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Underground gas production and migration induced by mining subsidence

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ABSTRACT: Since 2009, Ineris works on a former mining area of Lorraine coal basin (East of France) where gas emissions occur at surface. Local authorities reported dangerous gas emissions in the local school and in dwellings. Ineris has been mandated to diagnose the gaseous phenomena (origin of the emitted gas and mechanisms of the emissions). The gas emitted at the surface is strongly enriched in CO_2 and depleted in O_2. It does not contain methane and is not from old coalmines origin. It is produced in shallow rock formations of the unsaturated zone located above the local aquifer. The gas flows to the surface through crevasses resulting from deep mining activities. Here, we observed how geomechanical, hydrogeological and geochemical processes can interact to enable underground processes of gas production and migration.

1 INTRODUCTION

Stopping mining activities in underground mines leads to stopping water pumping and ventilation systems. As following, former mining voids can be flooded (entirely or partially). Unflooded voids form reservoirs where dangerous air or toxic gas can appear. If they are connected to the surface through adits or shafts, unflooded voids also form potential migration pathways that may enhance underground gas transfer to surface but also fresh air entrance in the voids. Gas can also migrate underground through overburden strata potentially affected by former underground mining activities (e.g. dewatering, subsidence, formation of cracks or fractures). Gas migration between mining voids and the surface is mostly driven by pressure and temperature gradients.

When emitted at surface, underground gas may lead to hazardous situations to people. Related hazards are explosion, suffocation or poisoning. They depend on the composition of the emitted gas, the dynamics of the emission (flow, duration) and the potential of accumulation in confined or semi-confined spaces (i.e. weakly or non-ventilated spaces, such as cellars, basements or underground networks).

Since 2009, Ineris works on a former mining area of Lorraine coal basin (East of France) where gas emissions occur at surface. Local authorities reported dangerous gas emissions in the local school and in dwellings but also faintings of elderly people when going down in cellars. Ineris has been mandated to diagnose the gaseous phenomena.

Understanding gas production processes underground and migration to the surface is a fundamental step to assess post-mining risks at surface. Ineris is involved in studies to characterize those processes since the mid-90s and has a strong feedback experience. We know that hydrogeology and geomechanics play a key-role on gas production and migration mechanisms underground (Lagny 2015, Pokryszka & Grabowski 2003).

2 CONTEXTS

2.1 *Local geology and hydrogeology*

Dwellings affected by O_2-depleted and CO_2-enriched atmospheres are in the district of the “Cité Belle-Roche” located in Cocheren city (East of France). The district is located on a small hill culminating at an altitude of 233 m above sea level (m a.s.l.). Down the hill to the west, the valley of river “La Rosselle” is located at 200 m a.s.l. To the east, the valley is at about 220 m a.s.l.

Local surface geology is Trias sandstone and the valley is filled with modern alluvium. Below Trias formations and down to about 1000 m a.s.l., underlying rocks are dated from the Permian and the Carboniferous periods. Permian rocks form an aquitard formation over which lies the Trias aquifer. Underlying Carboniferous formations were intensively mined for coal as they contain several seams with thickness from a few centimeters to several meters. In this area, the coal mining industry started in 19^{th} century and stopped in 2004 with the closure of the last shaft still in activity at that time. This area is known in France as the Lorraine coal basin (or “bassin houiller lorrain” in French) and is part of a larger basin extending towards Germany.

Straight below the “Cité Belle-Roche”, the Trias aquifer is up to 200 m thick. Mining has caused overburden strata subsidence which has induced a hydrogeological connection between Trias and Carboniferous bedrocks and Trias waters flooded the mining voids. Flooding during mining was prevented by pumping. All pumping operations having been stopped in 2006, the water table rose till reaching the lower bedrocks of Permian formation in 2012; meaning that all residual mining voids were fully flooded at that time. Nowadays, water table rise in the Trias aquifer is still monitored by the department for mine safety and risk prevention of the French geological survey; water table has still not reached its level prior mining period (~200 m a.s.l.).

2.2 *Surface impacts of mining activities*

Below Cocheren city, the most superficial mining works were located below 600 m depth. The longwall mining with roof caving method was used to mine coal and it has caused fractures in the overlapping strata due to rock deformation and induced tensile stresses. Those stresses developed at the edges of the mining panels (Dawei et al 2019, Al Heib et al. 2005). The presence of competent formations at shallow depth, such as Trias sandstones in the Lorraine coal basin, favors the formation of open fractures.

When they are close to the surface, fractures may be discovered during groundworks or appeared after a rainy period. More than 1000 fractures have been identified and mapped on the surface of the “Cité Belle-Roche”. They extend over lengths ranging from 10 to more than 100 m. They have centimeter to decimeter opening and may be more than 10 m deep (Fig. 1).

Figure 1. Photograph of a fracture discovered close to the surface (GEODERIS, unpubl.).

2.3 *Gas emissions at surface*

Measurements showed that gas atmosphere in the shallow underground of the "Cité Belle-Roche" is O_2-depleted and CO_2-enriched. Values down to 7% vol. for oxygen (O_2) and up to 8% for carbon dioxide (CO_2) have been measured in fractures located at surface. The gas does not contain abnormal quantity of other dangerous gases usually seen in post-mining voids of Lorraine coal basin such as methane (CH_4) and carbon monoxide (CO) (Tauziède et al. 2001).

Those values of O_2 and CO_2 concentrations have also been measured in some cellars in the "Cité Belle-Roche". This means that gas migrates from the ground to the basement of the dwellings. Those concentrations are hurtful for people because it is known that irreversible effects on human health are observed above 5% vol. for CO_2 and below 16% for O_2. Normal values are 20,9% vol. for O_2 and 0,04% vol. CO_2 (i.e. 400 ppmv).

In 2009, increase of the number of complaints from inhabitants and of reports from local fire and rescue department led the authorities to mandate Ineris to diagnose the gaseous phenomena.

3 ORIGIN OF THE GAS EMITTED AT SURFACE

3.1 *Discussion on the most relevant hypothesis*

Ineris first rejected 2 hypotheses concerning the origin of the gas emitted at surface that were:

– Mine gas from the post-mining voids or blackdamp from Carboniferous strata migrating towards the surface.
– Biogas produced in a peat bog close to the "Cité Belle Roche".

These two hypotheses have been rejected because (1) there is no CH_4 in the gas emitted at surface whereas methane is a common component of coal mine gas and peat bog biogas and (2) O_2/CO_2 abundance ratio for measurements made in fractures or dwellings do not match a biological origin (such as respiration) or a dilution process of a deep-originated gas (e.g. mine gas) in the soil gas. Indeed, as shown on Figure 2, slopes from measurements are lower than values that would be expected if the hypotheses were true (theoretical slopes for dilution = -0.19; for replacement = -1).

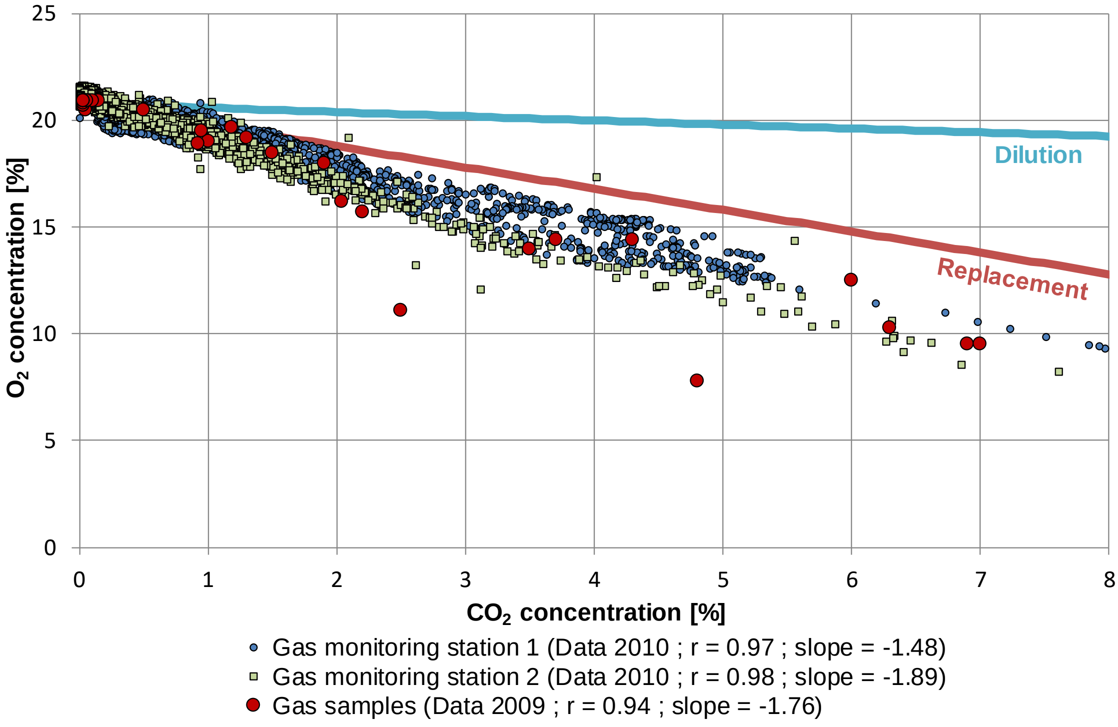

Figure 2. O_2 versus CO_2 concentrations measured in situ by sampling or continuous monitoring.

Furthermore, carbon isotopic analyses performed in lab on gas samples but also directly in situ by using a Picarro continuous analyzer revealed that the value of $\delta^{13}C$ signature of the emitted CO_2 is close to 0‰ VPDB and higher than the values commonly observed for a peat bog gas (-26‰ VPDB) or coal seam gas (-37‰ VPDB).

The most probable origin then appeared to be a geochemical process occurring in the shallow Trias bedrock. Oxidation of sulfides (as iron pyrite FeS_2) coupled with dissolution of carbonates (as calcite $CaCO_3$) lead to the consumption of O_2 and the production of CO_2. Oxidation of sulfides is a well-known process in mining contexts (Mayo 2000, Banks 1997). In France, it is observed in closed mines of the Lorraine basin where it causes noxious gas emissions at surface (Lagny 2015, Pokryszka & Grabowski 2003) and induces acid mine drainage (AMD). Acidification of mine outflow water can be buffered through carbonates dissolution according Equation 1.

$$4\ FeS_2 + 15\ O_2 + 8\ CaCO_3 + 6\ H_2O = 4\ Fe(OH)_3 + 8\ CO_2 + 8\ SO_4^{2-} + 8\ Ca^{2+} \qquad (1)$$

Equation 1 consumes 15 moles of O_2 when producing 8 moles of CO_2. This is consistent with measurements performed in situ (slope ~ -1.9; Fig. 2) and with the global hydrogeological context of the “Cité Belle Roche” area:

- Petrographic analyses performed on fresh cores sampled in a borehole drilled in the “Cité Belle Roche” have confirmed occurrence of both iron pyrite and calcium carbonate in Trias bedrock below 50 m depth; iron oxides have also been observed and could result from the reaction described above.
- Trias bedrocks are locally partially dewatered which increases the thickness of the capillary fringe and thus the pore volume where gas-water-rock reactions may occur.
- Sulfide oxidation is not limited if O_2 supply is renewed which is made possible by the fractures that enhance gas transportation between the underground towards the surface and in the opposite direction as well (i.e. fresh air entrance in the ground).

3.2 *Laboratory tests and geochemical modelling*

Laboratory tests have been setup to confirm the hypothesis concerning the origin of the gas emitted at surface in the “Cité Belle Roche”. 5 experiments have been run. They were performed on sandstone rock fragments sampled from the borehole cores below 50 m depth. Fragments contained both sulfides and carbonates. For each experiment, about 200 g of fragments have been crushed (to a few cm) and put with 50 ml of water in separate balloon flasks under monitored gas atmosphere. Rock samples and flasks have first been sterilized to prevent any biological contribution to experiments. Sterilized and deionized water has also been used. Experiments were performed at surface atmospheric pressure and at 20°C (lab conditions).

Experiments run for several days and gas atmospheres inside the flasks were regularly monitored. Results showed that O_2 and CO_2 concentrations evolved during experimental tests: O_2 was consumed and CO_2 produced following a linear trend with a slope close to 1.9. Results thus agreed the stoichiometry of Equation 1. Lab tests thus confirmed that gas emissions in the “Cité Belle Roche” are linked with geochemical reactions taking place in the Trias formation.

Geochemical modelling showed that the quantities of sulfides and carbonates consumed by the reaction are small and that the reaction process could last for more than 500 years if conditions are maintained. At short term, it highlighted that Equation 1 is limited by O_2 availability.

4 DYNAMICS OF THE GAS EMISSIONS AT SURFACE

Fractures have been identified as the carriers of the gas produced at depth towards the surface. Some dwellings in the “Cité Belle Roche” are built on fractures reaching shallow surface and are known to be affected by gas emissions from the underground.

To characterize the dynamics of the gas emissions at surface, Ineris equipped two shallow fractures with a continuous gas measuring system. One of the fractures was at that time still open and located in the basement of a dwelling; the second one was in a garden and was filled but measurements were still possible. Continuous measurements were performed by Ineris from 2010 to 2013 and included monitoring of O_2 and CO_2 concentrations in both fractures, as well as gas temperature, surface temperature and barometric pressure. In 2013, Ineris also set up a similar gas measuring system at 50 m depth in the borehole drilled in the “Cité Belle Roche”.

4.1 *Influence of barometric pressure changes*

First measurements in 2009 stated that gas emission at surface is strongly linked to changes in the barometric pressure. Indeed, the most deoxygenated and CO_2-enriched emissions are detected during low barometric pressure episodes. Continuous monitoring revealed that the highest CO_2 concentrations are mainly measured when the barometric pressure decreases (Fig. 3).

Comparison of measurements performed in the shallow fractures and deeper in the borehole helped to understand the dynamics of the gas migration in the underground and of its emission at surface:

- During anticyclones (high barometric pressure), fractures refill with atmospheric air entering the underground, which supplies the oxidation reaction of pyrite in O_2.
- During depressions (low barometric pressure), deoxygenated underground gas is emitted to the surface; surface emissions react quickly (in less than 30 mn) to a barometric pressure change and start when barometric pressure decrease reaches 5 to 10 hPa a day.

Besides barometric pressure changes, the contribution of two other mechanisms in the dynamics of the gas emission at surface has been considered: thermal draught and wind.

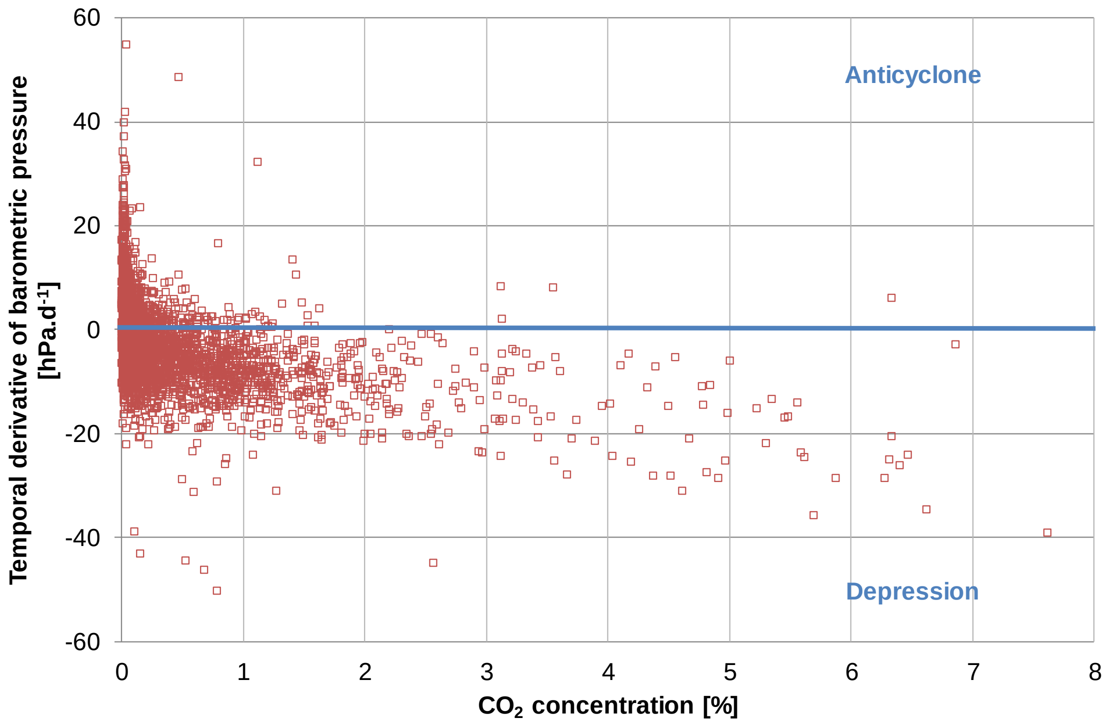

Figure 3. Temporal derivative of the barometric pressure versus the CO_2 concentration in a fracture at surface in the “Cité Belle Roche”.

4.2 *Influence of natural thermal draught*

The role of a thermal draught has been assessed. Whereas the underground temperature is almost stable between 11°C to 13°C, the outside air temperature fluctuates during a day (circadian cycle) but also according the seasons. The average outside air temperature is 18-19°C in summer and 1-2°C in winter.

Without taking into consideration other driving mechanisms, thermal draught can impact gas emissions:

– During summer, outside air temperature exceeds underground temperature. Therefore, outside air close to soil surface cools and its density increases which may lead to a migration of a cooler outside air through the underground fractures network from the “Cité Belle Roche” surface (local highest topographic area) to the “La Rosselle” valley (local lowest topographic area).
– During winter, underground temperature exceeds outside air temperature and thermal-driven flow of gas in the fractures network thus occurs from low to high topographic areas.

Influence of the thermal draught increases emissions of gas in the basements in “Cité Belle Roche” during winter time (Fig. 4) whereas emissions are favored in the valley and along the slopes of the hill during summer. But on a shorter timescale, the circadian cycle may also cause a change in the direction of the thermal-driven flow of gas in the fractures network whenever the outside air temperature reaches the 11-13°C limit during a day. According the outside air temperature, the influence of the thermal draught may enhance or lower the pressure-driven flow.

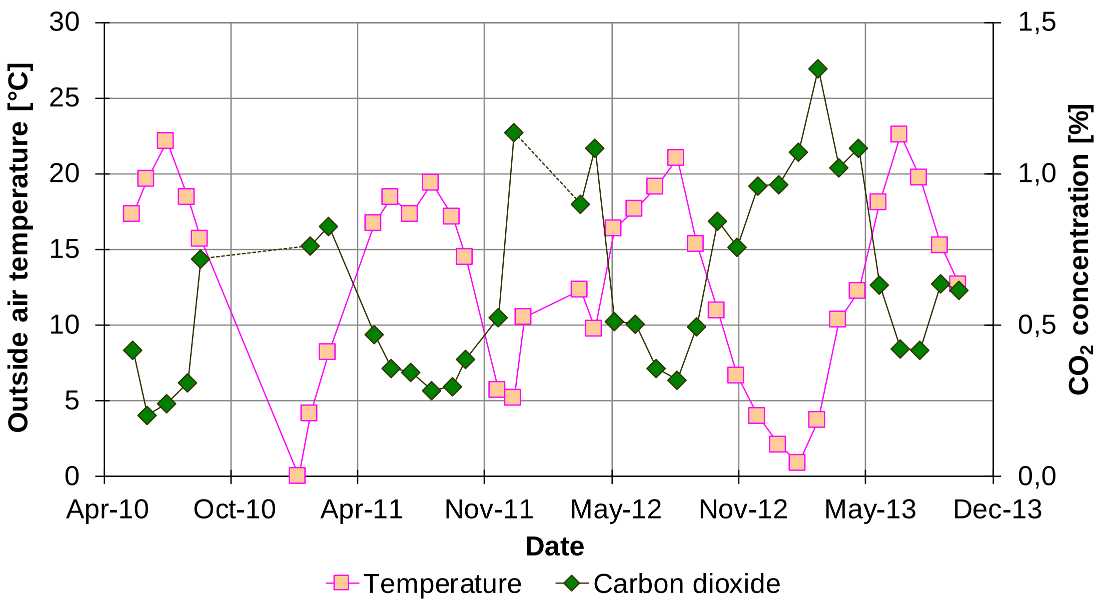

Figure 4. Influence of the natural thermal draught on CO_2 concentration in a fracture at surface in the “Cité Belle Roche”.

4.3 *Influence of the wind*

The “Cité Belle Roche” hill acts locally as an obstacle causing a change in wind speed and therefore a change in air pressure in the shallow underground. Overpressure affects the layers of the upwind slopes whereas decompression acts on the hill surface (by Venturi effect) and the downwind side (by wake effect). Here, the local prevailing winds are blowing from the SW to the NE.

Without taking into consideration other driving mechanisms, the wind may enhance fresh air intake within the underground fractures network mainly on S, SW and W-facing hillslopes. Consequently, deoxygenated underground gas may be emitted at the surface of the hill or at the opposite N, NE or E hillslopes. The higher the wind speed, the stronger its influence on the gas emissions at surface.

4.4 *Conclusions on the dynamics of the emissions*

Depending on the geographical and topographic location, effects of barometric pressure and outside air temperature changes and of the wind will add up or compete. There are a lot of possible combinations, but the three following ones must be highlighted:

– During depressions, gas emissions may occur wherever at the surface. But in that configuration, blowing winds will enhance emissions at the surface of the “Cité Belle Roche” hill and on the downwind slopes while limiting emissions on the upwind side.
– During winter, thermal draught directs gas flow from lower to higher topographic areas, i.e. from the valleys to the surface of the “Cité Belle Roche”. Wherever the wind is blowing from, it will enhance gas emissions at the surface according the Venturi effect.
– During summer, thermal draught directs gas flow in the opposite direction and leads to gas emissions in the valleys and on the hillslopes. Here, blowing winds will enhance emissions on downwind slopes when limiting them on upwind side.

5 CONCLUSIONS

In the underground below Cocheren city, coal mining has induced the partial dewatering of the Trias aquifer and the formation of an extended fractures network in shallow sandstone strata. Those impacts both increased the underground volume accessible to gas and enhanced gas exchanges between surface and the underground.

In situ measurements, lab tests and geochemical modelling pointed out that fresh air intake to the local underground leads to the oxidation of sulfides (as iron pyrite) and the production of CO_2 because oxidation it is coupled with dissolution of carbonates (as calcite). The underground deoxygenated and CO_2-enriched gas is emitted at surface modifying atmosphere in closed and poorly ventilated spaces as basements or some ground floors. In the area, dangerous atmosphere in classrooms and faintings of elderly people have for instance been reported.

Barometric pressure changes appeared to be the main driving mechanism of gas emissions at the surface in the “Cité Belle Roche”. But during periods when barometric pressure changes are low, thermal draught and wind can also drive the emissions. Indeed, the morphological shape of the “Cité Belle Roche” (hill) makes it particularly exposed to the effects of these two phenomena. Their combined action may even cause greater emissions of underground gas at surface.

During depressions, effects of thermal draught and wind may add up to the effect of a barometric pressure decrease to enhance emissions at the surface and expose inhabitants to dangerous atmosphere. This combination effect is stronger in winter as pressure, temperature and wind all enhance gas emissions at the surface in the “Cité Belle Roche” wherever the wind is blowing from (Figs 5-6).

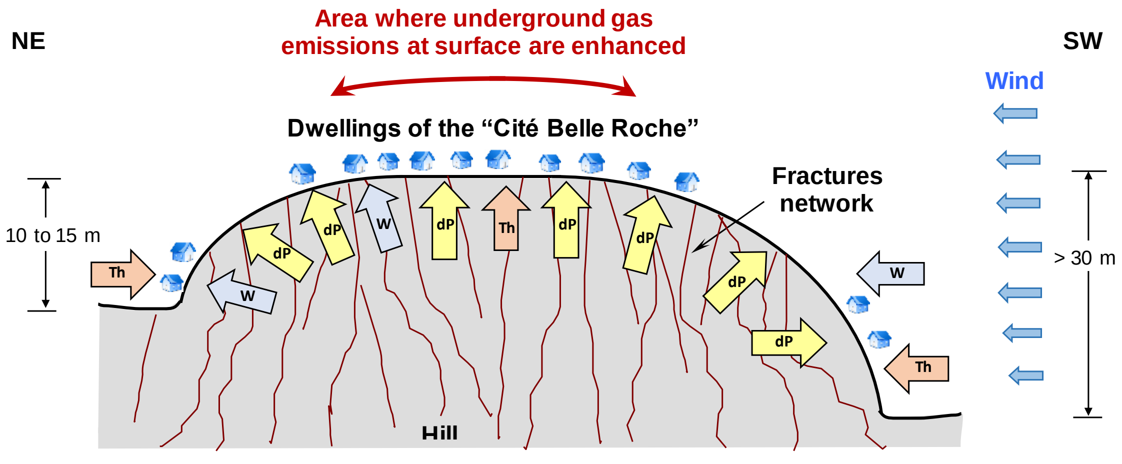

Figure 5. Schematic diagram of the combined action of a depression (dP; yellow arrows), thermal draught (Th; orange arrows) and prevailing wind (W; blue arrows) in the “Cité Belle Roche” during winter.

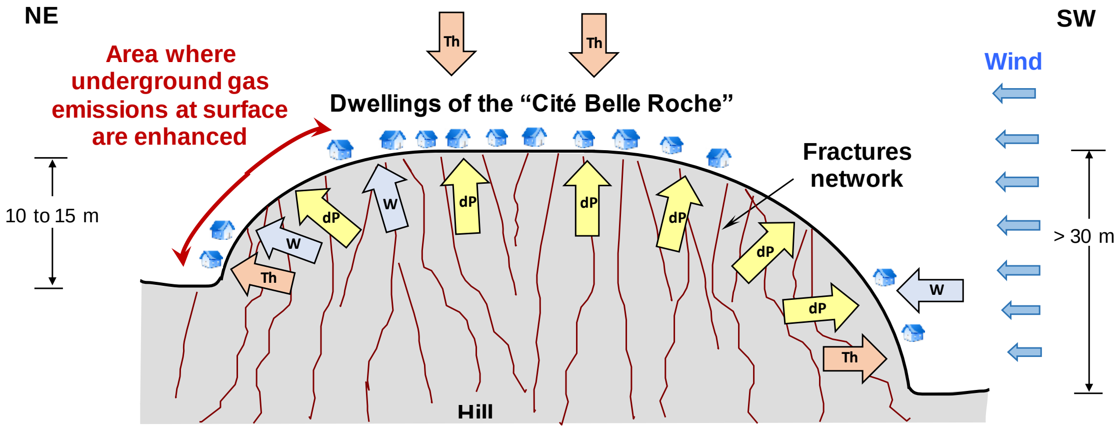

Figure 6. Schematic diagram of the combined action of a depression (dP; yellow arrows), thermal draught (Th; orange arrows) and prevailing wind (W; blue arrows) in the “Cité Belle Roche” during summer.

The work done by Ineris since 2009 helped understanding the origin of the underground gas emitted at the surface in the “Cité Belle Roche” but also describing the dynamics of the emissions. This is a case-study that reveals how geomechanics, hydrogeology and geochemistry can interact to induce gas production and migration complex processes.

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