristics of the main faults in the Budryk and Pniówek mining areas (JSW internal reports)

	Budryk	Pniówek
Latitudinal direction		
Name/throw size/throw direction	Dębieńsko/25–45 m/N	Krzyżowice I/20 m/NW
	Barbara Fault Zone/30–55 m/S	Krzyżowice II/25 m/NW
	North/25 m/N	Pniówek/3–25 m/S
	Knurów/30–100 m/ SE	Skrzeczkowice/70 m/NNE
	Paniowy/25–26 m/SE	P-1[a]/15–22 m/S
	Śmiłowice/15–65 m/NW	
	Barbara I/30 m/SE	
	Paniówki/8.5–20 m/SW	
Longitudinal direction		
Name/throw size/throw direction	Chudecki/0.7–20 m/W	Pawłowice I/40–80 m/W
		Pawłowice II/60–100 m/W
		Warszowice/4–60 m/E
		Graniczny I/10–100 m/NE
		Graniczny II/10–30 m/NW
		Graniczny III/20 m/NE
		P-2, W-2[b]/5–20 m/E

[a]Unnamed fault which divides part of the P-1 deposit in the north and south

[b]Unnamed faults which divide part of the P-2 and W-2 deposits in the east and west

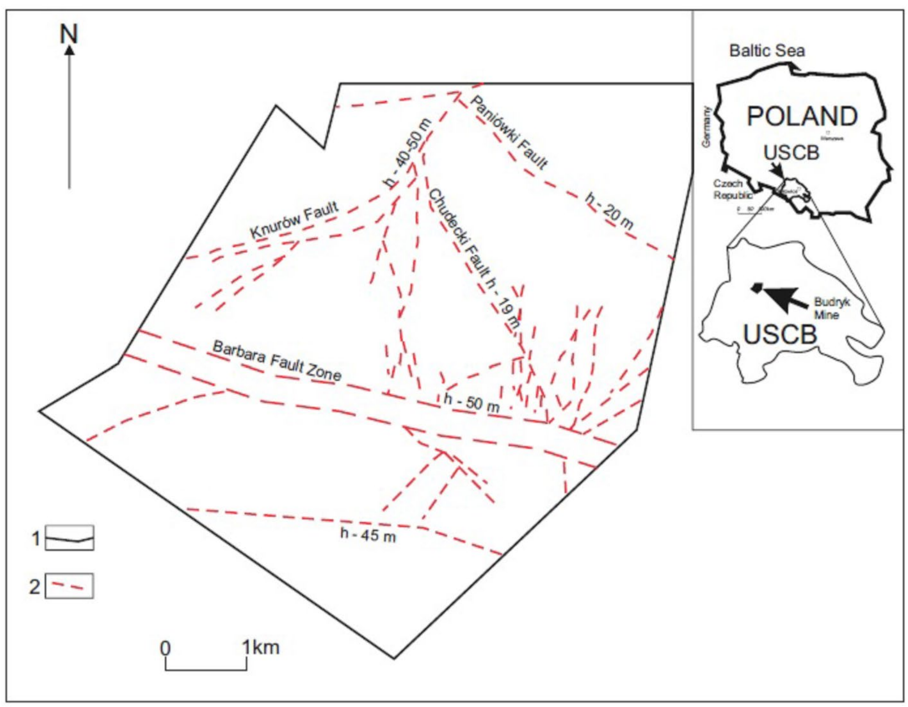


Fig. 2 Tectonic sketch of the Budryk Mine (402 coal seam), 1—the boundaries of the mining field of the Budryk mine, 2—faults with throw size h,

The Budryk mining area is represented by the Pennsylvanian Upper Silesian Sandstone Series (Namurian C; Serpukhovian and Bashkirian) and the Mudstone Series (Westphalian A and B; Bashkirian) (Table 2). In the profile of documented coal deposit Ruda (Namurian C; Bashkirian), Orzesze and Załęże (Westphalian B; Bashkirian) Beds were found.

The Upper Silesian Sandstone Series is represented by Ruda Beds occurring below the 407 seam where coarse and fine-grained sandstones were found. The following Załęże and Orzesze Beds (Westphalian A and B; Bashkirian) occur in all of the area with 800–1250 m thickness in total. They constitute the main stratigraphic unit in the deposit, built of mudstones, claystones and

Table 2 Upper Silesian Coal Basin stratigraphic division—modified after Heckel (2004) and Gabzdyl and Gorol (2008), C—carboniferous, M—Mississippian, P—Pennsylvanian

Stratigraphic division					Lithostratigraphic series	Layers
International (after 2004)			Local (modified after 2008)			
C	P	KASIMOV	STEPHANIAN	B	Kwaczała Arkose	
				A	Stratigraphic Gap	
		MOSCOVIAN	WESTPHALIAN	D	Cracow Sandstone Series	Libiąż
				C		Łaziska
		BASHKIRIAN		B	Mudstone Series	Orzesze
				A		Załęże
			NAMURIAN	C	Upper Silesian Sandstone Series	Ruda
				B		Saddle
				A	Paralic Series	Poruba
						Jaklovec
	M	SERPUKHOVIAN				Hrusov
						Pietrkovice
					Diastrophic sea deposits (flysch type)	Kyjovice (upper)
		VISEAN	UPPER VISEAN			Kyjovice (lower)

sandstones, with numerous coal seams which are the subject of mining.

Most of the Orzesze strata and the entire Carboniferous younger series (Cracow Sandstone Series) were removed by erosion in the mine area under study.

The overburden rocks lie discordantly on the Carboniferous erosion surface and consist of Triassic sandstones and carbonates, Miocene clays, as well as fluvial and glacial sediments of Quaternary origin. The total thickness of the overburden strata does not exceed 200 m (Table 3).

Pniówek mine

The Pniówek coal deposit is located in the south-western part of the USCB (Fig. 1) at the SW limb of the Main Trough, bordering with the Bzie-Czechowice fault zone in

Table 3 Overburden composition in the Budryk and Pniówek mining areas (JSW—internal reports; Kotas 1982; Buła and Kotas 1994)

	Budryk mine	Pniówek mine
Overburden	Quaternary, Neogene, Triassic	Quaternary, Neogene
Thickness	0–180 m	220–1000 m
Quaternary		
Thickness	0–79 m	6–80 m
Composition (lithology)	Sands, clays, gravels	Clays, sands, gravels
Description	Pleistocene glacier-water accumulation. Reduction in thickness in the S part of the coal deposit. In the SW part of the area deposits rest directly on the Carboniferous layer	Holocene alluvial and Pleistocene glacier-water and glacier accumulation
Neogene (Miocene)		
Thickness	< 134.8 m	150–900 m
Composition (lithology)	Clay, marl clay, marls, claystones, sand clays, sands, and sandstones	Marl, clay, sands, tuffites, sandstones, conglomerates
Description	Sediments found in the N, NE, W part of the mining area. Deposits lying on the weathered Carboniferous sediments and covered by Quaternary layers	Thickness is variable, with the thickest sediments in SE and the thinnest in N and W
Triassic		
Thickness	< 65.8 m	–
Composition	Clay and limestones marls, sandstones	–
Other	Sediments deposited directly on the Carboniferous layers. The biggest spread of sediments is found in the E part of the area	–

the south. The Pniówek coal deposit is a multilayer structure consisting of 62 documented seams of various thicknesses and qualities of the beds. Tectonic character of the deposit is also very complex, with fault throws between 10 and 300 m (Table 1, Fig. 3). Furthermore, we can distinguish many smaller faults accompanying larger dislocations throwing down the layers by a few metres.

The lithological profile of the Carboniferous strata within the discussed mine comprises the Pennsylvanian Paralic (Namurian A; Serpukhovian, Bashkirian), Upper Silesian Sandstone (Namurian B and C, Bashkirian), and Mudstone (Westphalian A and B; Bashkirian) Series.

All the Upper Carboniferous series are represented by clastic rocks, i.e. sandstones, mudstones and claystones in various quantitative proportions with numerous coal seams.

The Carboniferous top surface displays an erosive character and is morphologically varied. There are many paleo-ridges and washouts with a general NW orientation. There are clay and sandy Miocene deposits on the eroded Carboniferous surface. Their thickness is variable and ranges from about 200 m in the north to 1000 m in the south (Table 3).

Results and discussion

Methane distribution

Budryk mine

Current spatial distribution of the methane content in the Upper Silesian Coal Basin depends inter alia on the geological development of the basin in the past, the sorption capacity of the coal seams, the thick and hermetic Miocene overburden (methane accumulation), lithological character of Carboniferous sediments, and tectonic dislocations (methane migration) (Kozłowski and Grębski 1982; Kotas 1994; Kędzior 2009a, 2019; Słoczyński and Drozd 2018; Krause 2019) (Figs. 2, 3). In the Upper Silesian Coal Basin, two main geological patterns of vertical distribution of coal-bed methane (CBM) were distinguished (Kotas 1994; Kędzior 2009a) (Fig. 4). Pattern A is associated with northern and central areas of the coal basin, characterised by the presence of naturally degassed coal seams down to the depth of 400–600 m or deeper in some areas. With depths greater than 500 m, the CH_4 content increases rapidly until it reaches the primary methane zone with methane content of up to 15 m^3/Mg coal^{daf}. Going deeper, methane content tends to decrease. The northern pattern (A) is related to the Budryk mine, which is located in the north-western part of the basin (Fig. 1). Figure 4a illustrates the distribution of methane content in the Budryk coal seams (JSW—internal reports). The natural degassed zone is evident to the depth of 600 m, then methane content increases rapidly until the primary zone of methane content is reached. It is evident here, that thin and permeable Triassic and Miocene overburden is not sufficient to stop the migration of gases upwards (Table 3). The average and maximum CH_4 content in the Budryk seams tend to increase with depth, reaching maximum values of over 7 (average) and 15 (maximum) m^3/Mg coal^{daf} between − 750 and − 990 m above sea level (between ca. 1000 and 1200 m below ground level). (Fig. 4). The depth range of the primary methane zone has not been exactly determined so far in the mine under study.

Figure 2 shows the fault distribution in the Budryk mine field (402 coal seam). These dislocations form a dense network of faults with latitudinal (Barbara fault zone) and

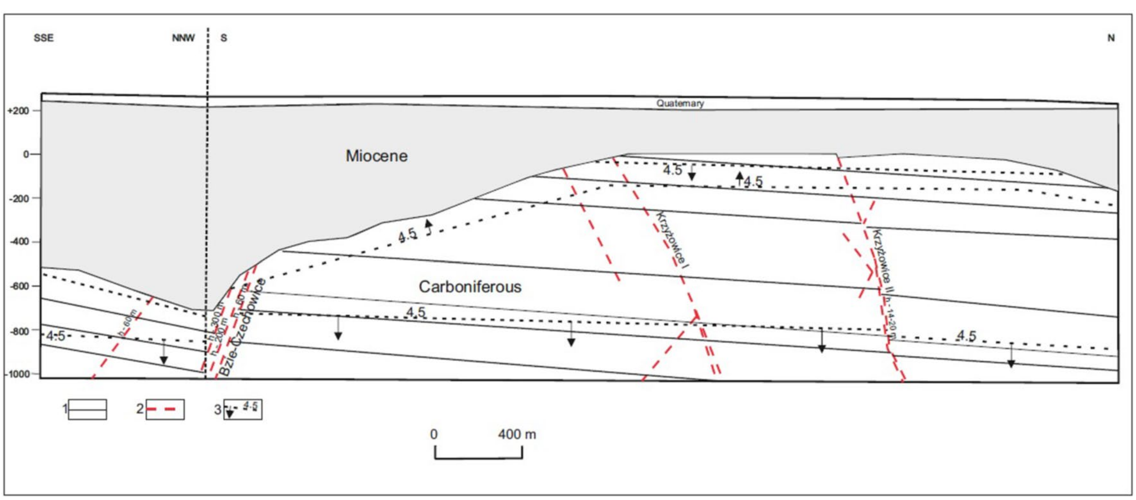


Fig. 3 The cross-section across the Pniówek Mine, 1—the more important coal seams, 2—fault with throw size h, 3—line of methane content 4.5 m^3/t coal^{daf}, increase in methane content in the direction of the arrow

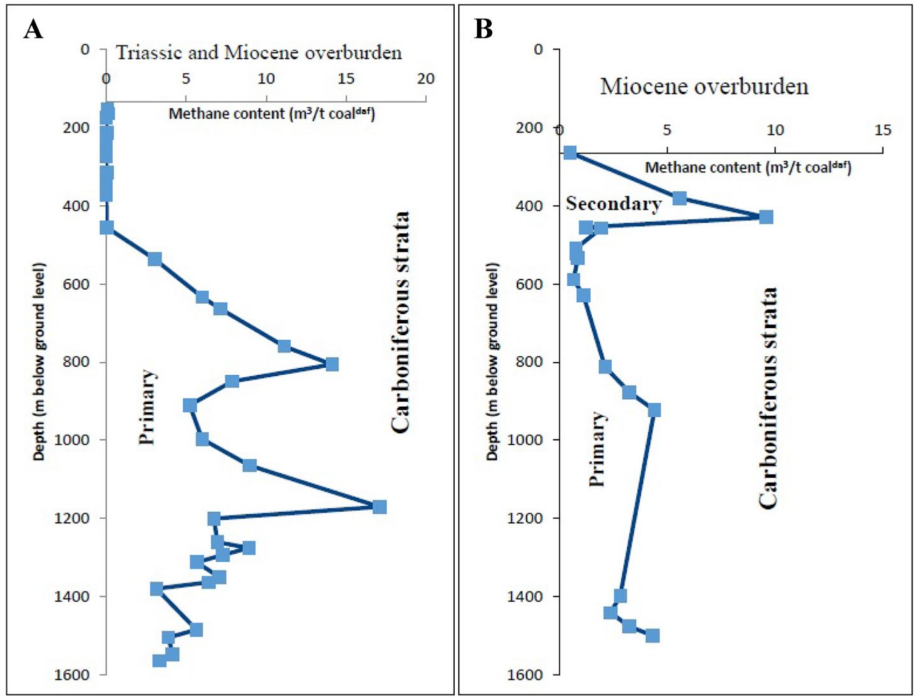


Fig. 4 Methane depth distribution in the Budryk (**a**) and Pniówek (b) mines. Primary – the primary methane zone in depth profile, secondary—the secondary methane zone in depth profile

longitudinal (e.g. Knurów and Chudecki faults) orientation (Table 1). The existing fault network probably aided the natural process of degassing the upper parts of the deposit in the geological past, and the faults themselves may today constitute the boundaries between the deposit parts with different level of gas saturation, and thus have different effects on the intensity of gas emissions to the mine workings of the Budryk mine. The role of faults in gas migration has also been studied elsewhere (e.g. Thielemann et al. 2001; Karacan and Olea 2014; Karacan et al. 2021).

Pniówek mine

Pattern B is associated with the southern part of the basin and includes two distinct zones of methane content (Fig. 4b). The first methane zone covers the secondary accumulation of CH_4 adsorbed in coal seams and free gas accumulated immediately below the thick and impermeable Miocene cover (Fig. 4b). The next methane zone, so called primary with increased concentrations of methane is separated by an interval of reduced CH_4 content in coal seams (400–800 m below ground level, Fig. 4b). The primary methane zone lies deeper (> 1000 m), with the CH_4 content of up to 10–16 m^3/Mg $coal^{daf}$ (Kotas 1994; Kędzior 2012). This zone contains thermogenic methane produced as a result of the coalification process in the late Carboniferous period (Kotarba 2001). Increased methane content in the uppermost part of Carboniferous coal-bearing series sealed with hermetic overburden is conditioned by the occurrence of microbial methane produced in the pre-Miocene period and then mixed with thermogenic methane (Kotarba and Pluta 2009; Kędzior 2019). The methane depth zones with faults in the area of the Pniówek mine are shown in Fig. 3. The main dislocation of Bzie-Czechowice, which is a regional dislocation in the basin scale, is located in the south of the studied area and displaces the primary gas-bearing zone in the throw direction (to the south, Fig. 3). Together with the remaining faults (e.g. Krzyżowice I and II), they seem to be migration pathways for gas between the primary and secondary methane zones. Probably thanks to them, thermogenic methane migrated towards the Carboniferous top and supplied the secondary gas-bearing zone (Kędzior 2009a, 2012).

The pressure of gas accumulated just below the Miocene cover is higher in comparison to the remaining parts of the Carboniferous series and oscillates around 6–7 MPa (Tarnowski 1971). After the Carboniferous period (especially in Mesozoic and Paleogene time), the top surface of coal-bearing formations were exposed and subjected to weathered and erosion processes. To the present, in the topmost part of the Pniówek coal deposit, a layer of coal-bearing detritus with a high 20–30% porosity has been preserved and now is sealed by the Miocene deposits. The currently observed zone of increased gas pressure is associated with porous coal-bearing weathered deposits in the Carboniferous top (Janas 1962; Tarnowski 1989), which is a reservoir of both secondary microbial gas and migrating thermogenic methane (Kotarba and Pluta 2009).

The differential vertical and horizontal methane distribution in coal basin caused by e.g. overburden occurrence, faulting and folding was identified in many coal basins (Ju et al. 2016; Diamond 1994; Noack 1998; Thielemann et al. 2001). The Pniówek mine corresponds to the southern pattern of the CH_4 vertical distribution (Fig. 4b). In contrast to the Budryk mine, the thick and impermeable Miocene Skawina Formation (Table 3) has prevented gases release from coal seams to the atmosphere in the geological past. A comparative description of the Carboniferous series overburden in both described mines is presented in Table 3.

Methane content vs. pressure and sorption capacity

The volume of adsorbed methane, in the same temperature and pressure conditions, depends on micropores and macropores content in coal. Kozłowski and Grębski (1982) showed that more microporous coals can accumulate more methane in the coal structure. Studies carried out on coals from Western Canada (Lamberson and Bustin 1993) revealed that vitrinite-rich coals have a greater sorption capacity than inertinite-rich colas in the same rank, however research from the 1970s (Harris and Yust 1976) displayed that coal micropores are predominantly located in vitrinite, while in the inertinite, meso- and macropores. Moreover, the temperature and moisture have a negative influence on the sorption capacity of coal (Kozłowski and Grębski 1982; Kędzior 2009b, 2019; Wierzbicki 2013). The gas (methane) pressure in the coal seam is determined by the methane content in coal (Tarnowski 1989, 1971; Lunarzewski 1998) and is defined by the desorption intensity. This method is commonly used in the Polish and worldwide mining industry (Kozłowski and Grębski 1982; Lama and Bodziony 1998; Wierzbicki and Skoczylas 2014; Krause 2019) to classify the methane danger, before the more accurate tests will be carried out by the certified mining laboratories. The collected data of the gas pressure, in the southern part of the Upper Silesian Coal Basin by Tarnowski (1971) revealed that methane content in the coal seam is fairly correlated with the methane pressure/desorption intensity (Fig. 5). The recent results of tests made by the CLP-B Sp. z o.o. in Jastrzębie-Zdrój (Poland) for the Budryk and Pniówek mines for the years 2018–2020 showed similar outcomes describing the methane content and gas desorption/pressure interdependence (Fig. 6a, b).

Coal mining

The most important economic factor in every mine is the annual coal production. Economic possibilities, natural hazards, technical difficulties and market size affect the annual coal output of each mine (Dreger 2019, 2020; Dreger and Kędzior 2019). Changes in coal production over time in both analysed mines are illustrated in Fig. 7.

The Budryk mine started production in 1994, while the production data from Pniówek starts from 1986. In 1994, the Budryk mine was getting started with just 580 thousand Mg of extracted coal (Fig. 7). Over the following years, coal production in Budryk was gradually increasing, reaching the highest production level in 2007 with 3.85 million Mg of extracted coal. In subsequent years, until the end of the study period, coal output dropped and retained a constant level of under 3 million Mg per year.

On the other hand, the highest hard coal output in Pniówek was reported at the beginning of the research period, in the late 1980s, with the coal production exceeding 3.8 million Mg. In the next years, to the end of the studies, the coal production fluctuated which can be seen on Fig. 7.

Hard coal extraction in Polish underground mining is deeper about 8 m per year on average (GIG 1995–2019). As a result, coal production takes place in coal seams of variable gas and physico-chemical conditions. In most mines, in the USCB, methane content increases with increasing depth (Kędzior and Dreger 2019; Krause 2019). As the depth of extraction increases, gas permeability in coal seams decreases and pre-mining methane drainage is not sufficient; therefore, the methane hazard increases. The average depth

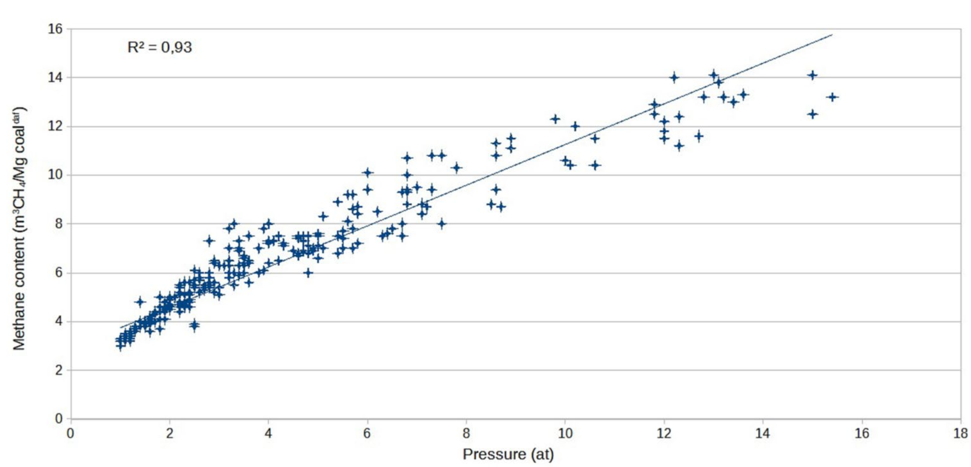
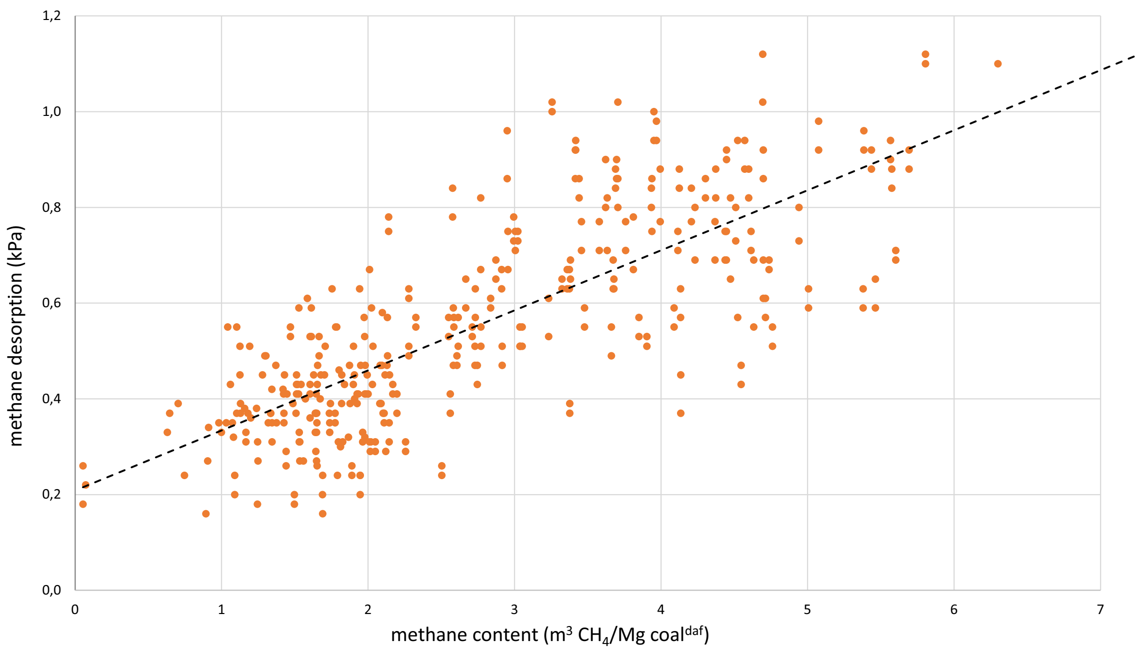
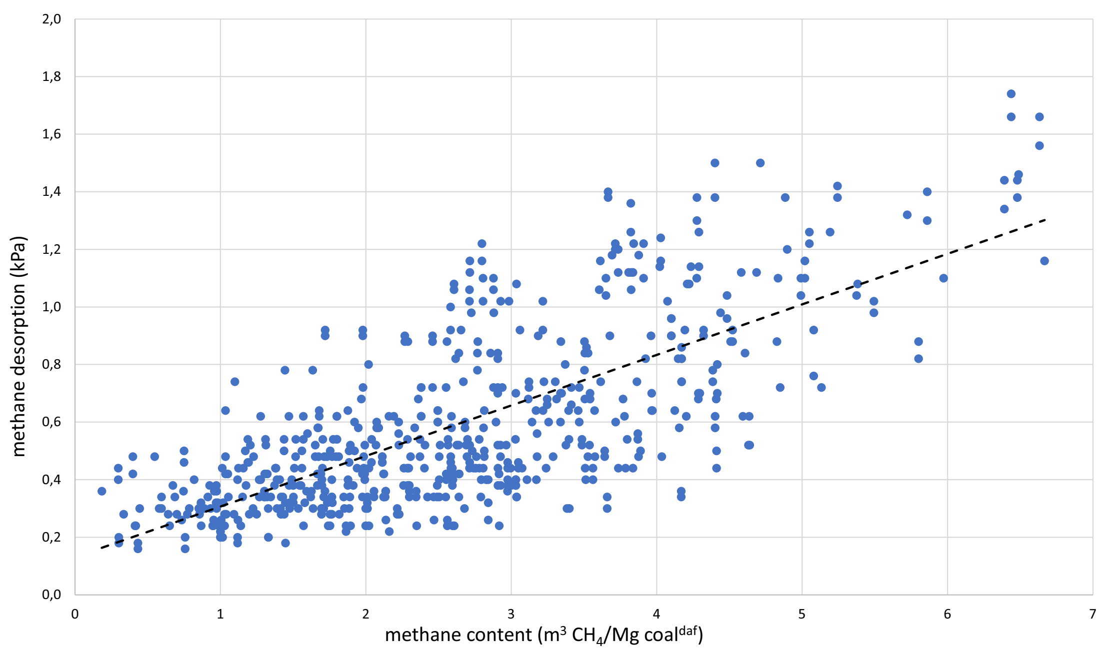


Fig. 5 The methane content and coal seam pressure studied in the USCB coal mines (Tarnowski 1971)



(a) The methane content and coal seam pressure studied on Budryk's coals by the CLP-B Mining Laboratory



(b) The methane content and coal seam pressure studied on Pniówek's coals by the CLP-B Mining Laboratory

Fig. 6 **a** The methane content and coal seam pressure studied on Budryk's coals by the CLP-B Sp. z o.o. **b** The methane content and coal seam pressure studied on Pniówek's coals by the CLP-B Sp. z o.o.

of coal extraction in 2010 was around 700 m, and from year to year it was permanently increasing by 8–10 m. Now, the average depth of coal production is 788 m and coal sorption capacity is much lower than in shallower seams and the gas pressure in coal seams increases with depth (GIG 1995–2019; Kotas 1995; Krause 2019; Szlązak et al. 2020). Studies conducted by Krause (2019), e.g. revealed that most of the methane emitted to the coal workings comes from

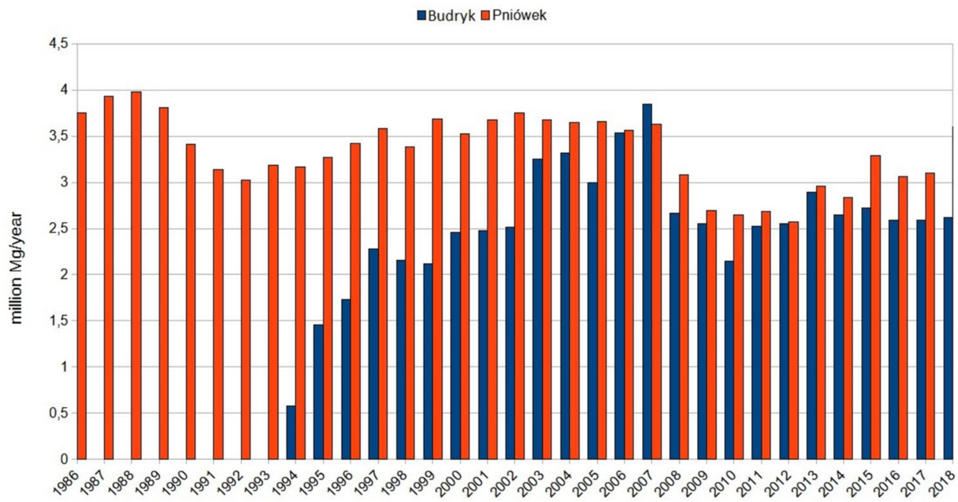


Fig. 7 The Budryk and Pniówek hard coal output (JSW—internal reports, GIG, 1995–2019)

depleted, overlying and underlying coal seams (60%), the remainder of CH_4 is emitted from extracting longwall (40%). Another important factor is the intensity of coal production. Hard coal in the USCB is almost exclusively produced by means of longwall systems with the use of heading machines and longwall mechanical coal miners (Krawczyk 2020). Longwall length and height, daily extraction progress are the main variables needed to determine the amount of the coal output. The longwall length increased by ~41% in recent years, coal production intensity rose and total methane emission also increased (Turek 2007; Krause 2019). As longwall length increases, the area of exploitation relaxation rises and the volume of released and migrated methane is also higher.

In the Budryk mine, with the greatest depth of mining in the USCB, currently reaching 1290 m, the number of operating walls has been changing during the studied period of coal production (1994–2018). Hard coal production at production levels becoming deeper every year does not change the technical parameters of extracting walls. No significant concentration of coal extraction was found, as the parameters of longwalls change regardless of the year, depth and amount of coal extracted changes.

During the last 4 years of the study, the average depth of coal production in the Pniówek mine rose from − 613 (2015) to − 665 m above sea level in 2018 (about 880 in 2015 to 930 m below ground level in 2018) which was 13 m deeper every year. Between 2015 and 2018, a greater amount of coal production was observed (JSW—internal reports).

Methane emissions

Budryk mine

The CMM from all the coal excavations of the Budryk mine was measured in the period from 1994 to 2018. From the beginning of the study to 2005, the total methane emission rose from 2.21 to 55.80 million m^3/year (Fig. 8). In subsequent years (2006–2012) methane emission was around 40 million m^3 of gas per year. From 2013 a large increase in methane emission was observed; in the last three years of the study (2016–2018), over 140 million m^3 of CH_4 was emitted yearly, which was three times more than the average emission in 1994–2012.

At the beginning, coal was mined at shallower, naturally degassed seams but when coal mining entered into a deeper zone with higher methane content, the total CH_4 emission increased rapidly. The methane content and gas pressure increase with depth within the Main Trough area, including the Budryk mine, what is the main reason of the large increase in methane emission at greater depths in the mine. The related data, such as degassing, ventilation air methane (VAM), and specific methane emission, follow the trend of the total methane emission (Fig. 8). The Budryk mine started degassing of the coal seams in the fourth year after coal extraction had been started (in 1997) (Fig. 8). Before that time, all of the methane was released directly to air. It is worth mentioning that from 1997 to 2013 between 30 and 50% of all of the emitted methane was captured by the underground methane drainage system. When the total methane emission suddenly rose in the last 5 years of the research period, the share of degassing and utilising methane in internal mining processes also increased, to reach 70–88% in the period 2014–2018. The specific methane emission shows the real methane hazard that miners and mining authorities have to deal with. From the beginning of the research period to 1998 the specific methane emission was below 10 m^3/Mg of extracted coal (Fig. 9). From 1999 until 2013 the amount of emitted gas was oscillating between 10 and 20 m^3 of CH_4 (Fig. 10). In the last five years of the study, the specific methane emission increased to 26 m^3/Mg and was doubled (54–59 m^3/Mg) in 2016–2018 (Fig. 9). The Budryk mine, as the youngest working coal mine in Poland, started

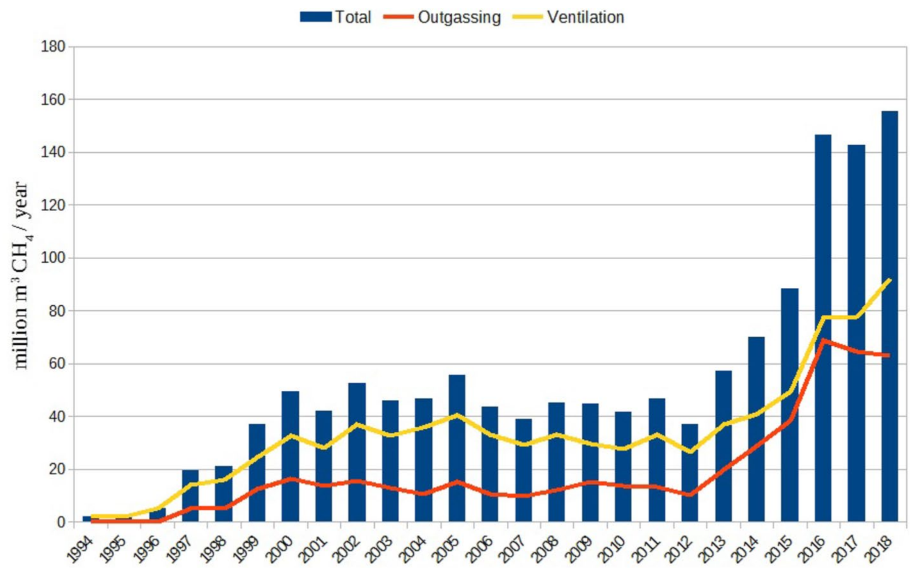


Fig. 8 The Budryk mine methane emissions (JSW—internal reports)

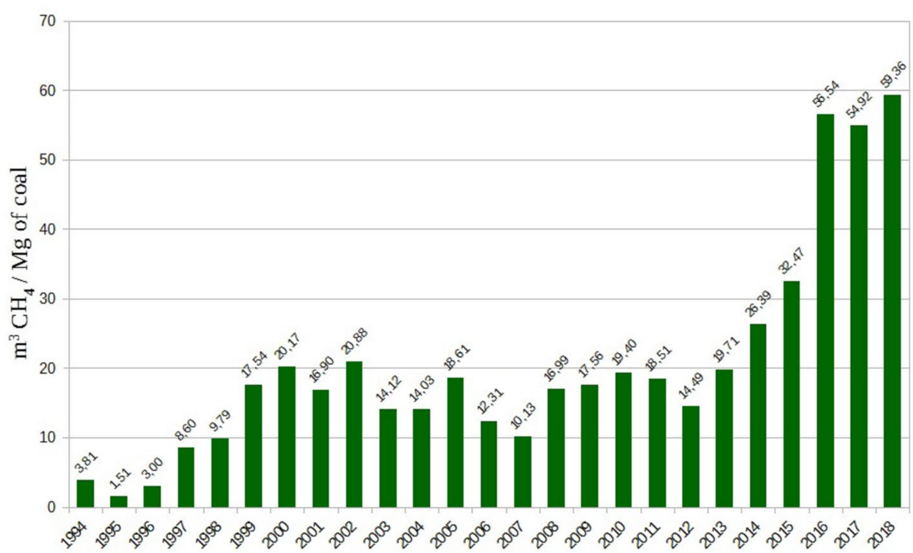


Fig. 9 The Budryk mine-specific methane emission (JSW—internal reports)

coal extraction in 1994. In the geological past, shallow lying coal seams (up to about 500–600 m deep) were naturally degassed, owing to erosion and hydrodynamic changes in the rock mass in the northern part of the USCB before the Miocene period. The degassing process was facilitated by faults constituting migration pathways for methane. As a result, methane emission values correspond to the pattern A of the vertical methane distribution in the USCB. Shallower seams were emitting less than 40 million m^3 of CH_4 yearly during mining activities. As the depth of extraction increased, entering the primary methane maximum at the depth of 600 m (Fig. 4), the CH_4 emission to mine excavations increased rapidly, exceeding 140 million m^3 of gas in the last three years of the study (2016–2018). The increase in methane content in coal seams and surrounding rocks results in an increase in gas pressure in the rock mass (Figs. 5, 6a), which also affects the intensity of methane emission into mine workings.

Pniówek mine

The Pniówek coal mine has been producing coal much longer than Budryk; hence, all the data come from the period 1986–2018. When we take a look at the total methane emission and the related emission data, we will see that those trends are completely different than in the Budryk mine. The largest total CH_4 emission values were observed in the late 1980s and at the early 1990s, when the coal was mining just below the sealed Miocene strata, where methane was accumulated in the coal seams as well as in porous

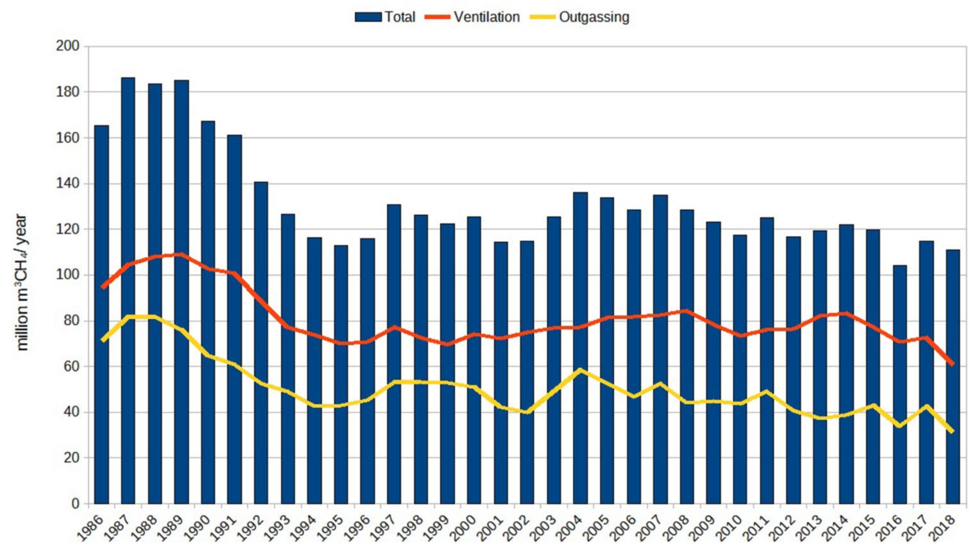


Fig. 10 The Pniówek mine methane emissions (JSW—internal reports)

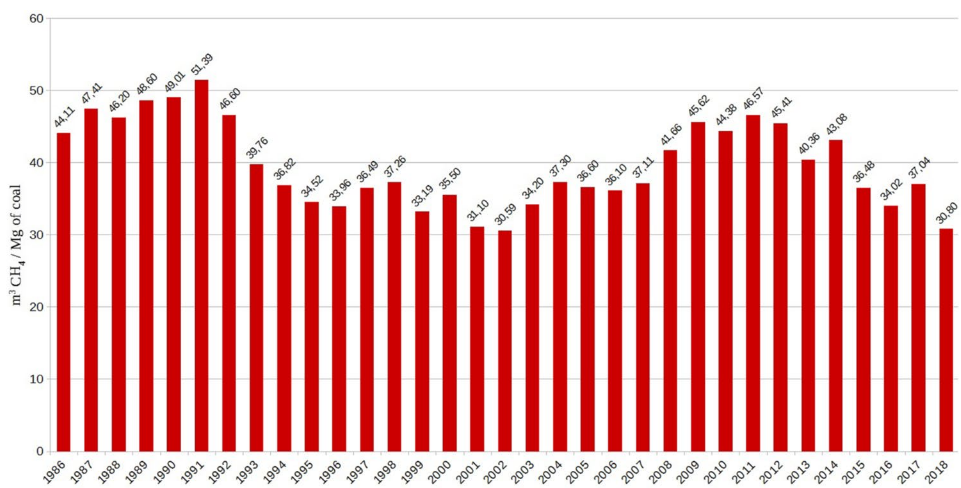


Fig. 11 The Pniówek mine-specific methane emission (JSW—internal reports)

rock strata in the geological past, forming the local methane maximum associated with the pattern B of the USCB vertical CH_4 distribution (Sect. 4.1, Figs. 3, 4). The largest coal mine methane emission was reported in the period 1987–1989, when over 180 million m^3 of gas was released to mine excavations over a one year period (Fig. 10). In subsequent years, the emission was decreasing from over 167 million m^3 in 1990/91 to the average of 123 million m^3 yearly during the next 26 years' period (1992–2017). The VAM adopts a similar trend as the total CH_4 emission, reaching maximum values from the beginning of the research to 1991, with the highest value in 1989, when over 109 million m^3 of this dangerous gas was discharged out of the mine (Fig. 10). Over subsequent years, the VAM trend is stable with small rises and decreases, reaching the lowest value similar to that of the CMM in 2018, when only 60 million m^3 of gas was removed by the ventilation systems out of the mine (Fig. 10).

Between 1991 and 2008, we can observe a decrease in specific methane emission with over 30 $m^3$of methane emitted per one Mg of coal (Fig. 11). In 2008–2014, the CH_4 emission over 40 m^3/Mg was noticed with slight, but constant decrease in the following years until the end of the study period when the lowest emission was recorded: 25.51 m^3 of CH_4/Mg in 2018. In the period 2015–2018, coal production increased to over 3 million Mg/year and the total methane emission decreased to under 120 million m^3/year (Fig. 10).

Due to complex and diversified faulting (Figs. 2, 3), geological structure and deeper coal extraction every year, the methane emission fluctuates in both mines with consistent trends. In the Budryk mine, the trend is increasing, but in the Pniówek mine, it is slightly, but constantly decreasing. Despite the different methane liberation trends, the total CH_4 emission in both mines remains at the highest level in the

Upper Silesian Coal Basin throughout the entire research period.

In addition to methane emissions in the Pniówek mine, much more dynamic events took place in the form of gas and rock outbursts. In 2002, during the blasting operations at the level of 1000 m, there was an outburst of approx. 250 m^3 of grinded down coal and ejection of ~ 55,000 m^3 of methane. The concentration of released methane in the mine air increased to ~ 86%.The gas and rock outburst in the neighbouring Zofiówka mine in 2005, which took 3 fatalities, resulted from the accumulation of methane in the mylonitic coal accompanying the two fault zones (Młynarczuk and Wierzbicki 2009; Jakubów et al. 2006; Kędzior 2012). The vertical distribution of methane content observed in the Pniówek mine is different from that in the Budryk mine. The difference concerns the occurrence of the zone secondarily saturated with methane under the Carboniferous top, which is evident by the high gas content in coal seams lying in this zone (Sect. 4.1.). The zone of increased pressure of free gas (7–8 MPa) associated with porous detritus lying at the uppermost part of the Carboniferous sediments is also important (see Sect. 4.1). Thus, coal extraction at the beginning of the study, when shallower seams were operated, was conducted under a higher methane hazard than when it was carried out in deeper seams in subsequent years. The secondary methane accumulation with methane content exceeding 10 m^3/Mg $coal^{daf}$ placed under the Miocene cover and also the occurrence of many faults (Fig. 3, see Sect. 4.1), considered as migration pathways for methane, were the cause of the high methane emission (over 160 million m^3 CH_4) to coal workings in a year period. In subsequent years, the total methane emission dropped to over 90 million m^3 in 2018, which may be associated with a decrease in the methane content of the seams as the depth of extraction increased and as it entered the zone of reduced gas content and pressure. The deeper occurring primary gas-bearing zone has a lower methane content (< 10 m^3/Mg $coal^{daf}$) than in the case of the secondary methane zone adjacent to the Miocene overburden (about 10 m^3/Mg $coal^{daf}$) (Fig. 4).

To sum up, methane emissions in the studied mines are the result of natural factors (geological and gas content of the rock mass), influencing in the first place, and anthropogenic (mining) aspects acting additionally. Details are shown in the Table 4.

Environmental aspect

Methane was recognized as the second-most important and powerful anthropogenic greenhouse gas (GHG) with a global warming potential (GWP) ranging from 20 to 36 times greater than carbon dioxide over a 100-year time period and 86 times greater over a 20-year period (Archer 2011; IPCC et al. 2013; Etminam et al. 2016; US EPA 2019a). Coal mining production is one of the largest sources of the methane emission, estimated for 11% of CH_4 emitted worldwide (US EPA 2019a, b; Global Methane Initiative 2020). Globally, the main methane emittants are: agriculture, wastes, biomass, coal mining, fuel combustion and natural emissions (Yusuf et al. 2012; Global Methane Initiative 2020). In Poland, the methane emitted to the atmosphere from underground coal mining accounts on 33.8% total methane emission in the country (Institute of Environmental Protection-National Research Institute 2020; Dreger 2021). When coal is mined, large amounts of CH_4 are released from coal and surrounding strata to the mining atmosphere due to drilling, grounding, transportation, explosives, etc. (e.g. Karacan et al. 2011; Kędzior and Dreger 2019). Methane

Table 4 Summarized division of the factors influencing the methane emissions in the Budryk and Pniówek Mines

Factors influencing the methane emissions		
Group of factors	Budryk mine	Pniówek mine
Natural (acting in the first place)	Geological—thin and permeable overburden of coal-bearing strata, deep reaching natural degassed zone Faults distribution, dislocations probably aided the degassing process of the upper parts of the deposit Gas content and pressure increasing with depth	Geological—thick and impermeable (sealing) Miocene overburden Secondary zone of increased methane content and elevated gas pressure placed in the uppermost part of the Carboniferous strata The occurrence of the primary and secondary zones of gas content and pressure in depth profile of coal-bearing sediments Fault tectonics, faults considered as migration pathways for methane and often responsible for gas and rocks outbursts
Mining (additionally acting)	Concentration of coal output Wall length, height and advance increase Methane emissions from now operating longwalls, underlying and overlying coal seams, as well as abandoned workings and goafs Depth of coal extraction	

emitted to the atmosphere is a mixture of unused captured gas (from underground drainage) and methane coming from the ventilation air emission (Tutak and Brodny 2019; Dreger 2021). Methane emission from mining ventilation shafts contributes the most to global methane emission from mining industry, nevertheless CH_4 is a potent source of energy and can be collected by underground drainage and can be used economically in the future (Global Methane Initiative 2020; Swolkień 2020; Dreger 2021). Unfortunately, in the Upper Silesia Coal Basin only 25% of all emitted methane is captured by underground drainage system. The vast majority of released gas to the coal workings is disposed by VAM (75%) (Tutak and Brodny 2019; Dreger 2021; Szlązak and Swolkień 2021). Unluckily, it is impossible to capture all of the emitted gas and gas mixture in the areas affected by mining works. The greenhouse effect magnification from coal mines does not stop, even when the mine is closed. The methane liberation from non-extracted coal seams, overlying and underlying seams can be active up to 15 years after colliery closuring. This problem was the purpose of numerous studies (e.g. Pokryszka and Tauziede 2000; Franklin et al. 2004; Krause and Pokryszka 2013; Kholod et al. 2020).

Besides the great heat absorption, methane is harmful to the human health and crops. There were recognized many indirect effects of CH_4 emission like heart and lungs diseases and yield losses (West and Fiore 2005; UNEP Synthesis Report 2011).

In 2018, over 1.9 million Mg of methane was emitted in the territory of Poland, including 0.53 million Mg from the USCB coal mines. It is worth to mention that 20% of all emitted GHG in Poland is covered by CH_4 but Polish gassy mines are responsible for only 3% GHG in the country (Dreger 2021). Coal production industry in Poland and worldwide will be struggling with more complex geological and mining conditions and also, with greater depths of mining when more methane is going to be emitted (Kędzior and Dreger 2019; Tutak and Brodny 2019; Karacan et al. 2021). The development of VAM gas production is the key solution to limit the CH_4 emission to the atmosphere. However, in Poland, to ensure safety, the concentration of methane in the VAM has to be reduced to $\leq 0.75\%$ in the ventilation shafts. Thus, the energy production from low caloric fuel is ineffective (e.g. Honysz 2015; Szlązak and Swolkień 2021). Globally, several technologies were developed to use air mixture with low CH_4 concentration in the turbine engines. The list of technologies can be found at: CMM energy (2021), EPA (2019a, b), Szlązak and Swolkień (2021).

Conclusion

The Budryk and Pniówek mines belong to the most gassy mines in the Upper Silesian Coal Basin. However, both are located in different parts of the basin, which are characterised by both different geological structure and spatial distribution of gas content. At the Budryk mine, the youngest in the basin, coal mining was initially carried out (1990s) in a shallow naturally degassed zone, then it entered into a deeper zone with high methane content of 12 and more $m^3/Mg\ coal^{daf}$. This resulted in a sharp increase in methane emissions from around 2 to over 140 million m^3 of methane per year (late 2010s).

At the Pniówek mine, coal was initially mined in high-methane seams occurring in the secondary methane-bearing zone with high methane content in coal seams ($>10\ m^3/Mg\ coal^{daf}$) and elevated free gas pressure (7–8 MPa) in weathered rocks, located just below the sealing Miocene overburden. This resulted in record-high methane emissions in the initial extraction period (1980s), reaching 180 million m^3 annually. In subsequent years, methane emissions decreased to around 100 million m^3 in 2018 with numerous fluctuations throughout the entire research period. This can be explained by the lower methane content and gas pressure in coal seams at a greater depths associated with the occurrence of a reduced methane content zone and the primary gas-bearing zone occurring deeper, but with a lower gas content than the shallow, secondary one. Thus, it may seem that the vertical zonation of the gas content in seams is the main factor that controls methane emissions in the analysed mines, because the temporal variability of methane emissions coincides with the depth of coal extraction corresponding to individual gas zones.

Faults, breaks and rock discontinuities are an important factor of methane migration, because in their vicinity a decrease or increase in gas content and gas pressure has been observed. Often, methane had migrated through faults in the geological past, and thus fault zones can also be now a source of methane emissions into mine workings. In special circumstances, they can also cause more dynamic phenomena, such as gas and rock outbursts, which took place in the Pniówek and Zofiówka mines.

Also important are the mining factors affecting methane emissions, such as the intensity of coal mining, the size of the mining longwalls, their number and the presence of goafs, which are an important source of methane emissions. Along with significant methane emissions in both mines, methane is captured by methane removal stations, which has a positive impact on safety of miners at work, economic balance of the mines and environmental protection (reduction of greenhouse methane emissions to the atmosphere).

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Declarations

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

Informed consent The authors have all the consents for using data and information from Jastrzębska Spółka Węglowa SA (JSW SA) and from the CLP-B Sp z o.o. in Jastrzębie Zdrój. All experiments which were done during research comply with the current law of the Republic of Poland.

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Article

Geological and Mining Factors Controlling the Current Methane Conditions in the Rydułtowy Coal Mine (Upper Silesian Coal Basin, Poland)

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Abstract: Methane emissions into mine workings and the atmosphere are still a significant environmental and work safety problem. Since 2000, the Rydułtowy coal mine, located in the western part of the Upper Silesian Coal Basin, has been struggling with significant methane emissions compared to the previous period. The distribution of the methane content in coal seams was analysed, and the factors that influenced it were reviewed. Then, the annual variability in methane emissions in mining excavations was investigated, and the depth of coal extraction was linked to methane conditions and the time of mining works. It has been shown that the currently observed distribution of methane in coal seams is the result of, inter alia, the geological development of the western part of the basin, the lithological character of coal-bearing Carboniferous deposits and overburden, and fault tectonics. The sorption capacity of coal seams decreases with increasing temperature and the coal rank. The amount of methane emitted into mine workings depends mainly on the methane content in the coal seams in mining sites and on the sorption capacity of the coal seams. The depth of exploitation, increasing from year to year, leads to an increase in the methane content in coal seams and a simultaneous decrease in the sorption capacity of coal, which will result in higher methane emissions in the future.

Keywords: methane content; methane emission; coal sorption capacity; Rydułtowy mine; Upper Silesian Coal Basin; Poland

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1. Introduction

Coal mining in the Upper Silesian Coal Basin (USCB), the largest coal basin in Poland and one of the largest in Europe, is in a constant downward trend. It has decreased threefold since the late 1990s. In 2020, 42 million tonnes of coal were extracted [1]. This decline in production has not diminished the methane hazard in mines. This is manifested by the significant emissions of methane into mine workings, which for many years have not fallen below 700 million m^3 of methane annually. The reason for this is the constantly increasing depth of mining and the associated greater gas capacity of the seams, as well as the methane concentration of the coal extracted [2]. Some mines in the basin initially had no or minor problems with methane. However, this has changed over the last two decades, with increasing gas emissions into mine workings. One of these mines is the Rydułtowy mine, with an annual coal production of approximately 1.5 million tonnes. It is located just off the western boundary of the Upper Silesian Coal Basin and is the westernmost working mine in the Polish part of the basin. After 2000, there was a significant increase in the total methane emitted into workings, and since 2002, data on the demethanation of the deposit have been reported [1,3].

The aim of this paper is a spatial analysis of the gas content variability and the identification of factors that led to the currently observed distribution of the methane in the deposit. At the same time, the volume of the annual methane emitted into the mine workings was analysed in order to correlate this with the gas content in the coal beds and geological and mining factors affecting the deposit. Thus far, the analysis of this issue has been carried out in the rest of the USCB and elsewhere, [4–12] and it has exposed a significant impact of the natural and mining factors on the changes in methane emissions over time. Therefore, it is important to verify whether such a dependence also occurs in the Rydułtowy mine, which is less frequently studied at this point. The relationships between the gas conditions and the individual elements of the geological structure of the USCB have been described in numerous works [11,13–21]. They show that the current distribution of methane content depends on the geological development of the basin and the origins of the gases, the degree of coalification of the seams, the petrographic composition of coal, and the lithology of the surrounding rocks, tectonics, as well as the temperature and pressure in the deposit. The results of these studies are mostly consistent with global outcomes [21–24]. The subject of the study is the Rydułtowy deposit, located within the folded zone of the USCB near the western boundary of the basin, which is characteristic of the predominance of Paralic coal-bearing series and varied overburden layers with a constant emission of methane into the mining works. The aforementioned analysis was based on the results of gas content tests on coal samples from the mine, data on methane emissions, and the results of coal quality tests. These data were collected in the geological documentation of the deposit and reports on methane emissions.

2. Geological and Mining Features of the Upper Silesian Coal Basin

The Rydułtowy hard coal deposit is located in the western part of the Upper Silesian Coal Basin, which is one of the largest in Europe, with an area of 7250 km^2, including 5650 km^2 in Poland. The other part is in the Czech Republic [22] (Figure 1).

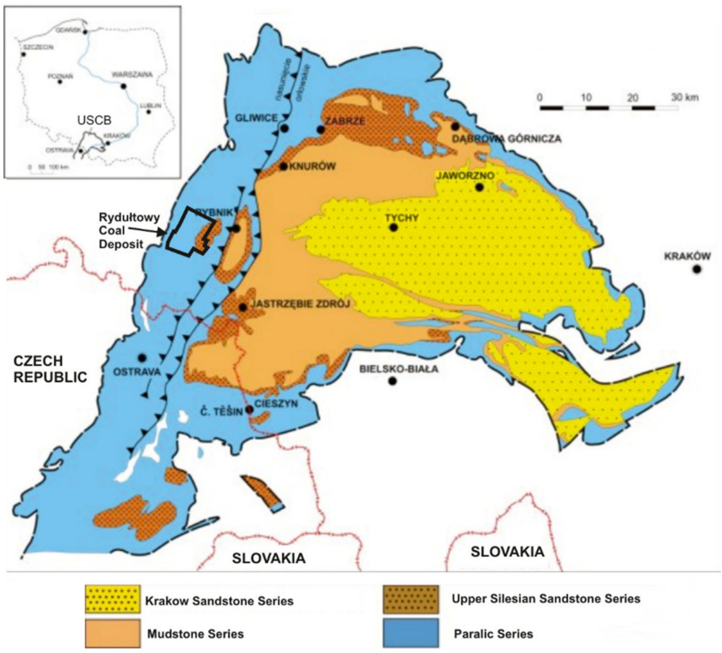

Figure 1. The Rydułtowy coal deposit against the background of the lithology and stratigraphy of the Upper Silesian Coal Basin.

The basin was developed in the foreland of the Moravian and Silesian Variscan fold zone, filled with molasses-bearing coal deposits [23]. The sedimentation of the coal-bearing formations took place in the Upper Carboniferous period (Mississippian and Pennsylvanian). The carboniferous sediments include interbedded packages of siltstones, mudstones, and sandstones, with numerous coal seams. Due to the variety of sedimentation, the coal-bearing complex is divided into four lithostratigraphic series, which differ in their lithological character, as well as in the number, thickness, and distribution of the coal seams, only two of which are located in the Rydułtowy coal deposit (Figure 1; Table 1).

Table 1. Summarised lithological description of Rydułtowy 1 coal deposit (Rydułtowy mine archive materials).

Stratigraphy	Lithostratigraphic Unit		Coal Seam Name	Description
Quaternary	-		-	Thickness 5–30 m. Sandy gravel deposits with glacial and fluvioglacial clays.
Miocene	-		-	Thickness 0–400 m. Lack of deposit in central, east, and southeast parts of the area. Loams, silts, fine sands and gravels, shales, sandstones.
Triassic	-		-	Thickness 0.1–56 m. Deposited as local patches. Loams, sands, marl loams, siltstones, mudstones.
(Carboniferous) Pennsylvanian	Namurian B-C	Upper Silesian Sandstone Series	Saddle Layers (500)	Coarse-grained sandstones (thickness up to 25 m) with 0.7–5.6 m thick coal seams.
	Namurian A	Paralic Series	Poruba Layers (600)	Total of 60 coal seams with coal inserts were recognised in the profile. Coal seams are generally thin and accompany surrounding rocks deposited as shales, sandy shales, and fine-grained sandstones.
			Jaklovec Layers (700)	Main production level. Total of 30 coal seams with coal inserts were recognised in the profile (<0.1–4.0 m). Siltstones, mudstones layered with sandstones.
			Hrusov Layers (800)	Siltstones, mudstones, sandstones. Numerous coal seam inserts but non-documented. Recognised by deep boreholes only.

The basin is complicated in terms of its tectonics. There are three main tectonic zones—(i) the folded zone, a 20 km-wide belt in the western part of the basin, consisting of meridian-oriented overthrusts and troughs; (ii) the disjunctive zone (Bytom Syncline, Main Saddle, and Main Syncline), occupying the largest part of the basin with the large latitudinal dislocations, with displacements of several hundred meters and smaller faults, often dividing the coal-bearing series into smaller tectonic blocks; and (iii) a fold-block zone in the north-east. Faults and tectonic disturbances often make coal mining difficult [23].

There is hard coal of all ranks in the USCB, ranging from low-rank, non-coking coal (subbituminous) and coking coal (high- to low-volatile bituminous) to high-rank coal (low-volatile steam coal) and anthracite [23]. Of these, only the low-rank and coking coals are mined. The remaining ranks are in the minority or lie at a depth inaccessible for mining, >1250 m (e.g., anthracite).

Coal is mined in every part of the Upper Silesian Coal Basin, where geological and mining conditions differ, which can be seen in the methane emissions and coal production quantities [2,10,11]. The methane concentration in coal seams is not homogenous; rather, the rule of increasing methane content with depth is evident in most of the working mines in the USCB today. In general, the Carboniferous strata in the northern and central regions are shallow deposited, mostly devoid of Miocene overburden. The overburden occurs here as local patches and thin layers, which have not prevented methane migrating into the atmosphere in the geological past. In the present day, the shallow coal seams (up to ~400–600 m) are mostly methane-free, but the methane concentration grows with increasing depth. On the other hand, the southern part of the USCB is covered by a thick, sealing Miocene screen. Migrating methane was trapped under the overburden, and the coal seams and surrounding strata were secondarily accumulated. The secondary methane zone consists of microbial gas mixed with thermogenic gas [24]. Coal production, which was focused on seams under Miocene overburden, was impeded by the high methane emissions caused by releasing methane from the coal being extracted and migrated from surrounded, unmined deposits. At greater depths, methane concentrations decrease, but deeper, the primary methane content zone can be observed (G~15 m^3/t coal daf).

The western part of the USCB is a mix of two types of vertical methane distributions, as described above. In some areas, the Miocene sealing deposits cover the Carboniferous coal-bearing surface, acting as sealing strata for the gases, but in others, Carboniferous sediments occur as outcrops, which are free of methane.

The average depth of extraction in the Polish part of the USCB increases by ~10 m every year, reaching ~800 m on average in 2020 (~524 m in 1989) and extending to ~1290 m at the deepest in 2020. In the same year, the deepest coal works were conducted at ~1315 m [3]. Coal production in the USCB has been falling since 1997 due to the closure of coal mines or their being merged into larger enterprises. Deeper deposited coal seams need to be mined to maintain production continuity, but operations at greater depths involve higher risks of natural hazards (e.g., temperature, tremors, and methane) [2,12,25]. Therefore, coal production is becoming increasingly burdensome every year, which can be seen in the lower coal production. Operations in more methane-rich seams are connected with intensified methane emissions, reaching ~820 million m^3 in 2020 [3]. The increasing trend in methane emissions is evident; despite periodic drops, the annual emission of >700 million m^3 has been maintained. The regional large dislocations, lithology, and stratigraphy of the Carboniferous strata, combined with the depth of extraction and mining factors, are the main reasons for CH_4 emissions in the USCB coal mines. Previous works have studied methane migration associated with geological and mining conditions [2,10–12].

Geological Setting of the Rydułtowy Coal Deposit

According to the geological documentation and the coal mine materials, the Rydułtowy 1 coal deposit is located in the Carpathian Foredeep, in the western part of the USCB, in the upthrow of regional tectonic discontinuity, the Michałkowice-Rybnik overthrust, with throw size ~750–1500 m. This deposit is represented by a fault-folded structure, with the form of an asymmetric trough (Jejkowice trough) inclined to the northeast. The incline of the western wing sediments reaches up to 15°, locally 60°/E close to the boundary, and ranges from 8° to 10°/W in the eastern wing. According to the division of Kotarba et al., the Rydułtowy coal deposit is part of the seventh gas region of the USCB [15]. The coal seams documented in the Rydułtowy area are recognised as Mississippian and Pennsylvanian (Namurian A-C) layers. The main lithological types of the rocks surrounding the coal seams are sandstones, claystones, and mudstones. Their summarised description is presented in Table 1.

The proportions between the rocks depend on the stratigraphic position of the layers and the sedimentary development of the basin. In the study area, the share of sandstones in the profile of the Poruba layers amounts to approximately 35%, and in the lower-lying, Jaklovec layers, it is reduced to approximately 29% [26]. The porosity of the sandstones is around 6% [26]. The others are claystones and mudstones.

3. Materials and Methods

Data comprising the total methane emissions, degasification, ventilation methane emissions (VAM), and annual net coal production were obtained directly from the PGG SA ROW Rydułtowy coal mine. The elements of the geological structure, such as lithology, stratigraphy, tectonics, hydrogeology, and coal parameters (firmness of the coal and the methane desorption intensity), were obtained from the geological documentation of the Rydułtowy coal deposit. Additional parameters regarding other coal mines in the basin and the entire USCB were obtained from annual technical reports published by the Central Mining Institute in Katowice (GIG) [3]. The data were carefully analysed and presented in charts, tables, and figures. The spatial distribution of the methane in the Rydułtowy coal mine was assessed by tests performed systematically in the coal works. In these tests, the sample holes are drilled in the fresh exposed coal face, and ~100 mg coal samples are enclosed in hermetic steel containers, which, in the next phase, are shaken to obtain crushed coal, then transformed into powder. All the methane is released into a pipette, and this released amount is then measured [27]. Knowing the amount of methane released and the mass of the coal sample allows one to calculate the methane content, i.e., the volume of methane per one tonne of coal. Subsequently, this volume is corrected for the moisture and ash content, coal dry ash-free state (daf), and gas losses during sampling.

Data on the methane content were obtained from mining excavations and two surface bore holes with depths of 1300 and 1700 m, located in the northern part of the studied area.

The depths of the sampling measurements of the methane emissions from each year were compared, and a chart displaying the average and the deepest annual works was created.

The specific methane emission values refer to the volume of methane that is emitted with every single tonne of coal (m^3/t). These values make it possible to adjust the total measured methane emissions according to the number of tonnes of coal extracted and compare the emissions between mines with different types of coal extracted.

The coal sorption capacity of the methane at a given pressure and temperature was obtained from the literature [28]. Additionally, it was measured using a coal sample taken from a depth of approximately 1000 m in the Rydułtowy mine. The measurement device was a Hiden Isochema sorption apparatus, model IGA 001.

4. Results and Discussion

4.1. Distribution of the Methane Content and the Coal Mine Methane Development

In the discussed deposit, methane is mainly associated with the coal seams and generally presents as adsorbed gas in the coal matter (micropores). Free methane is in the minority and is present in breaks and fractures, as well as in the coal macropores. Thus far, no gas has been found in the non-coal surrounding rocks. The gas occurring in the study field consists mainly of methane (80–90% in the methane zone). The share of ethane increases with depth, and below the level of 1000 m, it can reach several per cent, while propane and butane do not exceed trace levels. The other gas components are nitrogen, carbon dioxide, and hydrogen

The depth distribution of the methane content in the study area includes two zones (Table 2, Figure 2). The upper one, which was naturally degassed in the geological past, is located at a depth of about 600 m below ground level, where methane is absent or occurs in very small quantities (0.0 to 0.8 m^3/t coal daf), and the lower methane zone extends from a depth of about 600 m to the bottom of the deposit, where the methane content increases consistently, reaching a maximum measured value of more than 14 m^3/t coal daf at a depth of approximately 1160 m (-910 m above sea level). The depth range of the methane zone has not been identified thus far.

This distribution of the methane content in the Rydułtowy deposit corresponds to the so-called northern pattern of methane distribution in the USCB (see, e.g., [14,29]), which characterises the several hundred meter-thick degassed zone of natural desorption occurring in the upper part of the Carboniferous strata. The lack of secondary accumulation of the methane on the Carboniferous roof of the deposit proves that the Miocene and Triassic overburden is not tight enough here for migrating gases [15].

The configuration of the methane seam roof, with a methane content above 4.5 m^3/coal daf, as shown in Figure 3, is varied.

The position of the top surface spans between −540 m and −820 m above sea level. The top is clearly lowered to the north, because in the surface boreholes Jejkowice IG-1, being 1700 m deep, and Jejkowice 6, being 1300 m deep, located in the northernmost part of the area, the determined methane content of the coal seams does not exceed 1 m^3/t coal daf in the entire profile of these wells.

The balance resources of methane as an accompanying commodity in the Rydułtowy coal deposit are estimated at 508 million m^3, of which 183 million m^3 are developed reserves [1]. They are concentrated at a depth of 600–800 m below the ground level. The demethanation of the works started in 2002, and since 2013, it has exhibited a steady downward trend. In 2020, just over 6 million m^3 of gas was captured. In the best year, 2008, it was more than 15 million m^3. A total of around 130 million m^3 of methane has been captured in the last 15 years. Since 2016, the captured methane has been used to power cogeneration units producing electricity and heat that are sold to external consumers. The unused or sold gas is released into the atmosphere. The efficiency of using the captured methane in the Rydułtowy mine, i.e., the ratio of the methane consumed to the methane captured, was almost 89% in 2017 and 75.58% in 2020 [25], which means that 11% and 24.42% of the captured gas, respectively, was emitted into the atmosphere.

Table 2. Parameters of the methane content at individual depth intervals.

Interval (m above Sea Level)	Methane Content (m^3/t coal daf)				
	Minimum	Maximum	Average	Standard Deviation	Number of Data
0 to −200	0.004	0.04	0.01	0.01	14
−200 to −400	0.001	1.42	0.09	0.23	264
−400 to −600	0.001	6.27	0.61	1.07	916
−600 to −800	0.001	9.21	2.67	2.16	1104
−800 to −1000	0.003	14.76	3.83	2.5	1306

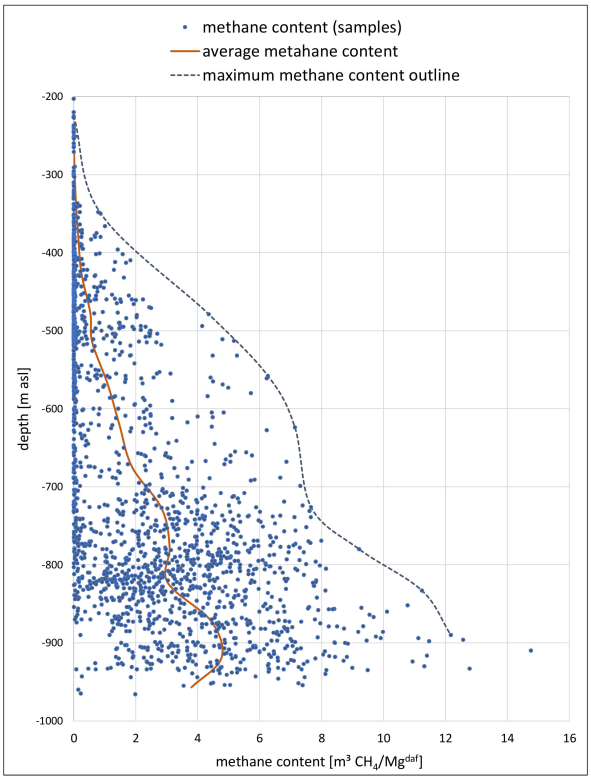

Figure 2. Depth distribution of the methane content in the Rydułtowy mine (Rydułtowy mine archive materials).

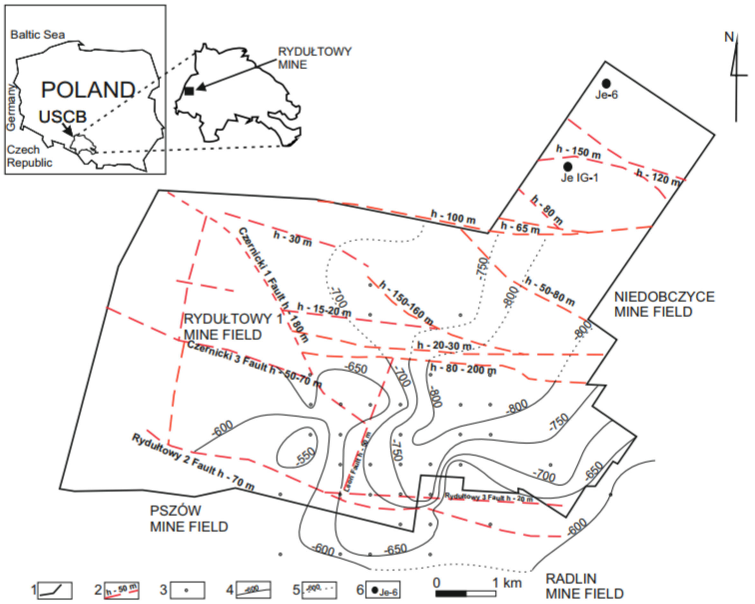

Figure 3. Top of the methane seams with G > 4.5 m^3/Mg coal daf against the background of the tectonics of the research area (modified after Rydułtowy mine archive materials): 1—boundary of the Rydułtowy mine field, 2—fault with the displacement value, 3—estimation point of the top of the methane seams, 4—line of the top of the methane seams (m above sea level), 5—presumed line of the top of the methane seams, 6—surface bore hole.

4.2. Sorption Capacity of the Coal

The sorption capacity is the volume of gas that coal is able to adsorb at a given temperature and pressure. The temperature and pressure of the rock mass increase with depth. The average geothermal gradient for the USCB Paralic and Upper Silesian Sandstone series ranges from approximately 2.75 to 4.75 °C/100 m [30] and is one of the highest in Poland. In the studied deposit, it is 3.25–3.75 °C/100 m [30]. Temperature significantly reduces the sorption capacity of coal, [17,18], while the overlying rocks' pressure positively affects the amount of adsorbed methane. Since both factors counteract the accumulation of methane, most of the methane accumulates in a strictly defined depth range, called the optimum methane zone, as a compromise between these two influences [17]. Above this zone, too low pressure prevents the accumulation of significant amounts of gas, while below it, too high temperature limits the sorption capacity of the coal. In the USCB, such an optimum methane zone occurs within the 800–1500 m depth range, with the possibility of fluctuations [17]. The maximum determined methane content in the Rydułtowy deposit, amounting to 14 m^3/t coal daf at a depth of approximately 1100 m, is within that range. However, as mentioned, the depth range of the optimum zone in the studied deposit has not been recognised.

The authors studied the sorption capacity of coals taken from the Rydułtowy coal mine from a depth around 1000–1200 m below ground level. The coal samples were placed in the gas sorption analyser (in the CLP-B laboratory) and saturated with methane at the rock mass temperatures (36–40 °C) under a pressure not exceeding 20 MPa. The Rydułtowy coals' Langmuir sorption isotherms were around 15–16 m^3/t coal (Figure 4).

The maximum methane content recorded at a depth of 900 m below sea level (~1200 m below ground level) was 14–15 m^3/t coal, which means that the coal seams are saturated with 95% methane (Figure 5). The methane content in the Rydułtowy area generally increases with depth; therefore, shallower deposited, less methane-rich coals are less saturated with gas, with a content ranging from 30 to 78% (depth of 500 to 900 m below sea level) (Figure 5).

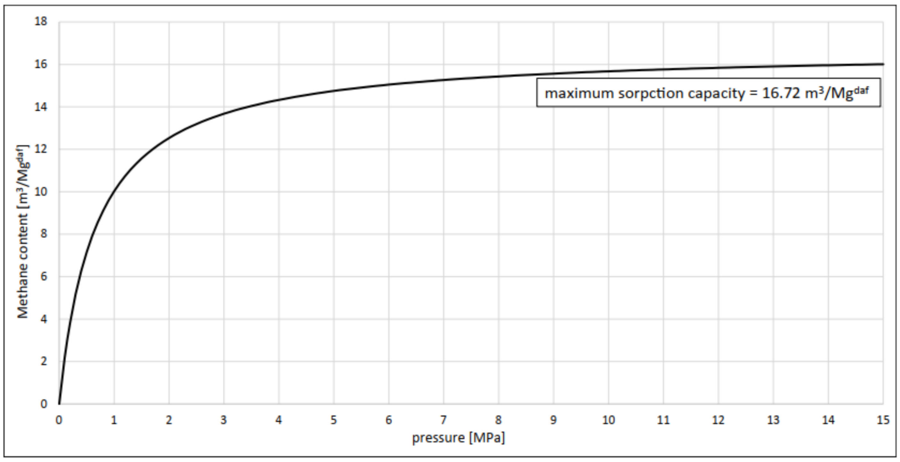

Figure 4. Langmuir sorption capacity of the coal from the Rydułtowy mine, taken from the depth of 1000 m.

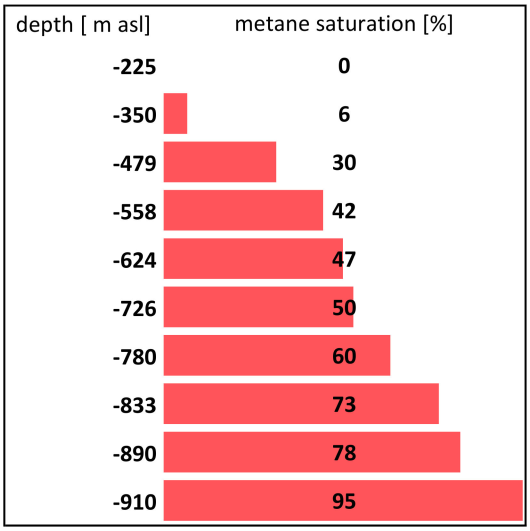

Figure 5. Saturation of the coal seams with methane, depending on depth, in the Rydułtowy deposit.

Teste performed in the CLP-B laboratory confirmed the negative influence of increasing temperature on the sorption capacity of the coal. The coal sorption properties decreased with increasing temperature at a rate of about 0.05 m^3 of gas per 1 °C. The effective diffusion coefficient, which describes the gas molecules' movement between the coal grains, was also studied at the rock mass temperatures (36–40 °C). The results were generally similar, centring around $D = 4 \times 10^{-10}$ cm^2/s. The methane diffusivity of the USCB coals tested by Wierzbicki increased with rising temperature and pressure [31]. This dependence was demonstrates for the Rydułtowy coal samples, where the diffusion coefficient increased by 0.2×10^{-10} cm^2/s with every increase of 1 °C. Taking into account the measured content of the methane in the coal seams in the studied deposit (up to approximately 14 m^3/t coal daf), we can observe the almost full saturation of the coal seams with methane, which can be seen in the greater methane emissions from the coal during coal works in the deepest parts of the coal deposit.

4.3. Geological and Mining Factors Influencing the Methane Occurrence

4.3.1. Geological Evolution of the Study Area

Coal-bearing formations of the USCB were deposited during the Late Carboniferous (Pennsylvanian) between 323 and 305 Ma. According to computer modelling of the coalification degree carried out using the PetroMod software, the maximum depth at which the

Carboniferous formation is buried was estimated to be between 3.3 km in the north-eastern part of the USCB and 5.5 km in the western part at the end of the Carboniferous period [19]. The coal-bearing formations in the Rydułtowy deposit located in the westernmost part of the basin are buried at a depth of approximately 5 km. During the Late Carboniferous, those sediments were subjected to a maximum heating temperature exceeding 90 °C [19,20]. The heating process resulted in the coalification of the seams, resulting in the present coal rank, which was accompanied by the production of gases, including methane (see, e.g., [18,32,33]). The USCB coals represent gas-prone type-III kerogen. Therefore, with the present-day degree of coalification of above 0.8% Ro in the western part of the basin, huge amounts of gas have been produced from the coal. The hydrocarbon potential of the coal seams of the Paralic and the Upper Silesian Sandstone series in the western part of the USCB was estimated at 45–65 and 65–75 mg of methane per gram of TOC, respectively [19]. According to the research conducted thus far [16,19,20,34], the methane generation took place in the Late Carboniferous and was completed by the end of the Variscan orogeny, at the turn of the Carboniferous and Permian. Later thermal events taking place in the Mesozoic did not lead to resumed methane generation but only caused its re-mobilization [19,20]. Due to the limited sorption capacity of the coal and subsequent erosion processes, not all of the methane produced was accumulated in the coal seams.

As already mentioned, after the burial of the coal-bearing sediments at the maximum depth at the turn of the Carboniferous and Permian, the area of the basin was subjected to uplift movements, with the most intense occurring in the Permian, which contributed to the erosion of the coal-bearing formations. The erosion process continued throughout the Mesozoic and the Paleogene up to the Miocene, when marine clays were deposited. The thickness of the eroded sediments has been estimated by various methods. According to Botor's research, it ranges from 2000 m in the east of the USCB to more than 4000 m in the west [20]. These values are similar to the estimates of Gerslova et al. in the Czech part of the basin, ranging from 2500–3400 m [35]. In light of the presented values, the level of erosion of the Carboniferous deposits in the Rydułtowy coal deposit is significant and may amount to approximately 4400 m. Changes in the static and hydrodynamic pressure regimes, resulting in erosion, enabled methane desorption from the coal seams and, consequently, their natural degassing [14,15,18]. The escape of methane from the coal seams may have also been favoured by endogenous fires caused by long-term exposure to the seams and their contact with oxygen [36]. The result of these processes is the approximately 600-thick zone of natural desorption of gases observed in the studied deposit.

4.3.2. Coal Rank and Maceral Composition

Using the data obtained from the geological documentation of the deposit, the seams of 600 (Poruba layers) and 700 (Jaklovec layers) groups were sampled. The caloric value of the examined seams is 13,832–32,609 kJ/kg, the volatile matter content is 26.3–37.4%, and the total sulphur content is 0.1–3.0%. As mentioned, the deposit contains both subbituminous (non-coking) and high- to medium-volatile (coking) coal. The coal rank increases with the depth of the seams. The boundary between these two ranks of coal runs at a depth of 400 m in the southern part of the deposit and 900 m in the northern part.

The dominant group of macerals in the coal is the vitrinite group (50–66%). The inertinite group's content varies between 12–25% and the liptinite varies between 7–18%. The vitrinite reflectance is within 0.8–1.0% and increases with depth (seam groups 600 and 700, [37]).

The coal rank and maceral composition of coal are both important for the amount of methane generated from the coal substance and for the sorption properties of coal. The coalification process is continuous, and various products, including methane, are generated during this process. The higher the coal rank is, the more methane is produced. The second coalification jump, which corresponds to coking coals, plays a special role here, since this is when the coal loses approximately 10% of its volatiles, which can affect the amount of gas generated [18]. Due to several subsequent processes, not all the produced gas is retained in the coal. The greatest levels of methane in the study area are accumulated below 600–800 m, which is partially consistent with the boundary between the steam and coking coal at a depth of 400–900 m. The maximum methane content in the study area (more than 14 m^3/t coal daf) was found at a depth of about 1100 m, which corresponds to the presence of coking coal. The hydrocarbon potential of the Rydułtowy field is discussed in Section 4.3.1.

The coal rank also affects the sorption capacity of the coal seams. The research conducted by Dutka on one of the coal deposits in the southern part of the USCB demonstrated that the coal rank has a dominant effect (about 89%) on the reduction of the coal sorption capacity [21].

The fact that the coal rank has such a negative impact on the sorption capacity of coal requires special attention, because other studies, [17,38] suggested a positive correlation between these values. Research carried out on Australian coals [39] showed that the trend of the changes in the sorption capacity of coal with increasing rank is a second-order polynomial and differs between the cases of bright and dull coal (Figure 6). At the lower coal rank, this difference is greater than it is at the higher rank. Moreover, up to the value of 1.65% Ro, we observed a negative influence of the increasing rank on the sorption capacity of the coal, especially in the case of bright coal. From this point, starting with a 1.65% Ro value, the trend becomes clearly positive (Figure 6).

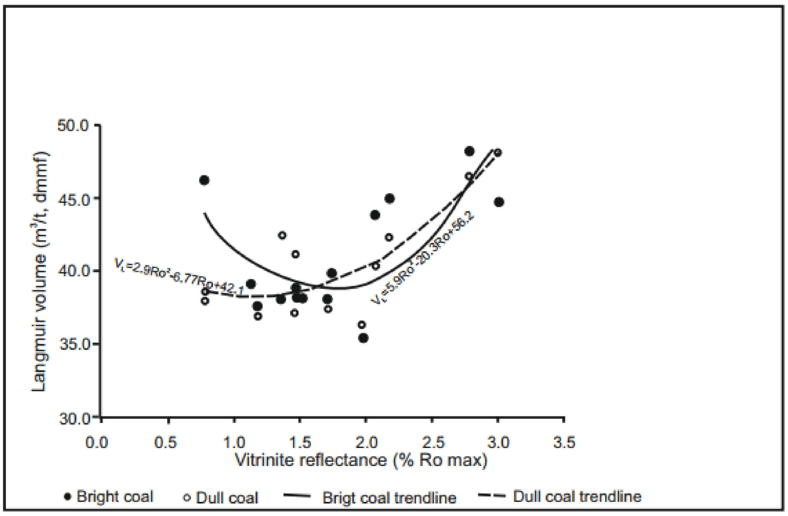

Figure 6. Trends in the Langmuir volume in relation to the coal rank [39].

The negative influence of the increase in the coal rank on the amount of sorbed gases can be explained by the presence of occluded oil in the coal micropores at a lower rank (from subbituminous to medium-volatile bituminous coal), which is produced at the oil window stage (0.7 to 1.3% Ro) and then cracked decomposed to obtain a higher coal rank (>1.65 Ro) [39,40]. Oil-depleted micropores with a larger specific surface area are able to adsorb more gas. Thus, in the case of higher-ranked coal, the sorption capacity increases with increasing rank [39]. The coal rank in the study area, ranging from 0.8–1.0% Ro, may therefore indicate a negative influence of the increasing coalification degree on the sorption capacity of the coal, as demonstrated by Dutka [21].

Due to the fact that the coal rank increases with depth, the effect of reducing the sorption capacity of the coal should be enhanced with increasing depth [41,42]. Tests of the sorption capacity of the coal in the southern and western part of the USCB, based on the analysis of Langmuir sorption isotherms, showed values of 9–15 m^3/t coal daf at a pressure of 2–12 MPa and a temperature of 40 °C [28], which is consistent with the results of the sorption capacity in the study area (15–16 m^3/coal daf, Figure 4).

From the point of view of the maceral composition of coal, macerals from the vitrinite and inertinite groups play an important role in the gas sorption process. As indicated by global research [43,44], vitrinite-rich bright coal generally has a higher sorption capacity than inertinite-rich dull coal at the same rank, while domestic studies [45] have demonstrated a relationship between the methane sorption capacity of USCB coals and the presence of cellular macerals of fusinite and semifusinite. The maceral composition of coal from the Rydułtowy deposit (the total share of inertinite and vitrinite coal exceeds 60–70%) seems to be favourable for the gas sorption process.

4.3.3. Methane Migration and Accumulation

Geological factors, such as the lithology of the Carboniferous strata and overburden, fault tectonics, and hydrogeological conditions, are responsible for gas migration and accumulation [16]. Sandstones are considered to be permeable, facilitating the migration of methane, in contrast to claystones and mudstones, which are impermeable and thus provide a sealing screen for migrating gases. The decreased share of sandstones, along with the increasing share of impermeable claystones and mudstones, in the Jaklovec Beds may be one reason for the increasing methane content in the coal seams with depth, which reaches the maximum value (more than 14 m^3/t coal daf) at a depth of over 1100 m. In this case, claystones and mudstones may act as a sealing screen for migrating gases and their accumulation at depths greater than 600 m. As can be seen from Figure 7, the upper boundary of the methane coal seams (G > 4.5 m^3/t coal daf) approximates the boundary of the Poruba and Jaklovec layers. According to the deep shaft borehole profiles, continuous sandstone-conglomerate sediments over 130 m thick were documented in the Poruba layers, which may have caused degassing in the deep coal seams and helped the methane to migrate from the deeper to the shallower parts of the profile or into the atmosphere. In the Jaklovec Beds, alternately deposited claystones, mudstones, and shales, being a few meters thick, dominate the lithological profile.

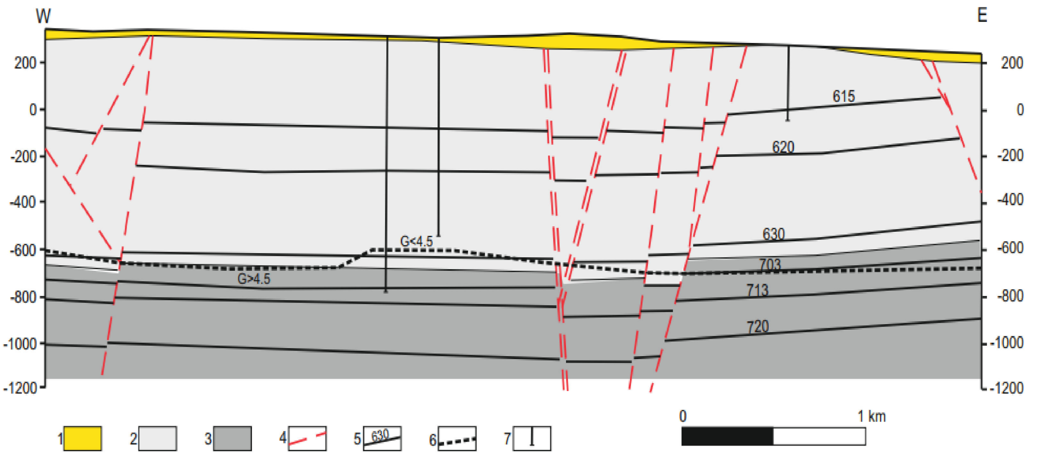

Figure 7. Cross-section across the Rydułtowy coal deposit (modified after Rydułtowy mine archive materials): 1—overburden, 2—Poruba layers, 3—Jaklovec layers, 4—fault, 5—coal seam, 6—top of the methane zone with G > 4.5 m^3/t coal daf, 7—shaft.

The coal-bearing formations are covered with Miocene clay sediments in the western and northern parts of the study area, while in the northern part Triassic formations ar also present. The thickness of the overburden is not large (Figure 7), slightly exceeding 400 m. However, in the central part of the deposit, the Carboniferous formations are covered with only a thin layer of Quaternary formations. This nature of the overburden means that the deposit is open to the migration of gases from the rock series into the atmosphere. The free migration of methane from the coal seams into the atmosphere through the discontinuous and permeable overburden is another cause of the approximately 600 m-thick degassed zone.

As mentioned, the migration of methane can take place through permeable sandstones, but also through faults. Discontinuous tectonic zones (Figures 3 and 7) are considered to be pathways for gas migration, as rapid increases or decreases in methane content have been observed around them. Faults can also act as sealings for gases or divide deposits into blocks with different gas capacities [13,17,46].

Carboniferous sediments are cut by numerous faults, with displacements up to 200 m with a latitudinal (predominant) and meridional course and an inclination of the fault planes of 45–85°. Zones of tectonic disturbance are up to 300 m wide; therefore, they can act as migration pathways for methane. Most likely, the majority of methane migrated through the faults and accompanying fractures in the past, contributing to the present-day distribution of the methane content in the deposit. The 4D modelling of the methane potential in the USCB [47] revealed that the decisive influence on the level of hydrocarbons accumulated today is the time of tectonic activity in the study area, i.e., the length of the fault opening interval.

Gas migration is often accompanied by water migration due to the permeable nature of the migration pathways (sandstones and permeable faults). The infiltration of meteoric waters into the Carboniferous formations is possible only in places where there is no tight clay cover of the Miocene formations, i.e., in the central and eastern parts of the area. The free infiltration of meteoric water from the surface into the Carboniferous deposits may have contributed to the dissipation of migrating gas in the past and may continue to contribute today, thus contributing to the expansion of the degassed gas zone of natural desorption [18–48].

4.3.4. Mining

Many years of coal mining in the Rydułtowy deposit have resulted in the relaxation of the rock mass, which has led to a pressure drop and, consequently, the desorption of methane from the coal seams. This process was further intensified by the demethanation of the deposit, which started in 2002 and continues today. The result of this is the methane migration from the coal seams and goafs to the methane drainage station, forced by negative pressure. This causes changes in the methane content (its significant reduction); thus, a different distribution from the natural (virgin) distribution of the gas content in the seams is observed. This applies in particular to the overlying and underlying seams, as the reach of mining degassing can vary from 60 to 100 m below and 120–200 m above the exploited seam [22,49]. Tests and observations of the operational range of degassing in a shallow coal mine in Australia [50] showed that the upper limit of the degassing range can reach up to 500 m above the exploited longwall; however, this study concerned a shallow deposit with coal seams of a high permeability, ranging from several dozen up to over 100 mD. In the case of the USCB, the coal permeability is much lower, often below 1 mD. Hence, the extent of degassing is not as large in the studied deposit. Nevertheless, the noted significant differences in methane content between coal seams at particular levels (sometimes in close vicinity) (Figure 2) may be the consequence of overlaps between the effects of exploitation on the natural factors influencing the distribution of the methane content.

4.4. Methane Emissions and Hard Coal Output in the Rydułtowy Coal Mine

The hard coal output was studied in the years 1994–2020 (Figure 8), while the methane emissions were studied in 2000–2020 (Figure 9), because earlier coal had been extracted from the methane-free coal seams; therefore, no CH_4 emission was recorded. At the beginning of these studies, coal was extracted from the Poruba and Jaklovec layers at a depth ranging from 400 to 700 m below sea level, including mostly degassed, methane-free coals (Figure 10).

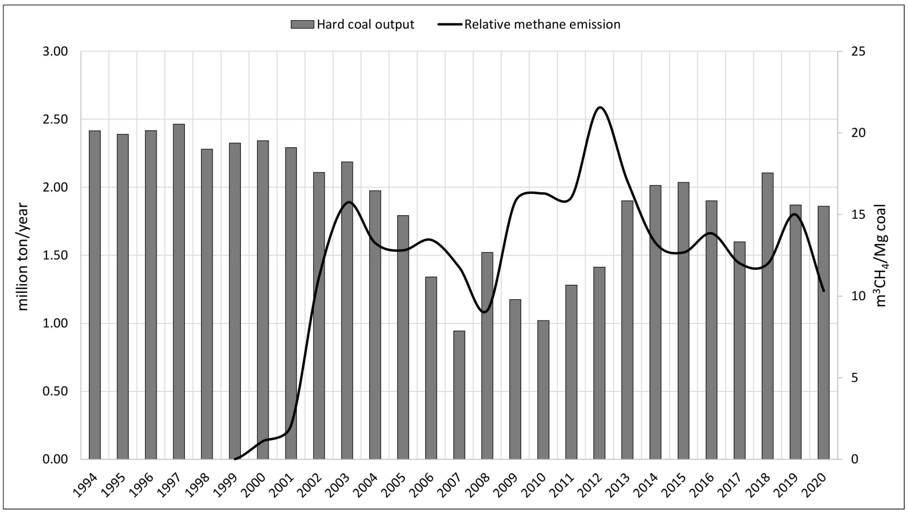

Figure 8. Hard coal output and specific methane emissions from 1994–2020 in the Rydułtowy mine.

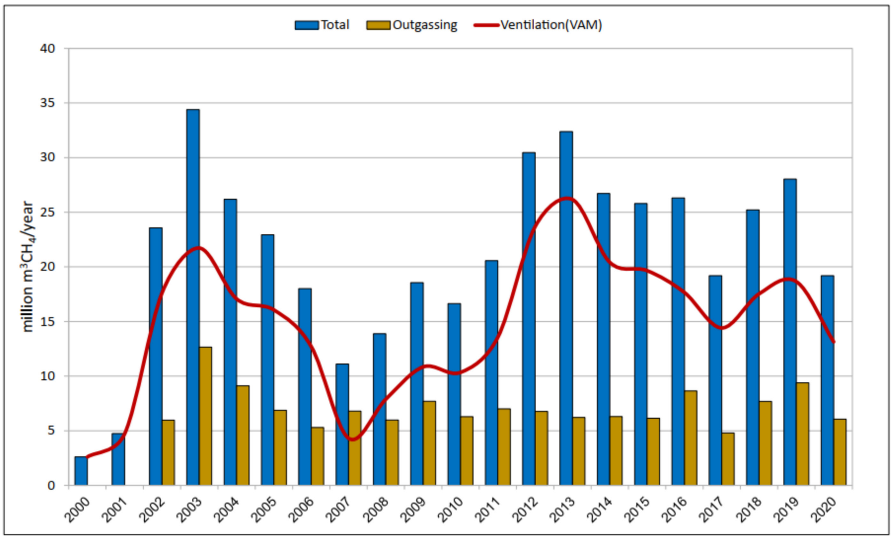

Figure 9. Total methane emissions and outgassing and ventilation air methane from 2000–2020 in the Rydułtowy mine.

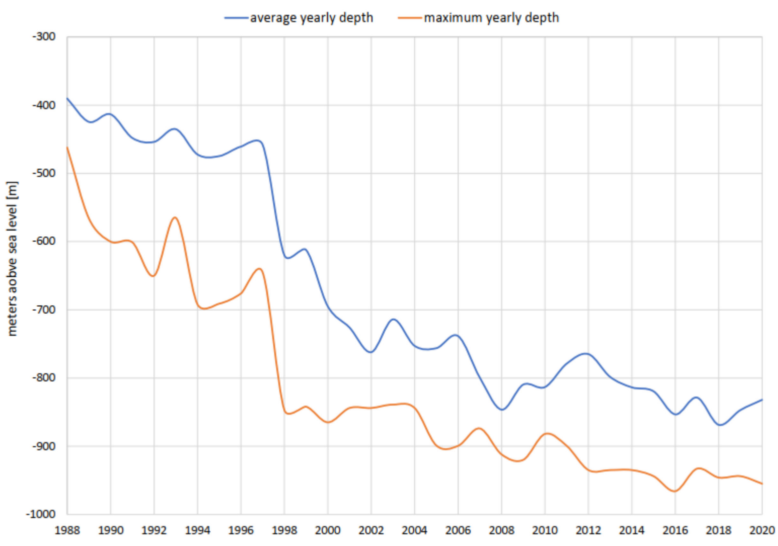

Figure 10. Changes in the average and total depth of the coal output from 1988–2020.

Since 2000, coal has been extracted almost exclusively in the southern part of the deposit, where the methane concentration tends to increase (G > 4.5 m^3/t coal daf), and the tops of the methane-bearing coal seams are located at shallower depths than in the central and northern parts of the deposit. Methane emissions increased rapidly from less than 3 million m^3 in 2000 to almost 35 million m^3 in 2003. At the same time, the coal extraction was at around 2.3 million t per year. Coal extraction from deeper, more methane-rich seams was the main reason for the increase in CH_4 emissions. In subsequent years (2004–2007), coal extraction and preparatory works were taken up for a short time in the western (less methane-rich) part of the Rydułtowy 1 deposit; therefore, emissions from the surrounding strata were not as evident and relevant as those observed in seams with higher methane contents (the southernmost area). Several years of coal production in comparatively harmless gaseous conditions resulted in a decrease in CH_4 emissions (from ~26 million m^3 in 2004 to 11 million m^3 in 2007); however, the coal production also decreased (from 2.0 million t to just 0.90 million t) (Figure 8). Methane that was released into goafs was systematically drained in the following years in order to provide safer conditions in adjacent coal works.

Since 2008, the average depth of the works has exceeded 800 m below sea level (over 1000 m below ground level), which has resulted in the mining process being performed at higher pressures and temperatures. The methane content at those depths constantly increases to over G > 8 m^3/t coal daf, which is related to the fact that the operation is performed within the primary gas-bearing zone, which constitutes the highest methane hazard in Polish mining (Figure 2). Mining in more methane-rich seams resulted in increasing amounts of gas released every year. The amount of released methane rose gradually from ~14 million m^3 in 2008 to 32 million m^3 in 2013 (Figure 9). In the following years, the methane emissions stabilised at 20–25 million m^3 annually due to stable coal production, at 1.5–2.0 million t/year (Figure 8).

If methane emissions increase, the most harmful gas must be discharged and vented out of the mine to keep working conditions safe and prevent an explosive atmosphere. In the Rydułtowy mine, almost 70% of the released CH_4 was directed to the ventilation shafts and then into the atmosphere during the entire research period (Figure 9). The rest of the methane was drained during mining (from the coal seams and goafs) and processed (for heat and power production) or released into the atmosphere (see Section 4.1).

Mining coal exclusively in the Jaklovec layers resulted in constant methane emissions into the coal works, combined with greater amounts of extracted coal, reaching ~2 million t of coal, and 32 million m^3 of CH_4 was emitted in 2013 (Figures 8 and 9). The deeper deposited and most productive 712 and 713 coal seams, which have been mined in the southernmost E1 area (thickness~2.50 m), are characterised by methane contents in the range from G < 1 m^3/t coal daf to G > 14 m^3/t coal daf. Most methane is released from the crushing of the coal during the mining activities (road heading or blasting). The moderate firmness of the coal (f = 0.81 on average), combined with a low intensity of desorption (dp = 0.70 kPa on average), results in the not-so-rapid methane emissions from the coal. Still, most methane is released at the beginning, when the coal face is exposed, which is in compliance with Langmuir's rule [51].

The surrounding strata in the Jaklovec layers consists of permeable sandstones (approximately 29% of the profile), which facilitate the migration of gases, such as methane, to the exploited wall environment. On the other hand, impermeable claystones and mudstones provide a sealing screen for migrating gases. The direct sandstone–coal contact may be burdened by intense methane migration and release during mining due to strata relaxation [52,53]. The last seven years of the study period (2014–2020) were characterised by the relatively constant methane release into the coal workings, amounting to ~24 million m^3 CH_4/year on average, and stable coal production from the Jaklovec layers, being ~1.9 million t/year on average. In the southern part of the Rydułtowy 1 deposit (e.g., the E1 area), there were many smaller faults (<1 m throw). These discontinuities may act as migration pathways for methane, contributing to coal degassing in the immediate vicinity of faults, which may be profitable in current and future coal production. However, at deeper levels, seams that are higher in methane will be subject to operations in the future (>1000 m below sea level), which may result in greater methane emissions and migration into the wall environment (>24 million m^3 CH_4/year).

Methane emitted with every tonne of coal indicates the actual gaseous danger posed by mining (specific methane emissions). The extension of coal production to the methane-dangerous part of the deposit is associated with gas migration from the surrounding strata, goafs, and coal. The specific methane emissions are around 14 m^3/t coal, with periodic drops and rises (Figure 8). In the following years, coal will be produced from the deeper, more methane-rich seams. Gas will migrate through faults and breaks from the surrounding unmined seams, goafs, and mined coal, which may result in greater amounts of released gas per tonne of coal. Coal extraction from the methane-rich coal seams is burdened by the emission of significant amounts of gas released directly into the atmosphere, which is the cause of the enhancement of the greenhouse effect. In the Polish economy, the majority of methane released into the atmosphere comes from fuel emissions (including methane) (47%), agriculture (30%), and waste management (23%) [54]. There is an urgent need to limit the CH_4 emissions in the general industries and economy. It is worth highlighting that coal mines located in the Upper Silesian Coal Basin emit around 25–30% of methane in relation to the entire Polish emissions, but the emitted methane contributes to just 3% of the total greenhouse gases emitted in the country [55].

5. Conclusions

- After 2000, an increase in methane emissions into the mine workings of the Rydułtowy coal mine was noted, ranging from a few million to over 30 million m^3 annually.
- During the period from 2000–2020, these emissions fluctuated and stabilized at 20–30 million m^3 per year.
- The variability in methane emissions results from the interaction between natural (geological) and mining factors.
- The Rydułtowy coal deposit exhibits a vertical zonation of methane. Up to a depth of approximately 600 m, the rock mass is naturally degassed, whereas deeper, the methane content rapidly increases to ca 14 m^3/t coal daf at a depth of approximately 1100 m.
- The sorption capacity of the coal at a depth of ca 1000 m is 15–16 m^3/t coal daf, which means that the coal at this depth is almost fully saturated with methane (95% saturation).
- The sorption capacity of the coal decreases with increasing temperature and the coalification degree of the seams, i.e., with the depth, which, given the high gas content of the seams, contributes to the high methane emissions into the mine workings.
- The firmness of the coal, methods of exploitation, and complicated fault tectonics are other factors influencing the emission of methane into the mine workings.
- Only 30% of the emitted methane is captured by methane drainage stations and then used. Increasing the collection of the emitted gas could reduce the amount of methane released into the atmosphere, which has approximately 30% more radiation power than carbon dioxide.

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Conflicts of Interest: The authors declare no conflict of interest.

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METHANE EMISSIONS AND HARD COAL PRODUCTION IN THE UPPER SILESIAN COAL BASIN IN RELATION TO THE GREENHOUSE EFFECT INCREASE IN POLAND IN 1994–2018

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Abstract: The Upper Silesian Coal Basin (USCB) is the largest coal basin in Poland and one of the largest in Europe. It is the most industrialised region in the country. The main natural source of energy is hard coal, which was produced by 65 mines in the early nineties. The USCB geology is very diverse and not homogeneous. Coal deposits situated in the central, southern, and western regions are mostly covered by impermeable Miocene deposits, which helped methane (CH_4) to accumulate in the past. Methane is one of the most dangerous natural hazards in Polish underground mining because it is an explosive gas. CH_4 is also the second strongest greenhouse gas after carbon dioxide, but its radiative power is 20–25 times stronger than the radiative power of CO_2. Polish coal mines release 470 thousand Mg (average) of CH_4 yearly and it contributes to the greenhouse effect increase. Year after year, Upper Silesian coal mines are going to extract hard coal from deeper seams where the methane content in coal seams is much higher. To keep workers safe, CH_4 needs to be captured and released to the open-air atmosphere or used in the power and heat production.

Keywords*: *hard coal production, methane emissions, greenhouse effect, the Upper Silesia Coal Basin, Poland

1. INTRODUCTION

Air pollution and the greenhouse effect increase are ones of the main problems in industrialised regions such as the Upper Silesian Coal Basin in Southern Poland. The Upper Silesian Coal Basin (USCB) is the largest coal basin in the country and one of

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the largest in Europe. USCB is located in Silesia and Małopolska provinces and it covers the territory of 5600 km^2 in Poland (Fig. 1). USCB is also located in the Czech Republic (area of 1900 km^2). This paper focuses only on the Polish part of the basin.

During hard coal exploitation, many cubic metres of CH_4 get released to coal workings, enlarging the danger and making coal production very difficult at the same time (Kotarba and Ney, 1995; Łukowicz and Krause, 2004). Methane (CH_4) is formed in parallel with hard coal formation processes, during coalification of plant materials. Difficult geological conditions (e.g., hermetic overburden) could have prevented methane from escaping in the geological past. (e.g., Szlązak, 2015). Methane occurs in coal seams in the form of free or adsorbed gas. Gas sorption depends on temperature, pressure, and the type of coal. Free methane fills voids, pores, and breaks in seams and surrounding rocks. In USCB methane occurs mainly as adsorbed methane (tied gas), bound with coal physically or chemically. During coal extraction, CH_4 is released into mine workings and the methane danger increases (Czapliński,1994; Karacan et al. 2011; Honysz, 2015).

Fig. 1. Position of the Upper Silesia Coal Basin

Most coal mine methane (CMM) needs to be directed to ventilation shafts and released to the atmospheric air – magnifying the greenhouse effect at the same time. The objective of the paper is to determine the greenhouse effect increase in the context of hard coal production processes (mainly methane emissions) in USCB and the entire territory of Poland. The period between 1994 and 2018 overlaps with a large decrease in the hard coal production, an increase in methane emissions, and important changes in regulations, heating technologies, and methods that coal is used in the heat production. The Polish government together with the European Union aim to reduce air pollution and the greenhouse effect increase.

Year after year, Polish mines need to produce coal from deeper and deeper seams to maintain profitability and keep mines working (Dreger and Kędzior 2019; Kędzior and Dreger, 2019; Dreger, 2020). Reaching deeper coal seams is associated with entering high methane zones where the methane content in one Mg of coal^{daf} (daf is a pure carbon substance, without moisture and ash) is much higher (Kędzior, 2009). It forces to struggle with CH_4 emissions in order to keep the work in the mine as safe as possible. Year after year the number of operating mines in the Polish part of USCB has been decreasing. At the beginning of the study (1994) 65 coal mines were active, but twenty-five years later, in the last year of the research (2018), the number of the mines decreased to 21 (Annual Report 1995–2018). These mines which still produce coal need to struggle with very hard conditions, such as gas hazard. Despite a decreasing number of working coal mines, the methane danger is not lower; on the contrary, the CH_4 hazard can increase every year as a result of complicated mining and geological conditions (Kędzior, Dreger, 2019).

Methane disposal is necessary for the underground production to be as safe as possible. Methane accompanying coal bearing formations can cause ignition and explosion. When the concentration of methane in the air mixture is between 5 and 15% with the oxygen content above 12%, a single spark or open fire can initiate an explosion. Ignition of the mixture occurs at temperatures above 650 °C, but explosion temperature is up to 1875 °C (e.g., Kozłowski and Grębski, 1982; Karacan et al. 2011; Honysz, 2015).
A methane explosion is very difficult to contain, because it spreads quickly due to a small cross-section of the wall; therefore, there are many fatalities and serious injuries in the Polish mining history (Borynia Mine – 6 deaths, 17 injured; Śląsk Mine – 20 deaths, 34 injured, Mysłowice-Wesoła Mine – 5 deaths, 25 injured) (Honysz, 2015; State Mining Authority 2019). To protect workers, mining industries have to keep the mining atmosphere free of methane by extracting used mining air outside the mine by underground ventilation systems directly to the atmosphere, or by draining coal seams by drillings and collecting the collected gas for internal mining processes (Kozłowski and Grębski, 1982).

Hard coal is the main natural source of energy produced in USCB. From the chemical point of view, coal substance can be divided into three groups: organic substances, non-organic (mineral) substances, and water. Hard coal flammable substances are built of hydrocarbons and organic compounds (sulphur, oxygen, and nitrogen) (Lorenz 1999). Out of all elements forming hard coal, only carbon (C), hydrogen (H), sulphur (S), and nitrogen (N) are flammable. Therefore, the final products of oxidation of flammable elements are CO_2, H_2O (steam), SO_2, and SO_3. All these products are very harmful to natural environment and atmospheric air (Lorenz, 2005). Environment and air can be contaminated, but these deleterious processes take place in coal power plants or in home furnaces. Underground coal extraction processes themselves do not pollute the air. Rail and wheeled transport can cause dust pollution, noise, and shakes, but it does not have a significant effect on the environment. Coal-bearing formations do not consist of coal only. Rocks like sandstone, claystone, or shale form coal-bearing formations together with coal as the fossil fuel. After underground extraction, useless material such as gangue or coal waste needs to be deposited somewhere. The easiest way, used in USCB for years, is to deposit useless material as close to the mine as possible (transport limitation), creating dumps. High dumps with regular shapes (cones, cuboids) covering a considerable area can be unattractive visually and can be a big dust issuer when they are not properly developed (e.g., afforestation) (Uberman and Ostręga, 2004). Underground coal production is not flawless. Water coming from mining and technological processes can contaminate surface water, which leads to soil pollution and lack of arable lands (Bednorz, 2011). It should be clearly emphasised that combustion products such as CO_2, dust caused by heavy transport, and dumps are created after coal extraction. Hard coal production itself does not affect air pollution.

Table 1. Characteristics of the most common greenhouse gases
(after United States Environmental Protection Agency 2006, modified)

	CO_2	CH_4	CFC-11	CFC-12	N_2O	SF_6
Existence in the atmosphere (years)	50–200	10	65	130	150	3200
Global warming potential	1	20-25	4600	10600	310	23900
Concentration in the atmosphere in year ~1800	280 ppm	0.8 ppm	0	0	288 ppb	0
Concentration in the atmosphere in 1990	353 ppm	1.72 ppm	280 ppt	484 ppt	310 ppb	–
Concentration in the atmosphere in 1998	365 ppm	1.75 ppm	–	–	314 ppb	4.2 ppm
Annually concentration increase in 1990s	1.5 ppm	0.007 ppm	9.5 ppt	–	0.8 ppb	0.24 ppm
Annually concentration increase in 1990s in %	0.5	0.9	4	–	0.25	6
Estimated influence on greenhouse effect in %	50	19	17		4	–

Contribution in anthropogenic emission in %	–	–	100	100	–	100

The presence of such gases as carbon dioxide in the atmosphere makes temperatures rise due to a limited heat outflow, with its relatively free inflow. This mechanism, which forms amounts of outflows and inflows, is called *the greenhouse effect*. Not so long ago, the greenhouse effect intensification was identified with increasing concentrations of CO_2 in the atmosphere (Kożuchowski and Przybylak, 1995). Many other gases besides CO_2 were found in subsequent studies to absorb long-wave radiation of Earth and atmosphere. Consequently, it contributes to an increase of Earth's temperature. The most commonly known greenhouse gases (besides CO_2) are: methane (CH_4), which is the most important gas included in the study and tackled in this paper, ozone (O_3), nitrous oxides (NO, NO_2, N_2O), sulphur dioxide (SO_2), ammonia (NH_3), carbon oxide (CO), and freons CFC-11($CFCL_3$ and CFC-12 (CF_2CL_2) (Kożuchowski and Przybylak, 1995; Kundziewicz, 2013). Short characteristics of the gases are presented below in Table 1.

Poland as a signatory of the UN Framework Convention On Climate Change (1994) and Kyoto Protocol (2002) works for the limitation of climate changes, including greenhouse gases emissions to the atmosphere.

The convention requires than industrialised countries help developing countries to reduce greenhouse gases emissions. It also points out that wealthy nations which have built their opulence and prosperity thanks to fossil fuels are responsible for large CO_2 emissions. The main assumption of the Protocol is to decrease the volume of emitted greenhouse gases (5.2 % on average) in time. Not all greenhouse gases are covered by the limitation; in fact, only six of them are: carbon dioxide(CO_2), methane (CH_4), nitrous oxide (N_2O), industrial gases (HFC,PFC), and sulphur hexafluoride (SF_6) (*Kyoto Protocol*). To achieve the assumption of a reduction in the global gases emission, each of the 15 members of the European Union (as of 1997) and Bulgaria, the Czech Republic, Estonia, Lithuania, Latvia, Malta, Romania, Slovakia, and Slovenia agreed to reduce emissions by at least 8%, the USA by 7%, Poland, Canada, Hungary, and Japan by 6%, and Croatia by 5%. All of these countries needed to limit the emissions in the 2008–2012 period in reference to the base year (every country sets the limit individually, but it is around 1990). New Zealand, Russia, and Ukraine can keep their emissions at the same level as in 1990, but Iceland, Norway, and Australia can increase their emissions (by 10, 1, and 8%, respectively) (Kundziewicz, 2013; *Kyoto Protocol*). It is worth mentioning that the USA has indicated its intention not to ratify the Kyoto Protocol (*Kyoto Protocol*). Asian countries do not reduce greenhouse gases emission due to their dynamic economic development and an increasing energy demand in the Asian region (Teluk, 2008).

During the Climate Change Conference which took place in Paris in 2015 over 190 countries signed a global commitment called the Paris agreement. The main assumption was to limit the global temperature growth to 1.5–2 °C. The agreement is binding when at least 55 countries which produce 55% of greenhouse gases sign the agreement and take steps to fulfil the promises (*Paris Agreement*).

During *COP 24* in Katowice in 2018 political and technical decisions concerning the Paris Agreement were clarified. The European Union is responsible for just over a dozen percent of greenhouse gases emissions. The main issuers are USA, China, and India. These three countries are not obligated by any regulation to working on the reduction of greenhouse gases (Kundziewicz, 2013). Without a global agreement and commitment, the reduction in greenhouse gases emissions may fail.

1.1. OUTLINE OF THE GEOLOGICAL STRUCTURE AND METHANE OCCURRENCE

The geological structure of USCB is very diverse. Northern parts of the basin are not covered by the Miocene overburden (apart from local patches); hence, coal deposits were naturally degassed in the geological past (Mesozoic, Cenozoic, and the modern era). In some areas outcrops of older rock formations (permeable Triassic, Jurassic, and Quaternary deposits) cover Carboniferous coal-bearing deposits. Carboniferous formations are shallowly deposited (e.g., Grzybek and Kędzior, 2005; Kędzior, 2012).

Southern and southwestern areas of the basin are almost entirely covered by a thick and continuous Miocene cover consisting of clays, sandstones, and silt ranging from 200 to a maximum of over 1000 m. These impermeable deposits helped methane and other gasses to accumulate in coal-bearing units in the past. Therefore, deep hard coal exploitation (coal seams are deeper deposited than seams in the middle and in the northern parts of the basin) in conjunction with many fault zones (which helped CH_4 to migrate) is very complicated. Western areas of USCB are covered by the Miocene overburden (clays and silts) of various thicknesses – ranging from 0 to a maximum of over 1000 meters, but in some locations outcrops of coal-bearing strata are found (e.g., Grzybek and Kędzior, 2005).

In USCB two main geological settings of vertical distribution of coal bed methane (CBM) are distinguished (Kotas, 1994). These settings are closely connected with deposits covering the Carboniferous coal-bearing strata (Fig. 2). Northern and central areas of the basin where Carboniferous deposits appear as outcrops or are covered by thin and permeable Miocene and older formations are characterised by the occurrence of naturally degassed coal seams to the depth of 600 meters with the methane content lower than 4.5 m^3/Mg $coal^{daf}$. As the depth increases, the methane content grows rapidly – reaching the primary methane maximum when the CH_4 content exceeds 10 m^3/Mg $coal^{daf}$. The methane content slowly decreases at levels lower than the level of the methane maximum.

Southern regions, where the geological structure is characterised by impermeable Miocene deposits covering the coal bearing strata, consist of two maxima of the methane content. The first includes the secondary accumulation of CH_4 adsorbed in coal seams immediately below a thick and impermeable Miocene cover (400–600 m). A deeper maximum of the primary methane content occurs below 1300 m, but deeper than 1600 m the methane content tends to decrease. An interval of a lower CH_4 content (methane minimum zone) separates these two maxima (Kotas, 1994; Kędzior, 2012). The number of operating coal mines in USCB were changing during the study period. At the beginning of the research, in the early 1990s, 65 mines were producing coal. Over the years the coal mines were abandoned or merged into one big enterprise. As a result of the restructuring processes the number of coal mines was decreasing, to reach 21 in 2018 (*Annual Report 1995–2018*). The mines producing coal in northern and south-western parts of the basin were closed as a result of the depletion of shallow-lying and easily-extracted coal reserves. Natural and technical conditions were also a big difficulty preventing further coal production (Kędzior and Dreger, 2019). A dropping number of coal mines and the need to reach deeper coal seams in order to maintain profitability are some of the reasons for diminishing coal production every year in USCB (Dreger and Kędzior, 2019).

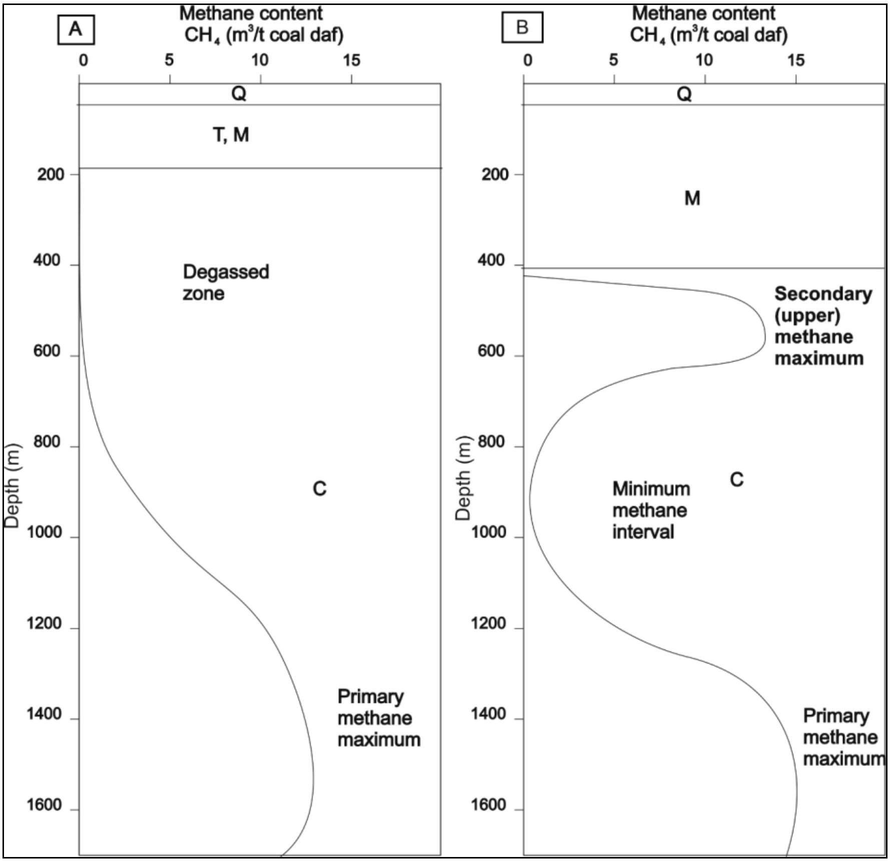

Fig. 2. Methane distribution in the northern (A) and southern (B) region of USCB (Kędzior, 2012)
Q – Quaternary, M – Miocene, T – Triassic, C – Carboniferous

At the beginning of the research (1994-1997) hard coal production in USCB exceeded 120 million Mg yearly. In the remaining period of the study (1998-2018) USCB mines were producing less coal every year. The decreasing trend was stable and coal production dropped from 112 million Mg in 1998 to 52 million Mg in 2018, which was just 39% of the production in relation to the highest coal extraction over the analysed years, when 133 million Mg of coal was extracted in 1996 and 1997 (*Annual Report 1995–2018*). Restructuring processes, increasing difficulties of extraction (thermal, methane hazards), concentration of production, exploitation of shallow-lying coal seams located mainly in the northern part of the basin contributed to the reduction of the hard coal production year after year. On the other hand, in order to maintain profitability and keep thousands of workplaces safe, coal enterprises need to reach deeper coal seams, where the methane content in coal is higher. In the modern era and in the future, the methane hazard is going to be the main natural danger which coal companies need to face (Dreger and Kędzior, 2019).

2. METHOD AND RESULTS

In order to investigate and demonstrate how methane emissions and coal production in USCB coal mines affect the greenhouse effect increase, figures such as coal production, emissions of CO, CO_2, CH_4, NO_x , SO_x were taken into account.

All essential data were obtained from:

- Resources, Use, Pollution and Protection of Waters (in: Environment, Central Statistical Office, 2005–2020)
- A national inventory report 2020 – inventory of greenhouse gases in Poland from 1988 to 2018 (Institute of Environmental Protection – National Research Institute, 2020)
- Annual report about basic, natural and technical threats in hard coal mining (*Annual Report 1995–2018*).

Based on the analysis of the most important data, figures which show changes and the percentage share of the responsibility for the greenhouse gases emission have been developed.

2.1. GREENHOUSE GASES EMISSION IN POLAND

In order to describe how much greenhouse gases was emitted to the Polish atmosphere, all the greenhouse gases were summed up. Every gas has a different weight and volume; for these reasons all the collected gases (CO_2, CH_4, N_2O, HFC, PFC, SF_6, and NF_3) were calculated as CO_2 equivalent [eq]. The biggest emission was noticed at the beginning of the study (1994–1997) (Fig. 3). Heavy industry and rapid economic growth caused big emissions, exceeding 430 million Mg of emitted greenhouse gases yearly, with the highest emissions in 1996 (453 million Mg of CO_2 equivalent) (Institute of Environmental Protection – National Research Institute, 2020). In the next five-year period (1998–2002) the biggest decrease in the greenhouse gases production was observed. Government programmes and actions for the efficient energy use contributed to the fact that the emission of carbon dioxide, methane, nitric oxides, and other gases was rapidly dropping to the lowest volume in the entire research period – 380 million Mg of CO_2 eq in 2002. Subsequent years (2003–2007) were marked by the economic recovery, which translated into a gentle but constant increase of gases emission into atmospheric air. From 2008 to 2014 the emission was slowly decreasing to 383 million Mg of CO_2 eq in 2014, but over the last four years of the study (2015–2018) a constant rise in the emission was observed. From 386 million Mg (2015) to 402 million Mg of CO_2 eq (2018) was emitted to the Polish atmosphere. This fast and constant increase was caused by dynamic economic development (Central Statistical Office, 2005–2020).

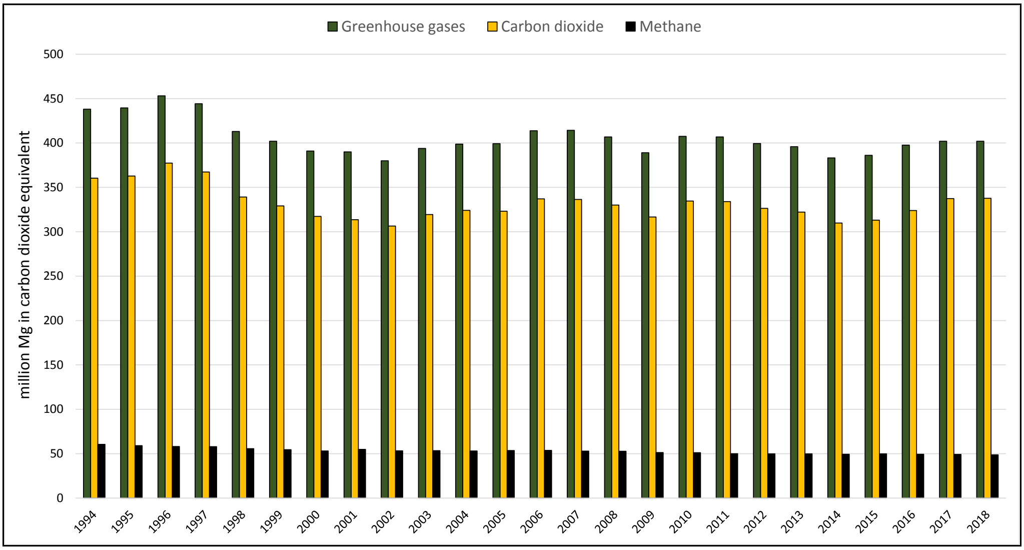

Fig. 3. All greenhouse gases, carbon dioxide and methane emissions in Poland in 1994–2018

2.2. CARBON DIOXIDE EMISSIONS

The dominant greenhouse gas in Poland is CO_2 (81.8% of the total greenhouse gases emissions). The majority of CO_2 in Poland comes from fuel combustion and power industry with over 50% of the total emission. The rest of carbon dioxide emission is shared by the cement production, transport, and industrial processes (Institute of Environmental Protection- National Research Institute, 2020, Central Statistical Office, 2005–2020) In the entire research period (1994-2018) over 7982 million Mg of CO_2 was emitted to the Polish atmosphere (Fig. 3). The biggest emission took place between 1994 and 1997 during a rapid economic growth, when 366 million Mg of carbon dioxide on average was emitted to the atmosphere. Subsequent years (1997–2002) saw a constant decrease in CO_2 emission– down to 305 million Mg in 2002. This decrease was caused by many actions promoting effective energy use, which resulted in the lowest CO_2 emission over the entire research period. Over subsequent years periods of increase and decrease (with small fluctuations) were observed, but emissions of the most dangerous greenhouse gas never exceeded the highest emissions in 1996 – when the biggest volume of CO_2 was released to the Polish atmospheric air – 375.30 million Mg. During the entire research period, the CO_2 emission trend was not uniform. It was changing year after year, but over the last five years (2014–2018) emission increased from 310 to 337.7 million Mg as a result of the economic recovery.

2.3 METHANE EMISSIONS

Methane is a 20 to 25 times stronger heat absorbent than carbon dioxide, but its existence in the atmosphere is shorter and its origin is varied (Ramaswamy et al. 2011; Archer, 2011; Kożuchowski and Przybylak, 1995; Ginty, 2016). The main sources of methane emissions in Poland have been divided into three main categories:

a) fuel emissions – 47% of the total emissions (as of 2018),
b) agriculture – 30%,
c) wastes – 23%.

The majority of the issue (a) comes from underground mining (33.8% of total emission). The rest derives from oil and gas exploitation, processing, and distribution (5.5% of total emission). In agriculture (b) the main emission of CH_4 hails from intestinal fermentation (26.8% of entire emissions), but in the last category (c) the emission from landfills contributes to the methane concentration increase in the atmosphere by 17.6%. It is clearly visible that the most heat-absorbent greenhouse gas emissions come from underground mining and cattle farming (Institute of Environmental Protection- National Research Institute, 2020). Globally, the largest methane issuers are agriculture (including cattle farming and rice cultivation), thermokarst lakes and peat lands (Yusuf et al. 2012; Kundziewicz, 2013; Matveev et al. 2018). Methane is also responsible for 17 % of the greenhouse effect (*Adler 1994*), but global hard coal mining accounts for about 6% of global methane emissions (*Best Practice Guidance* 2010).

Human activities over the past two hundred years have increased the CH_4 concentration in the atmosphere from a base global average of 722 ppb in 1750 to a global average of 1,823 ppb in 2015 (Ginty, 2016). Globally, agriculture is the key emitting sector of methane emission, responsible for 40% and over 60% of releasing CH_4 to the atmosphere comes from human activities. Methane as the second most harmful greenhouse gas does not affect direct on human health, agriculture or ecosystems. There are many indirect and long-term effects of methane emissions like premature respiratory deaths, heart and lungs diseases (estimated for 1 million worldwide per annum) caused by tropospheric ozone formation (Crutzen, 1973; Bates, 1998; Westi and Fiore, 2005; *UNEP Synthesis Report* 2011). There are also 15% annual yield loses in soy, wheat, maize and rice cultivation (*UNEP Synthesis Report* 2011).

The paper is focused on the geological origin of methane, its utilisation, and disposal out of the mine.

In USCB almost all CH_4 comes from hard coal mining. The mining methane gas can be distinguished due to the method of its acquisition. Coal Mine Methane (CMM) is a gas mixture captured during underground mining works with 25–60% of CH_4. Coal Bed Methane (CBM) is a gas almost entirely composed of CH_4 (90–98%) captured from virgin (unmined) coal seams (Kozłowski and Grębski, 1982; Karacan et al. 2011; Kędzior, 2012). When methane is released from coal to the mining atmosphere due to underground quakes and coal extraction, there are two ways to dispose of it. Firstly, the most common solution is to extract used mining air (heated and rich in methane and other gases) outside the mine by underground ventilation systems directly to the atmosphere. Degassing is the second method to keep the mining atmosphere free of methane. Underground degassing leads to draining many coal-bed gases outside of the mine or to a place equipped with a ventilation network, where these gases are not dangerous. Collected gases can be used economically or sold to external customers (Kozłowski and Grębski 1982; Szlązak, 2015; Dreger, 2020). Not all captured gas is used or sold outside. A significant part of collected and undeveloped CH_4 needs to be released directly to the atmosphere magnifying the greenhouse effect. Methane which goes to the atmospheric air is a mixture of undeveloped coal mine methane gas and methane coming from underground ventilation systems, described as *Ventilation Air Methane* emission. The emissions of CH_4 in Poland and from hard coal mines located in the Upper Silesia Coal Basin have a completely different course.

The largest methane emissions in Poland took place at the beginning of the study (1994), when 2.42 million Mg of this gas was emitted to the atmosphere (Fig. 4). Over subsequent years until the end of the research period (1995-2018) emissions of this strongest greenhouse gas were decreasing gently but constantly, from 2.36 million Mg released in 1995 to 1.95 million Mg of CH_4 in 2018. Only in 2001 the decreasing trend was disturbed by a 2.20 million Mg peak. Restructuring processes, greater awareness of the society, and better management in agriculture, heavy industry, and waste management caused a 19.4% drop in methane emission in Poland in the entire research period.

Methane emissions to the atmosphere from the USCB coal mines are completely different than the emission in the entire territory of Poland. From 1994 to 2004 CH_4 released by hard coal mines was variable and fluctuated between 410 and 480 thousands Mg of gas yearly (Fig. 5). Next, there was a four-year (2005–2008) increase period, during which the ventilation air methane emission (VAM) rose from 500 to 520 thousand Mg. Over the next six years (2009–2014) methane emissions were decreasing (between 460 and 500 thousands Mg of CH_4). But in the most recent period (2015–2018) a big increase in emissions was observed –more than 520 thousand Mg of CH_4 was released every year. Due to the increasing depth of coal extraction every year and the concentration of coal production connected with entering more methane rich seams, methane emissions are going to increase or remain at a high level of CH_4 emitted in the forthcoming years (Dreger, 2019; Dreger and Kędzior, 2019).

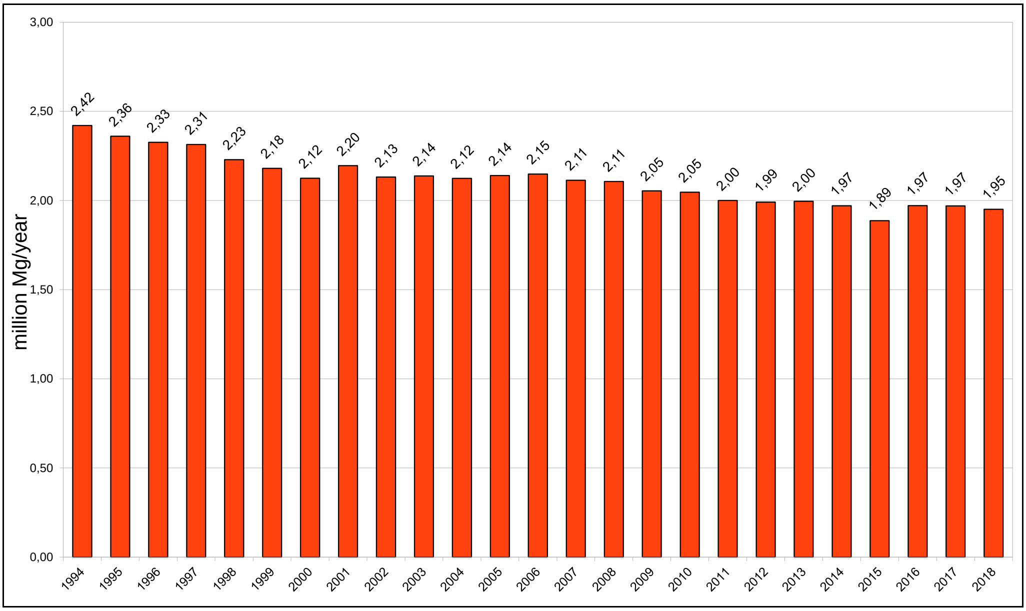

Fig. 4. Methane emissions in Poland in 1994–2018

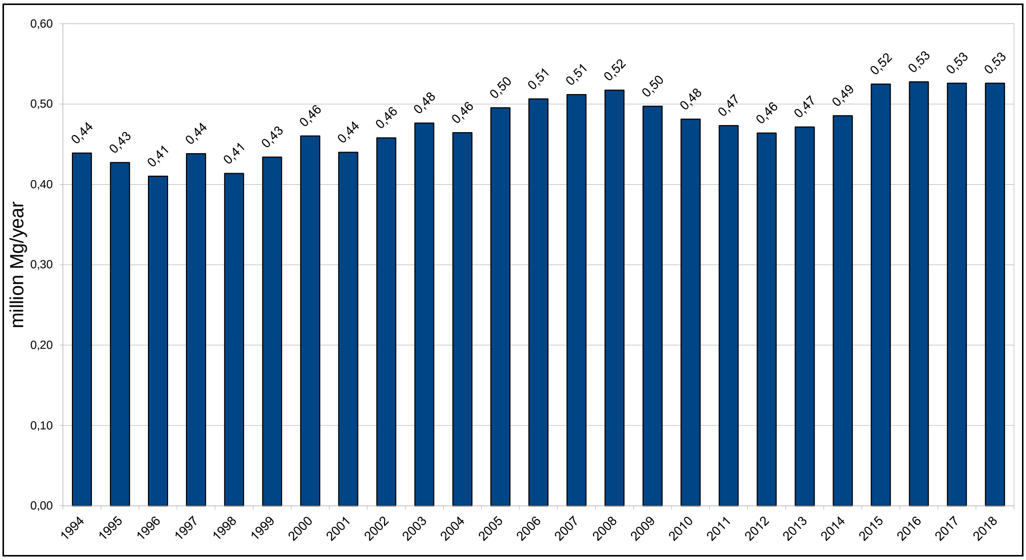

Fig. 5. Methane emission in USCB in 1994-2018

2.4. CONTRIBUTION OF METHANE EMISSION IN USCB TO THE TOTAL EMISSION IN POLAND

As mentioned above, methane is 20 to 25 times stronger heat absorbent than the commonly known carbon dioxide (e.g., Central Statistical Office, 2005–2020; Ginty, 2016). More than thirty percent of methane emissions in Poland come from underground mining. Total methane emissions in USCB are a significant part of all methane emissions in Poland (Institute of Environmental Protection – National Research Institute, 2020). The coal mine CH_4 emissions reported in this study consist of captured and undeveloped methane from mine drainage systems which is released directly to the atmosphere and from the ventilation air methane (VAM emissions). The total methane emissions in Poland consist of emissions from agriculture, waste management, hard coal mining, and other fuel emissions.

At the beginning of the study (1994-1998) the contribution of methane emissions in USCB to the total methane emission in Poland oscillated at about 18% and it was rising over subsequent years, reaching a 24.56% share in the entire emission of CH_4 in 2008 (Table 2). Similarly to the methane emission trend in 2009–2014, the share of emitted gas decreased to 23–24% in this period. In subsequent years (2015–2018) USCB coal mines released over 26% of all the methane emitted to the Polish atmospheric air. It is clear to see that the trend relating to the share of methane emissions by USCB mines increased by 49% between 1994 and 2018.

In the near future, USCB mines need to extract coal from deeper and deeper seams, where methane-related danger will be increasing. To keep exploitation safe, CH_4 utilisation (methane emission) should be at a very high rate, possibly higher than in the last three years (2015–2018). In this way, the contribution of USCB methane emission to total CH_4 emission in Poland can be at the same high rate or can exceed 30%.

We can observe the same trend in emissions when we take a closer look at methane emissions in USCB as compared to the total greenhouse gases (CO_2, CH_4, etc) emissions in Poland. Trends in emissions were changing in a very similar manner as compared to total methane emissions in USCB and the contribution in the CH_4 emission of USCB to the total emissions in Poland. In Table 2 we can see that underground coal mining in Silesia and Małopolska region is responsible for 2.26 to 3.40 % of greenhouse gases emissions in Poland (CH_4 was only counted as the strongest heat absorbent and the main greenhouse gas occurring in hard coal mining). Developing new, pure technologies, such as solar energy and windmills farms, can reduce greenhouse gas emissions in Poland in the coming years. Thus, the contribution of methane emissions from the USCB coal mines is going to increase, because power production in Poland is still based on coal and it will not change for a long time.

Table 2. Contribution of the methane emissions

Year	Contribution of methane emission in the USCB to the total emission in Poland in %	Contribution of methane emission in the USCB to the total greenhouse gases emission in Poland in %
1994	18.14	2.51
1995	18.11	2.43
1996	17.64	2.26
1997	18.94	2.47
1998	18.56	2.50
1999	19.91	2.70
2000	21.67	2.94
2001	20.04	2.82
2002	21.49	3.01
2003	22.29	3.02
2004	21.87	2.91
2005	23.15	3.10
2006	23.57	3.06
2007	24.22	3.09
2008	24.56	3.18
2009	24.21	3.20
2010	23.52	2.95
2011	23.66	2.91
2012	23.31	2.90
2013	23.63	2.98
2014	24.64	3.17
2015	26.34	3.40
2016	26.77	3.32
2017	26.71	3.27
2018	26.97	3.27

2.5. GREENHOUSE GASES EMISSIONS IN EUROPEAN COUNTRIES

Changes in greenhouse gases emissions are noticeable in almost each country which signed the Kyoto Protocol. The highest increase in greenhouse gases emissions between the base year (1990) and 2017 was noticed in Cyprus (53.8% increase), Iceland (45%), Spain and Portugal (19%). On the other hand, the biggest decrease in the emissions was observed in the Baltic region countries, such as Lithuania (57%), Latvia (54%), Estonia (50%), as well as in Romania (53%). Almost nothing has changed in Malta, Slovenia and Luxembourg– these three countries have been emitting similar volumes of greenhouse gases in comparison to the base year. Poland is classified in the middle of the statement with a 13% reduction in emissions. Changes in greenhouse gases emissions were caused by a diverse economic structure, using or not using renewable energy sources, and emission trading between countries (Eurostat database on 2017 in Central Statistical Office, 2005–2020).

2.6. OPTIONS TO REDUCE METHANE EMISSIONS

The European Union's International Energy Agency attempts to include CH_4 in the European Emissions Trading System (ETS) treating methane as 25–30 times stronger heat absorbent than carbon dioxide. This type of solution is going to impose extra fees on every Mg of released methane direct into the atmosphere and force the improvements in, e.g., coal mining sector (EU Emissions Trading System). Capturing methane during underground mining works (CMM) and direct from the virgin coal beds (CBM) can limit the CH_4 emission to the open-air. Captured gas mixture, rich in methane can be sold to external customers or used in the internal mining processes to produce energy (Karacan et al. 2011; Jureczka et al. 2015; Dreger and Kędzior 2019; Kędzior and Dreger, 2019; Dreger, 2020). In the European Union's Final Report from 1998 titled *Options to Reduce Methane Emissions* points some solutions to utilize mining methane like: steam turbines, gas turbines, spark-ignition reciprocating engine, dual-fuel compression-ignition engine or flaring (EU Final Report 1998). The main source of CH_4 within the European Union and worldwide is the agricultural sector, where emission comes from enteric fermentation in ruminant livestock, manure and rice cultivation (Bates, 1998; Curnow 2020; *Global Methane Initiative* 2020). One of the possibilities to reduce methane is the reduction in the livestock numbers or adding feed additives and supplements which inhibit methanogens in the rumen, and subsequently reduce enteric methane emissions. The other opportunity to limit the gas emission is to recover and use methane from animal waste (Bates, 1998; Curnow, 2020).

3. CONCLUSIONS

Methane is one of the strongest greenhouse gases, produced by underground coal mines in the Upper Silesia Coal Basin. To protect workers and keep the mining atmosphere free of methane, thousands of Mg of this gas need to be extracted out of the mine directly to the air.

Over the last four years (2015-2018) methane emissions from coal mines exceeded 520 thousand Mg annually due to the increasing depth of coal extraction and more methane rich coal seams which are being operated. In the forthcoming years methane emissions are going to increase or remain at a high level. Deeper coal seams are highly rich in methane, which accounts for the fact that the contribution of the USCB mines methane emissions is bigger and exceeds 3% in the total greenhouse emission in Poland

and 26% in the total CH_4 emission.

On the other hand, methane emissions from all sources in Poland have dropped by 20% in the entire research period. European and world leaders have been working on the greenhouse effect slowdown. Kyoto, Paris, and Katowice agreements determine how to improve air quality, but without a global consent, mainly from the Asian part of the globe, the reduction in greenhouse gases emissions may fail.

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