Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)

doi:10.36487/ACG_repo/2315_011

Forecast and mitigation of the pressure build-up in a depleted mine gas reservoir: case study in a French coal basin

S Lafortune *French national institute for industrial environment and risks (Ineris), France*

A Gouzy *French national institute for industrial environment and risks (Ineris), France*

I Vuidart *GEODERIS, France*

Abstract

Closing mining activities in underground mines leads to stopping water pumping and ventilation. Unflooded voids form reservoirs where dangerous air or toxic gas can appear. If those reservoirs are connected to the surface through adits, shafts, or wells, they not only shape potential migration pathways for gas transfer to surface but also fresh air entrance. Gas can also migrate underground through strata if affected by former underground mining activities (e.g. dewatering, subsidence, fractures). Eventually gas migration between mining voids and surface is mostly driven by temperature and pressure gradients that cyclically change with seasons. Once emitted at surface, mine gas may lead to hazardous situations to people. Related hazards are explosion, suffocation or poisoning. Understanding gas production processes underground and migration to the surface is fundamental to assess post-mining risks at surface.

The Nord-Pas-de-Calais (NPdC) basin is the largest coal basin ever exploited in France. A total of 2.4 Gtons of coal have been produced over 270 years. Mining was completed underground, and more than 600 shafts have been documented, although some have not been precisely located. The flooding of the mining voids is ongoing and will not be complete until 2150.

Several sectors of the mine gas reservoir are currently at a pressure value below the surface atmospheric pressure due to abandoned mine methane (AMM) exploitation. Today, the depletion limits the mine gas migration from the underground towards the surface. Moreover, water level, gas pressure and gas composition within the reservoir are monitored at about 500 measurement locations, such as former mine shafts, pressure-relief boreholes or piezometers.

Since 2019, Ineris and GEODERIS have been revising the gas monitoring plan of the NPdC basin. The purpose is to determine if the monitoring plan requires improvement to control the mine gas emissions at surface. Special consideration is given to pressure-relief boreholes as they are important mitigation measures that prevent pressurization of unflooded sectors of the mine gas reservoir located outside the drainage area related to the AMM production.

Here, we detail how the 3D geometric model inherited from the mine operator and since then regularly updated is used to forecast the flooding of the aeraulic connections within the mine gas reservoir and the consecutive gas pressure build-up in the isolated sectors. This makes it possible to plan and prioritize the works to be done to improve the gas monitoring plan of the NPdC basin. The objective is also to anticipate any failure of the pressure-relief boreholes by having increased vigilance on the sectors at the end of flooding.

Keywords: *drainage, emissions, flooding, gas, mitigation, monitoring, post-mining, risk prevention*

1 Presentation of the Nord-Pas-de-Calais coal basin

The Nord-Pas-de-Calais (NPdC) basin is located in northern France (see Figure 1) and is the largest coal basin ever exploited in France. A total of 2.4 Gtons of coal have been produced over 270 years (from 1720 to 1990). Mining was completed underground, over an area of about 900 km^2. Coal mining was most often very extensive, both horizontally and vertically, with an exploitation of several superimposed coal seams.

In the NPdC area, more than 600 shafts have been documented, even if some of them are still not precisely located. During the shutdown of mining operations, these wells were closed. They were mainly backfilled with materials from mining heaps and/or with ashes from thermal power stations.

Figure 1 Location of the Nord-Pas-de-Calais coal basin (red) and of the other coal basins (black) in France. Modified from a map by A Bourgeois. License: https://creativecommons.org/licenses/by-sa/4.0/

1.1 Underground reservoirs created by residual mining voids

When mining stopped, the residual voids had an estimated volume of around 700 Mm^3. These voids correspond to large and interconnected coal mining sectors, often on several levels (i.e. working platforms in the underground mine). The interconnections are mainly made via the old underground infrastructures (e.g. adits, shafts) and rocks fractured by mining.

All residual voids in the NPdC are made up of several independent reservoirs. Limits of each reservoir are determined by three main factors:

- The geological and hydrogeological structures of the coal deposit.
- The spatial structure of the former mining operations and their geomechanical influence areas which determine the connections between the residual voids.
- The distribution of pressures within underground voids, which are subject to the influence of mine gas capture from the surface.

The division of the NPdC basin into five main reservoirs was formalized in 2014 by the French Department for Mine Safety and Risk Prevention (BRGM-DPSM). These five main reservoirs have significatively different extents (see Figure 2). From the point of view of gaseous phenomena, the envelopes of these reservoirs are likely to change over time depending on the progress of flooding of the mining voids and of the evolution of the influence of mine gas drainage. Volumes of each reservoir?

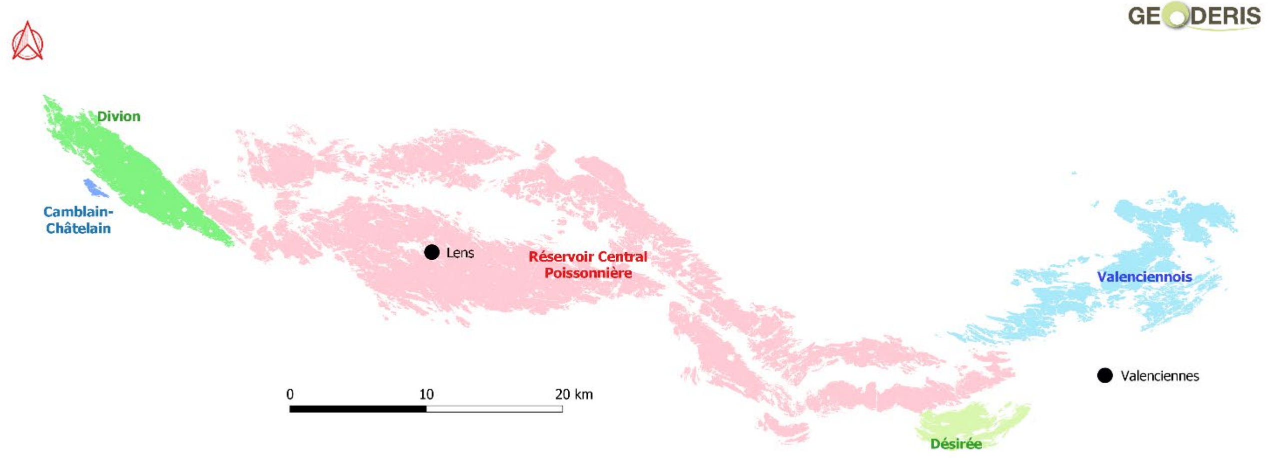


Figure 2 **Map of the five main reservoirs in the Nord-Pas-de-Calais coal basin. Each reservoir is indicated by a specific colour (from West to East: Camblain-Châtelain reservoir, Divion reservoir, Poissonnière central reservoir, Désirée reservoir, Valenciennois reservoir). Lens and Valenciennes are two main cities**

1.2 Mine gas drainage and exploitation from the surface

During mining operations, the entire coal deposit was known to be "gassy". In several areas, one ton of coal in place could contain more than 10 m^3 (and even more than 20 m^3) of methane. After coal mining stops, gas continues to be released from unmined seams of the coal deposit. The gas can thus accumulate in residual mining voids (reservoirs) and can migrate in an uncontrolled manner to neighbouring mines still in operation and/or to the surface. This can lead to hazardous situations. The observed mean mine gas composition is the following: 40 to 65%vol. of methane (CH_4), 10 to 15%vol. of carbon dioxide (CO_2) and about 1%vol. of oxygen (O_2).

The drainage and exploitation of mine gas from the surface were implemented by the French coal mining company (Charbonnages de France or CdF) from the 1970s, in parallel to the gradual end of the mining operations. Mine gas is drained and exploited from dedicated boreholes, which were drilled for that specific purpose, or from former mine shafts that were abandoned and filled so that an aeraulic connexion between the underground reservoir and the surface still exists (e.g. via a pipe). Mine gas drainage and exploitation have gradually led to the depression of large areas of post-mining voids compared to atmospheric pressure (760 mm Hg; see Figure 3).

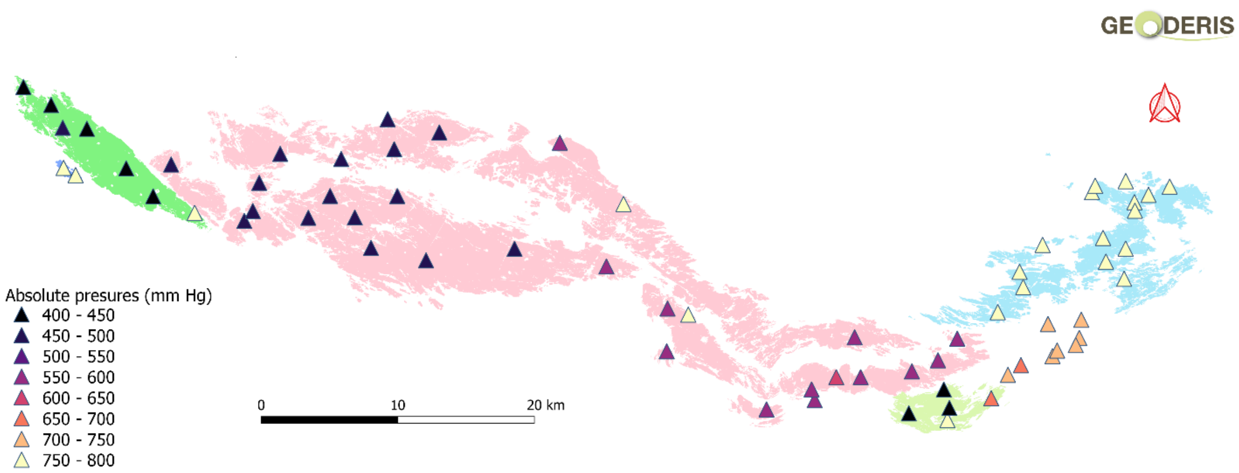


Figure 3 Map of pressures measured within the main reservoirs in the Nord-Pas-de-Calais coal basin (date of measurements: late 2020). The atmospheric pressure value is about 760 mm Hg

Underground gas transfers have very slow kinetics, and the underground flow regime can therefore be considered semi-stationary. This induces little pressure drops during gas transfer from post-mining voids to drainage and exploitation boreholes. Therefore, the pressure is quite homogeneous within each residual reservoir.

1.3 Flooding of the mining voids

Flooding of the residual voids in the NPdC basin is slow, because of two main factors:

- The low permeability of the overburden, which limits the inflow of water from the overlying formations and from the surface.
- A very low inflow of water from the unmined coal seams.

Consequently, flooding is not very advanced within the NPdC basin (except in the eastern part of the basin), and hydrological equilibrium is forecasted to be reached in more than a century: it will not be complete until 2150. Thus, the flooding is presently ongoing.

Flooding must be carefully considered, as it may lead to the closure of aeraulic connections and to the isolation of sectors of residual voids to which drainage and exploitation boreholes are connected. The depression of the gas drainage can no more be effective on the volumes thus isolated. From this moment, mine gas pressure can thus increase within the isolated volumes, due to the rise of the water level (piston effect) and the desorption of CH_4 from the unmined seams of the coal deposit. This situation causes a risk of mine gas migration towards the surface.

1.4 Mine gas monitoring plan

The mine gas management and monitoring plan of the NPdC basin was setup by CdF between the end of the 1980s and 2006. CdF oversaw the monitoring until 2006, when BRGM-DPSM took over.

To date, mine gas monitoring is performed on a total of 542 locations including:

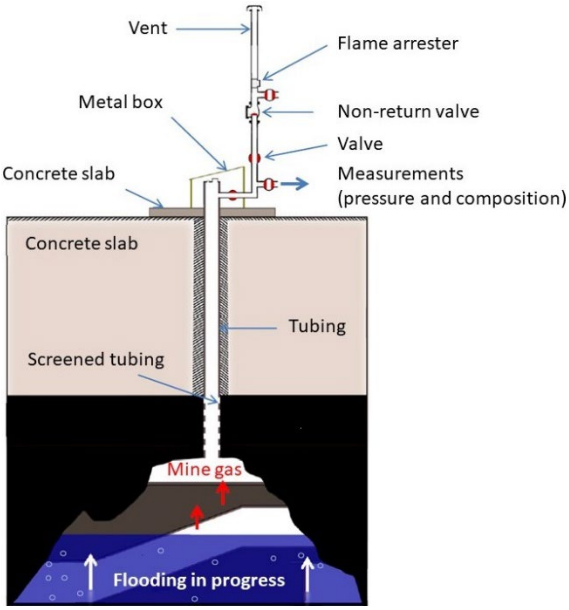
- 462 former mine shaft heads.
- 74 pressure-relief boreholes (or "SDEC" which stands for the French "Sondages de DÉCompression") connecting the mine gas reservoirs to the surface atmosphere (see Figure 4). They make it possible to monitor the behaviour of underground residual voids (in terms of change

in pressure or gas composition) and they also play a preventive role, as they allow to control the emissions of mine gas to the surface in case of reservoir overpressure.

- 6 deep piezometers, drilled to monitor the flooding dynamics (evolution of the water level within the reservoirs).

BRGM-DPSM is performing continuous monitoring on 26 of these locations (mostly for mine gas pressure, and sometimes for barometric pressure and gas composition measurements). Monitoring is completed quarterly or half-yearly in measurement campaigns on the other locations. These campaigns include an integrity check by visual inspection of the location and its immediate environment (check for vandalism, control of wellhead stability, etc.), the measurement of the barometric pressure, of the wellhead pressure, of the CH_4, O_2, CO_2 and trace gas (CO and H_2S) concentrations and of the water level. Additional measurements can be carried out if needed on an ad hoc basis, depending on the behaviour of monitored locations, mainly with the aim of diagnosing the risk of possible disorders and to better understand the observed phenomena.

The interpretation of the measurements carried out by BRGM-DPSM helps to identify eventual technical problems or changes in the behaviour of reservoirs which may require action or remediation (such as additional investigations or safety improvement works for instance).



(a)

(b)

Figure 4 **Schematic diagram and photography of a pressure-relief borehole (SDEC). (a) Schematic diagram showing the connection between a mine gas reservoir and the surface atmosphere, and all safety equipment on a SDEC head (modified from a document by BRGM-DPSM); (b) Photography of a SDEC head (the vent, the metal box and the concrete slab are visible on the picture)**

2 3D geometric model of the Nord-Pas-de-Calais coal basin

2.1 Initial version of the 3D geometric model

The geometric model of the NPdC basin was first developed by CdF during mining operations and then updated to a 3D model and maintained by BRGM-DPSM until 2019 using a computer-aided design (CAO) software.

The 3D geometric model includes:

- A 3D representation of all the mined coal seams (see Figure 5; but the thicknesses of the seams, between 0.5 and 2 m, are not mapped).
- A simplified representation of the main skeleton of the underground works, showing the shafts, and the main connections between the shafts via the underground galleries (see Figure 6). But these connections are only drawn by direct schematic lines which do not represent their real geometry.
- The pressure-relief boreholes.
- The deep piezometers.

But the geometric model does not include:

- The watertight geological structures or formations (e.g. closed faults) or, on the other hand, the permeable ones (e.g. permeable geological layers, open faults, etc.). Porous and permeable layers overlying the coal deposit are for instance not represented, whereas they were well-known during mining to cause significant water inflows.
- The volumes of geomechanical influence around the mined seams (layers with increased permeability induced by mining; see below).
- The secondary infrastructure mine workings (mining galleries in mined areas).

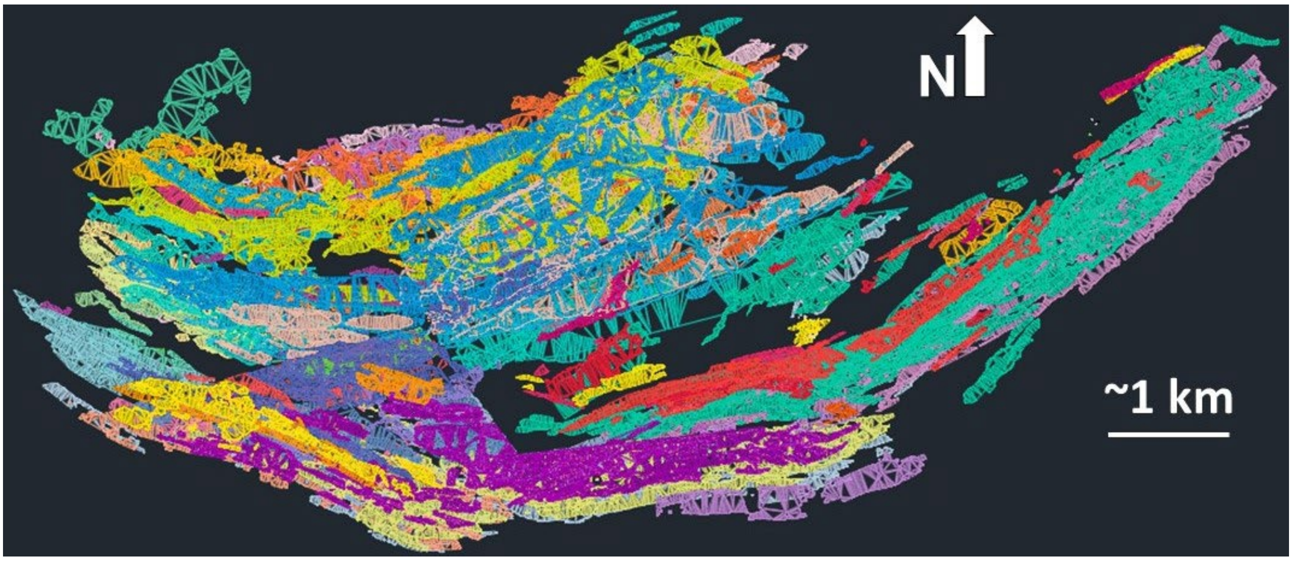


Figure 5 Top view of overlapping mined coal seams in the Nord-Pas-de-Calais coal basin extracted from the 3D geometric model (detail of the 3D geometric model)

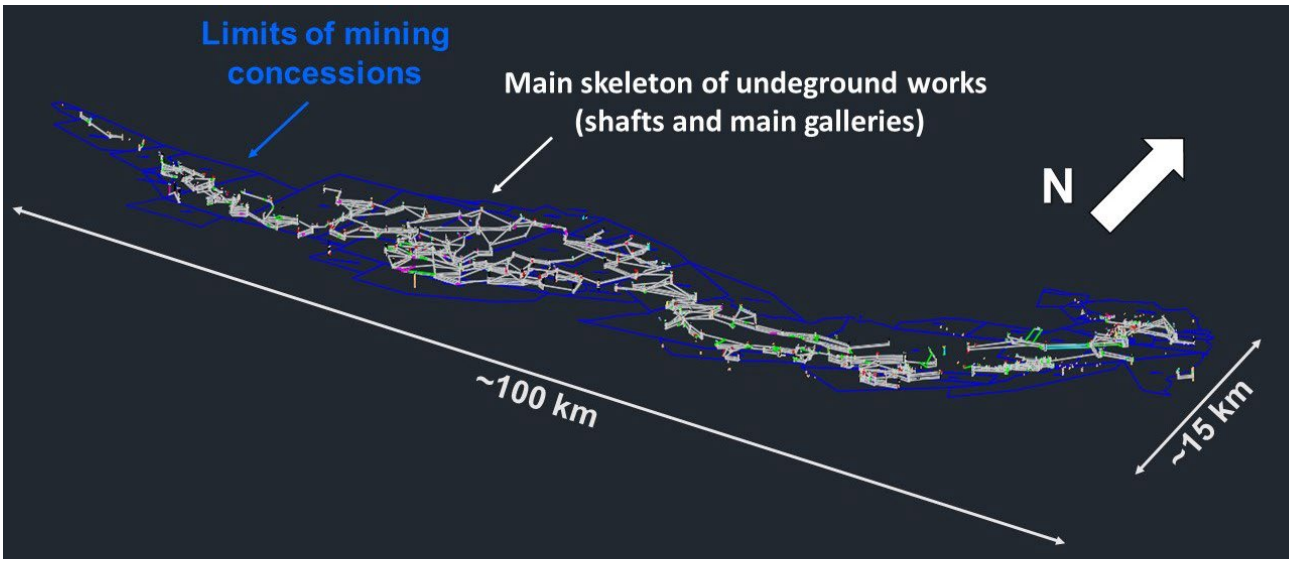


Figure 6 Global view of the 3D geometric model of Nord-Pas-de-Calais coal basin showing the main skeleton of underground works (the scale is here larger than on Figure 5)

2.2 Addition of the volumes of geomechanical influence to the 3D geometric model

Underground mining causes fracturing and cracking of surrounding formations. This leads to a strong increase of the initial porosity and permeability, and to the drop of the water table in aquifer formations.

Volumes of geomechanical influence on permeability induced by mining and fracturing extend both vertically and laterally from the mined seams. The extents of the volumes depend on several factors, as the geometry of the mined seams, the mechanical properties of the surrounding formations, the mining method, and the geometry of the underground workings. As they constitute potential pathways for gas migration, these volumes with increased porosity and permeability must be considered for mine gas management and monitoring and should therefore be added to the existing 3D geometric model of the NPdC basin.

To define the vertical extents of the volumes of geomechanical influence within the 3D geometric model, we used the conceptual model established in the 1970s by CERCHAR, the research centre of CdF (Jeger et al. 1976). This conceptual model has been validated experimentally on several mining areas of the NPdC basin (Jeger 1980) and considers that the maximum thickness limiting the volume influenced by mining operation (i.e. limit of geomechanical influence) is 200 m above a mined seam and 50 m below. According to the conceptual model, beyond these distances, there is no influence of mining on aeraulic and hydraulic properties.

The conceptual model has been established considering the geomechanical behaviour and gaseous transport taking place during and shortly after the mining of a coal seam (from one year to a few years). After the cessation of mining operations, the ground influenced by mining partially recompacts over time. Nevertheless, its porosity and permeability remain higher than the initial value and thus it still constitutes a possible migration pathway for underground fluids (gas and water).

In order to take into account the partial recompaction, we have set the limit of vertical influence at 100 m above a mined seam according to our expertise. Two sub-zones are distinguished (see Figure 7):

- 0 to 50 m above the seam: extent of the *high* increased permeability volume allowing water and gas migration.
- 50 to 100 m above the seam: extent of the *limited* increased permeability volume allowing only gas migration (in layers not saturated with water), as gases have a higher capacity for migration compared to water, due to the size of the gaseous molecules and to the dynamic viscosity of gases.

There is also a geomechanical influence below a mined seam, but it is less extended than above. Here, due to recompaction, we considered a value of 20 m for the increased permeability volume below a mined seam (both for water and gas migration).

To define the lateral extents of the volumes of geomechanical influence within the 3D model, we used another conceptual model established for the NPdC basin (Proust 1964). This model concerns underground mined areas whose horizontal extent is large enough to generate subsidence on surface. The two same sub-zones as for the vertical influence are distinguished. The *high* increased permeability volume is defined by a traction angle (or fracture angle) of an average value of 10°. The *limited* increased permeability volume is defined by the value of the extension angle of the subsidence area, whose value is set to 35° by the conceptual model (see Figure 7).

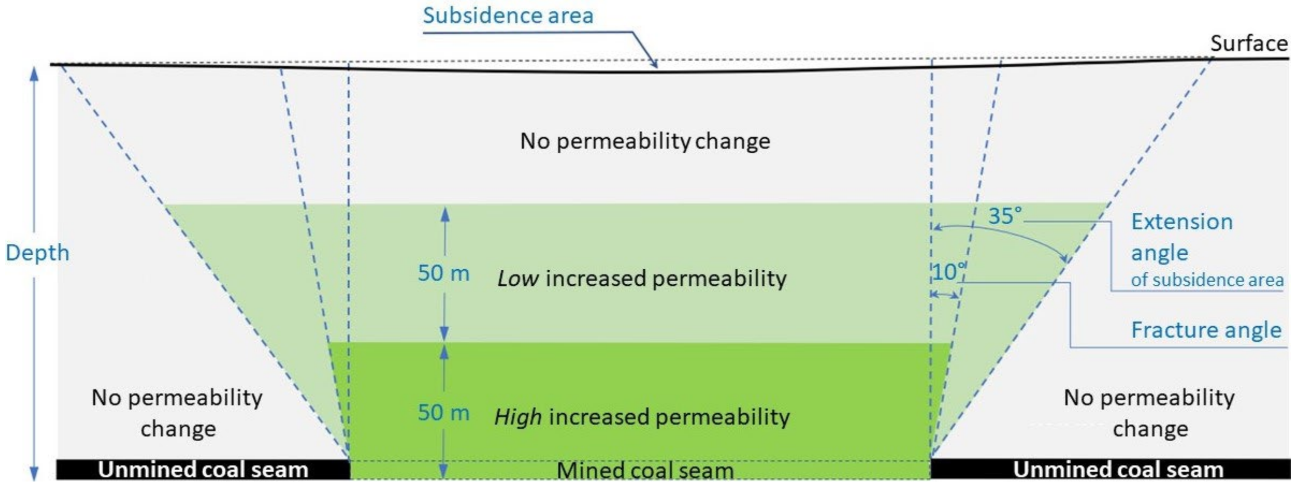


Figure 7 Conceptual model to define vertical and lateral extents of the volumes of geomechanical influence above a mined coal seam

Using the conceptual models, the geomechanical influence volumes of each mined coal seams have been added to the 3D geometric model. Because mined seams are sometimes close, their geomechanical influence volumes may be partially superposed (see Figure 8). In that case, the increased permeability volumes constitute possible migration pathways, both for gas and water.

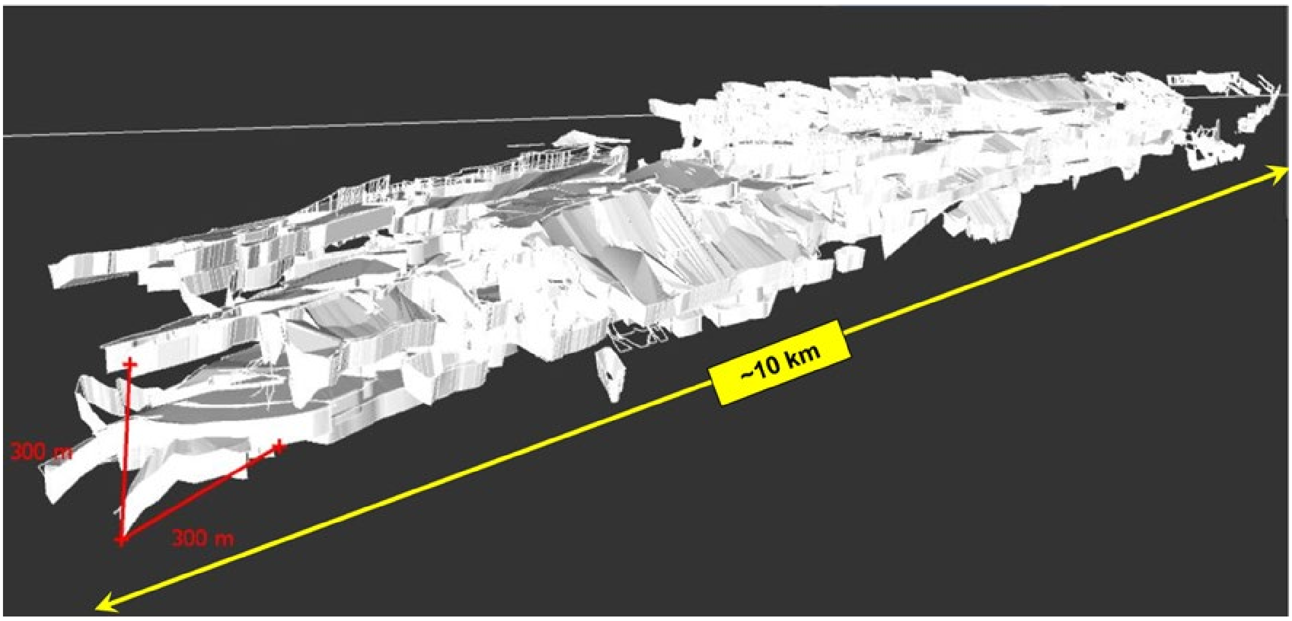


Figure 8 **Superposition of influence volumes of overlapping mined coal seams in the Nord-Pas-de-Calais coal basin**

2.3 Addition of overlying permeable formations to the 3D geometric model

Porous and permeable geological formations are located above the coal beds within the NPdC. These formations are sandstones. Prior to coal mining, they contained an aquifer formation, but it has generally been dried up because of the fracturing caused by mining. There is thus a hydraulic connection between the sandstones formations and the coal beds.

Sandstones are overlaid by a series of thick and predominantly clayey lithologic units. These overlying plastic and impermeable formations constitute a tight screen that helps prevent the migration of mine gas from the underlying coal beds to the surface through the overburden.

Because mine gas can migrate and accumulate within the sandstones formations, these must be taken into account for mine gas management and monitoring and was added to the 3D geometric model. Indeed, sandstones porous volumes increase the total volume of underground gas reservoirs to which they are aeraulically connected.

2.4 Present updated version of the 3D geometric model

The 3D geometric model of the NPdC basin has been updated from 2019 to get a better view of the global volume accessible to mine gas, considering both the volumes of geomechanical influence and the overlying permeable formations.

Currently, the work has only been done for one of the five main reservoirs of the basin, as a test phase to confirm the feasibility and the relevance but also to identify the limits of the improvement. Only the high increased permeability volumes located above each mined seam have been added to the 3D geometric model. Since the porosity values are unknown, several hypotheses are considered (e.g. from 5% to 15%). And because the 3D model is only geometric, it does not provide permeability values.

Examples detailed in section 3 highlight the benefits of the updated version of 3D geometric model when dealing with mine gas management and monitoring within the NPdC basin. That’s why it is planned to continue the update work with the other reservoirs in the coming years.

3 Examples of uses of the 3D geometric model of the Nord-Pas-de-Calais coal basin

Here, we detail how the 3D geometric model is used to improve the gas monitoring plan of the NPdC basin. Two examples are presented:

- Use of the model to forecast the flooding of the aeraulic connections (such as exploited seams, galleries, shafts) within a mine gas reservoir and the consecutive gas pressure build-up in the isolated sectors.
- Use of the model to confirm the connection between a pressure-relief borehole and a mine reservoir, to verify that control of emissions of mine gas to the surface in case of reservoir overpressure remains possible.

3.1 Use to forecast the flooding of the aeraulic connections within a mine gas reservoir and the consecutive gas pressure build-up in the isolated sectors

The flooding of the mine workings led to the gradual closure of aeraulic connections within the mine gas reservoirs and to the consecutive gas pressure build-up in the unflooded isolated sectors. These aeraulic connections are either former galleries or shafts, mined seams, or also the porous and permeable volumes accessible to mine gas such as the volumes of geomechanical influence and the overlying permeable formations.

Based on new data added to the 3D geometric model, the potential impact on gas migration of the compartmentalization of one of the five main reservoirs of the basin was assessed. This work has been carried out for the reservoir studied during the test phase. It allowed for potential consequences of compartmentalization on mine gas drainage and exploitation and on flooding monitoring.

Handling the 3D geometric model being quite complex, a method has been specifically developed to analyze the compartmentalization of the reservoir. It relies on slicing the 3D geometric model in 2D horizontal views (top views) every ten meters deep. Each view highlights the continuity of mine workings and of their volumes of influence allowing gas or water migration over a thickness of ten meters (see Figure 9).

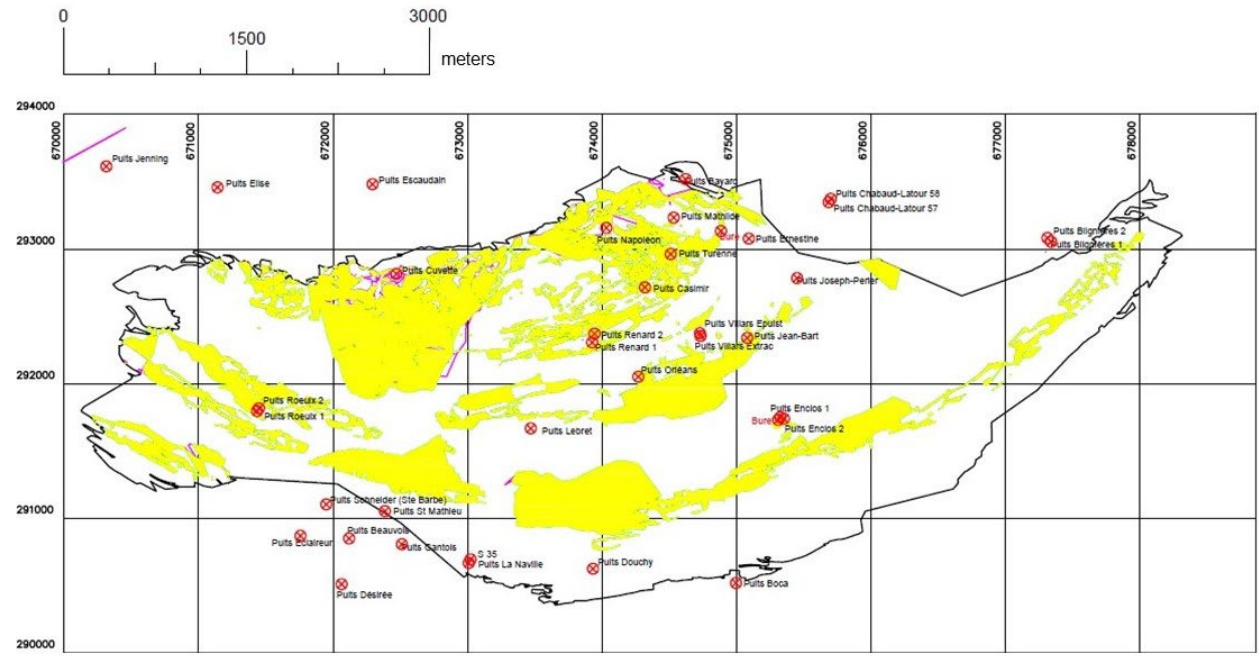


Figure 9 2D horizontal view (top view) highlighting in yellow the continuity of mine workings and of their volumes of influence allowing gas or water migration over a 10-m height section of a reservoir in the Nord-Pas-de-Calais coal basin. Former shafts are located by crosses circled in red

Analyzing the horizontal views provides information about the depths at which the aeraulic connections will disappear with flooding. It is thus possible to determine the depths at which flooding induces a compartmentalization of a main reservoir into independent smaller reservoirs. The volume of each isolated reservoir can then be assessed using the 3D model, by adding the influence volumes of all the unflooded mined seams.

As the depression of the gas drainage can no more be effective on the isolated reservoirs, there is a risk of mine gas migration towards the surface. Thus, numerical simulations have been carried out to predict the evolution of the mine gas pressure in each isolated reservoir. The objective is to simulate the pressure increase and to assess the time required to reach the value of atmospheric pressure within each isolated reservoir, as it is a fundamental data for the management of the risks of mine gas emissions at surface (as soon as reservoir pressure reaches atmospheric pressure, there is a risk of mine gas emission at surface). To run the numerical simulations, we used a simple mathematical model developed by Ineris in the 1990s to predict the behaviour in terms of gas pressure and methane content of a firedamp mining reservoir subject to mine gas capture (Couillet 1998).

3.2 Use to confirm the connection between a pressure-relief borehole and a mine reservoir

Several pressure-relief boreholes (SDEC) have been drilled within the NPdC basin to ensure a natural drainage (purging) of mine gas from mining voids to the surface. SDEC are outlets ensuring the control of mine gas emissions at surface. They are usually located far from surface stakes (e.g. dwellings) and designed considering the risk of formation of explosive atmospheres (ATEX).

The role of pressure-relief boreholes is to prevent significant and uncontrolled emissions of mine gas to the surface. They must be drilled to ensure the drainage of mine gas from the most important mine voids and from volumes of influence (fractured areas). SDEC must be operational throughout the entire flooding phase, and they must reach the highest sectors of the mining voids.

There are four conditions to ensure effective drainage by a pressure-relief borehole:

- Migration of mine gas must be possible between the mining voids and the borehole. The migration can be ensured by a direct connection between the voids and the borehole (it is for instance the case when drilling reaches a former gallery or a mined seam). It can also take place by an indirect contact through volumes of influence or permeable formations overlying the mined coal field, but only when they have sufficient draining properties to ensure an effective connection between the voids and the borehole.
- In case of indirect contact, the voids must not be too far from the borehole in order to limit head losses induced by the permeability of draining formations: the greater the distance, the greater the head losses are likely to be. The head losses reduce the drainage effectiveness of the borehole, by preventing the pressure balance between the surface and mine voids.
- The thickness and permeability of the formations overlying the coal seams must be sufficient to promote a lateral migration of the mine gas towards the borehole, rather than a vertical migration to the surface.
- The screened section (or the uncased one) of the borehole must be placed in the most superficial sector of the voids to be drained, so that the borehole remains functional until the very last phase of flooding. In the event where screened section is positioned deeper, the drainage would cease as soon as the water level reaches the plain casing.

Among the 74 pressure-relief boreholes drilled within the NPdC basin, 17 (23%) have been identified to be not representative of the known gaseous or hydrogeological conditions within the mining voids. It means that the connection of these 17 boreholes with the mining voids may not be effective: they may not ensure a natural drainage of the mine gas and may be useless to control mine gas emissions at surface.

A pressure-relief borehole is considered not representative of the conditions within the mining voids when there is an inconsistency in terms of pressure (values of pressure measured in the borehole different from those obtained in neighboring boreholes), of water table (because of meteoric water inflows within the boreholes, inflows from a shallow aquifer though the borehole casing, connection to a perched aquifer hydraulically isolated from the rest of the mining reservoir, presence of residual drilling fluids within the borehole), or of gas concentrations (mine gas is expected to be a mixture of atmospheric air penetrating the mining voids and mainly methane desorbing for coal still in place).

The 3D geometric model makes it possible to confirm whether there is a (direct or indirect) connection between a pressure-relief borehole and the mining voids (see Figure 10), to point and name the seam(s) reached during drilling according to the depth of the borehole, to assess the distance between the borehole and the voids, to check whether the borehole reaches the most superficial sector of the voids, etc. It is thus a useful tool to diagnose the origin of an inconsistency between what is observed in a borehole and what is known for the reservoir. It makes it possible to propose further auscultation or adequate treatment solutions for non-representative pressure-relief boreholes (visual inspection, logging, maintenance, workover or plugging and abandonment).

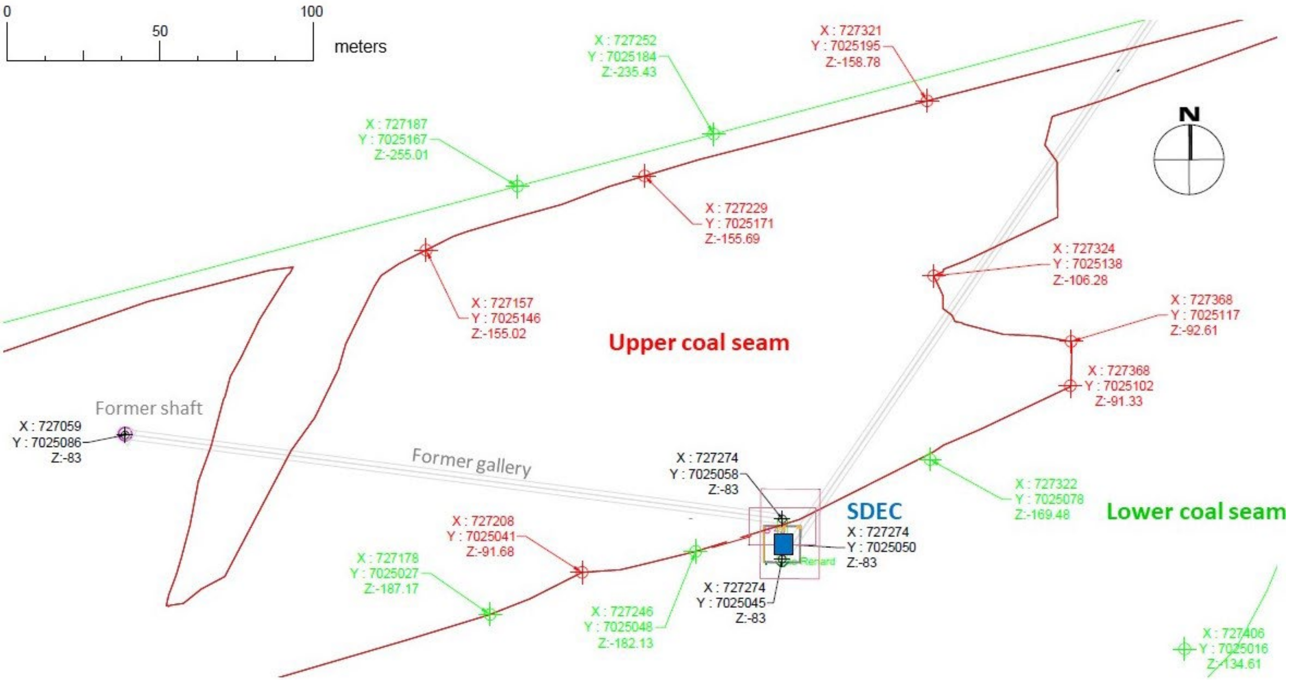


Figure 10 **Location of a pressure-relief borehole (SDEC, in blue) on a top view map showing the extension of 2 mined coal seams. The map shows that the SDEC does not reach the upper coal seam, but it was drilled very close to the former mine workings. X and Y are coordinates. Z is the depth in meters from the surface**

4 Conclusion

The unflooded residual mining voids in the NPdC basin (the largest coal basin ever exploited in France) constitute an important reservoir in which mine gas accumulates. The mine gas can migrate to the surface and may induce specific risks. Since 1980s, mine gas is thus monitored in the whole NPdC basin.

The 3D geometric includes all the mined coal seams, a simplified representation of the main skeleton of the underground works, as well as gas and water monitoring and mitigation equipment such as the pressure-relief boreholes and deep piezometers. This model is still maintained and updated as it is a useful tool for the management of mine gas emissions in the NPdC basin.

The model can for instance be used to forecast the flooding of the aeraulic connections within the mine gas reservoir and the consecutive gas pressure build-up in the isolated sectors, or to confirm the connection between a pressure-relief borehole and a reservoir. These 2 examples illustrate how the 3D geometric model is useful to understand and interpret monitoring measurements but also to propose adequate mitigation solutions in case something is not going as planned. Furthermore, the use of the 3D geometric model may make it possible to plan and prioritize the works to be done to improve the monitoring plan.

References

Jeger, C 1980, 'Éléments nouveaux dans la prévision du dégagement de grisou dans les tailles en plateures et dans les traçages situés dans des zones détendues dans ces tailles', *Recueil de communications des Journées d'Information 'Grisou, climat et aérage dans les charbonnages de la Communauté européenne'*, Luxembourg.

Jeger, C & Liabeuf, J 1976, 'Gisement et dégagement de grisou'. *Revue de l'industrie minérale, série spéciale Mine*, vol. 2, no. 76, pp. 25-53.

Proust, A 1964, 'Étude sur les affaissements miniers dans le bassin du Nord et du Pas-de Calais'. Revue de l'Industrie Minérale, vol. 46, no. 6-7.

Couillet, JC, Pokryszka, Z, Tauziède, C & Prince, M 1998, 'Mathematical model for firedamp reservoirs', *International conference on coal-bed methane technologies of recovery and utilization*, Ustron (Poland).