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# Post-mining management in a major French mining area – example of the Lorraine iron ore basin

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## Abstract

*The Lorraine iron ore basin, located in the north-east of France, near the border with Luxembourg, extends over about 1700 km<sup>2</sup>, in a largely urban region.*

*The mines were closed in 1997. In a little more than one century, 40,000 km of galleries were excavated, creating more than one billion residual empty cubic meters. Modern mining was conducted by the room and pillar method, sometimes followed by complete removal of the pillars.*

*At the end of the 1990s, a series of major problems (subsidence, sink holes) occurred, affecting safety for persons and property in some cases. After these events, France developed a mining risk management policy and implemented various tools to first make sure that the right expertise and research was in place, then followed that with operational tasks.*

*The considerable extent of the Lorraine iron ore basin, the importance and multiplicity of the identified hazards and the surface challenges meant that a specific hazard assessment methodology had to be defined and put in place, and also a method for identifying and dealing with risks.*

*This is how an approach based on the retro-analysis of past events, and common to all of the one hundred and twenty towns in the basin, was defined and validated by a Committee of Experts. The importance of surface challenges meant that risks were prioritized and specific studies were conducted in a second phase on some sectors. The results of this work, conducted over the last 10 years, have taken concrete form through the publication of hazard maps to which municipalities refer to conduct their town planning development projects. All of the documents used for these studies and the results are in a database called LorFer.*

*In parallel, risk management solutions for surface challenges are used. Given the specific nature of the iron ore basin, special monitoring is planned for underground voids (below ground or surface inspections, microseismic monitoring, levelling, etc.). When the safety of persons and property can no longer be ensured by monitoring, measures are taken: treatments (filling, betterment, etc.) or expropriation.*

*The global approach applied to the iron ore basin is a concrete example of the policy implemented for managing former mine sites in France.*

*Currently, the administrative and political control is managed by State Departments and in particular the Ministry of Ecology, Sustainable Development and Energy and its Regional Divisions. The French government charges BRGM's Department of Prevention and Mine Safety with work on safety and operational management of facilities and safety equipment. Mining expertise is outsourced to an independent entity, GEODERIS, (a French "Groupement d'Intérêt Publique [Public Interest Group]" between BRGM and INERIS). To complete this approach a scientific interest group (GISOS) with several partners researches in this area.*

# 1 Introduction

The Lorraine iron ore basin, located in the north-east of France, near the border with Luxembourg, extends over about 1700 km<sup>2</sup>, in a largely urban region.

Major problems (subsidence, sink holes) have occurred in the basin, affecting the safety of persons and property in some cases. Following these events, France developed a mining risk management organization and implemented various tools to determine the origin of the phenomena, to assess how they progressed and their effects, to lead to *ad hoc* research programmes and to act operationally to prevent risks by both monitoring and work to make areas safe.

## 2 Lorraine iron ore basin

### 2.1 Geographic and mining contexts

#### 2.1.1 Geography

With a surface area of about 115,000 hectares, the Lorraine iron ore basin extends from the border with Luxembourg in the north to south of Nancy, i.e. almost 120 km long and about 30 km wide. It is divided into two sub-basins: the Briey-Longwy basin in the north, and the Nancy basin in the south, covering 1,300 km<sup>2</sup> and 380 km<sup>2</sup> respectively (Figure 1).



Figure 1: location of the Lorraine iron ore basin

#### 2.1.2. Geology

Iron formations are found in oolitic sedimentary deposits dating from the Aalenian period (about 150 million years ago).

The deposit is alternating mineral-rich seams containing 30-35% iron, separated by less rich areas called interseams. The formation ranges from a few meters to about sixty meters thick. The various seams are found over the entire basin but with variable contents and thicknesses. Depending on the area, one to six seams were exploited in a single vertical operation.

The Lorraine deposit lies underneath the Bajocian marl-limestone series

The deposit outcrops in the north, at the borders with Belgium and Luxembourg, and in the east along the Moselle valley. It sinks with an average dip of 3% towards the west to reach a depth of 280 meters at the western limit of the exploitable, managed area.

### 2.1.3 Mining methods

Ore has been extracted since the middle ages, but industrial mining only began in the 19<sup>th</sup> century after the Thomas-Gilchrist<sup>1</sup> process was invented. Iron ore was first removed manually (extraction and loading). When it was necessary, timber was put in place to support the ceiling.

The first mining operations were conducted where the seams outcrop and became deeper gradually, leaving support pillars of diverse shapes and sizes. The galleries were partially filled in with stacked blocks of barren material intended to support the hanging wall (Figure 2). This mining work was generally poorly understood. Its age and the work's amateur nature means there was no written or mapped trace of the work. Most of the mining work was underground. In some very small areas close to the outcrop, some open-pit mines were made.

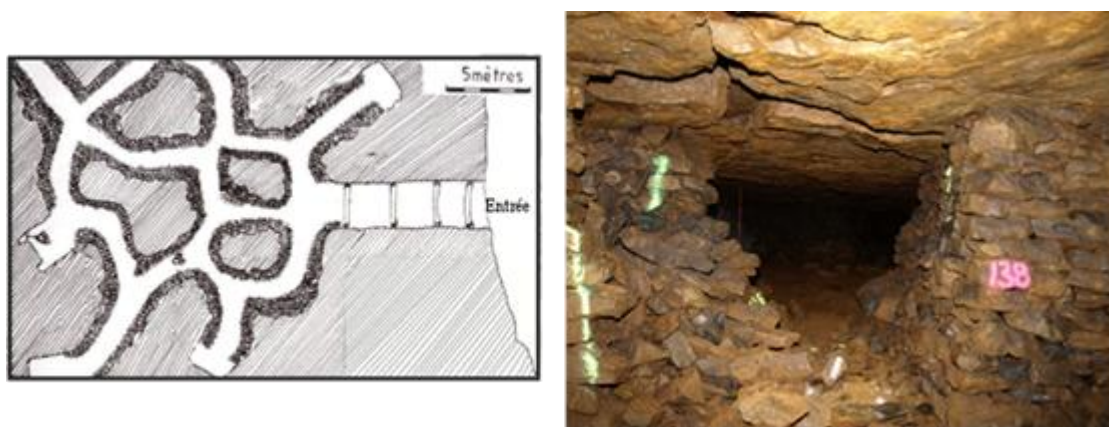


Figure 2: old mining methods (Dalstein, 1994; BRGM)

After the Second World War, mechanization developed progressively. Miners could bolt the roof. The last working mine in Lorraine closed in 1993.

Modern mining methods for Lorraine iron ore can be classified into two categories, depending on whether or not they leave underground voids:

- The most commonly used method in iron mines was the "abandoned room and pillar method" (Figure 3). This consists in digging galleries or rooms, usually 4-7 m long, separated by pillars of ore left in place. The pillars of ore left in place are various shapes (square, rectangular, trapezoid, etc.). They are generally between 2-7 meters tall, the same height as the thickness, and between 5-30 m wide. The abandoned pillars support everything above the pillars. The rooms made by extracting the material are left empty after mining. They sometimes represent a high volume. By using precise, correctly sized pillars, this technique guarantees, for a varying time period, ground stability, protecting the area above the mining structure.
- The method of complete pillar extraction, also called "caving room and pillar" mining, is similar to the "abandoned room and pillar" method in its first phase: rooms are dug and ore pillars are left. However, in a second phase, the pillars are made narrower then deliberately caved in (since narrower pillars are only stable for the short term) or by triggering (shooting pillars by blasting). This caving deliberately creates a subsidence bowl on the surface whose effects extend out from

<sup>1</sup> Ore dephosphorization process

the area where the pillars are removed underneath along an angle compared to the vertical. This technique was used in areas that presented no major challenges for protection on the surface.

More than three billions of tonnes of ore have been extracted from iron mines in Lorraine, which represents about 40,000 kilometres of galleries.

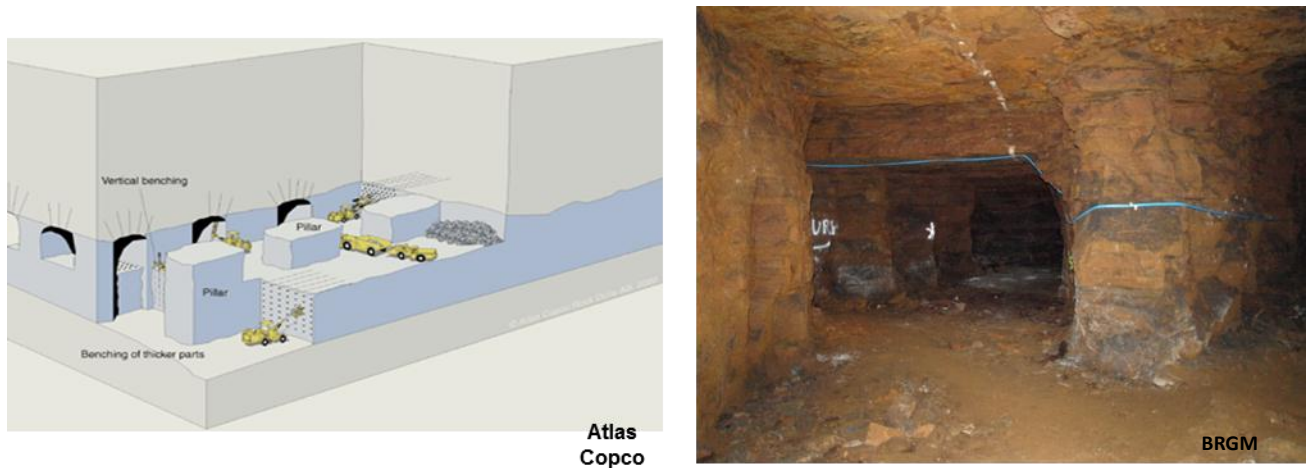


Figure 3: room and pillar mines

## 2.2. Phenomena feared for the Lorraine iron ore basin

The different mining methods used in the Lorraine iron ore basin may cause instability phenomena whose characteristics depend not only on the method itself but also on the depth of the work, the nature of the ore and the characteristics of the overburden.

### 2.2.1 Sink holes

For mining work near the surface, instability phenomena that can appear are sink holes, conical collapses a few meters in diameter. They result from progressive degradation of the hanging wall of a gallery that rises little by little in overlying strata until it breaks through the surface suddenly. Under the conditions of the Lorraine iron ore basin, sink holes cannot appear for voids located at a depth greater than 50 m. This limit value may be reduced in some cases by particular study of the area.

Moreover, iron ore mining caused more than 150 shafts to be sink. The end of mining meant a large number of these sites were abandoned. The wide variations in characteristics (diameter, depth or casing), and the record of sites that close over time, make shafts a potential risk for property and people.

Depending on the context, various scenarios may lead to collapse of the shaft head:

- either the shaft has not been back-filled and the casing ruptures then the shaft head collapses;
- or the shaft has been back-filled at the end of mining and cleaned i.e. back-filling materials are washed in the galleries communicating with the shaft. Now that it is void it has no more support for its casing, which breaks and will lead to the shaft head collapsing.

These instabilities may be related to the effects of a sink hole.

### 2.2.3 Progressive subsidence

Progressive subsidence results from the progressive ruin of pillars underground, sufficiently widespread for the effects to rise to the surface. It leads to a bowl appearing similar to those caused by deliberate pillar extraction. In the centre of the bowl, the ground drops vertically. On the inner edges of the bowl, signs of

compression appear (banks). The outer edges show signs of extension (cracks appearing). The kinetics of the bowl appearing on the surface vary from one subsidence to another but classically spread in one day for the fastest (Auboué-Coinville in 1996, Moutiers in 1997) to several months for the slowest (Roncourt in 1998, Angevillers in 2009). After this active phase, settling type movements can continue for several years, like those seen above pillar extraction.

#### **2.2.4 Sudden collapses**

In some cases, the mining structure is not destroyed progressively but we observe the sudden collapse of the entire ground between the underground and the surface. The surface then collapses dynamically in a few seconds. It is frequently accompanied by an earth tremor. Some have been recorded in Strasbourg and even one in Moscow (Roncourt in 1959). The suddenness of the underground collapse is shown by the air draft, whose effects can be devastating for the entire mine. Warning signs (cracks, signs of pressure and convergence) sometimes having allowed prior evacuation of sites, have often been obvious during the days before the collapse. However, the sites remain accessible, without major degradation before the phenomenon is triggered. On the surface open crevasses, up to 1 m wide according to witnesses, appear immediately around the collapsed area. By contrast with subsidence, sudden collapse is therefore a discontinuous phenomenon over time and space.

For a brutal collapse to occur, at least two conditions must be met:

- the underground structure must be very fragile (high levels of ore extraction, slender pillars): this constitutes the geometric criterion;
- a thick and strong bank must exist in the overlying strata. This bank, which protects the pillars from the weight of the ground breaking, triggers the collapse process. This is the geological criterion.

The phenomenon of sudden collapse may also occur in the presence of sub-surface cavities, characterized by large ceiling spans and small pillars subject to high stress.

Because of how fast it occurs (a few days) and the sudden manifestation, sudden collapse presents particular danger both during mining and after the mine has closed. This explains the substantial attention paid to developing a method, described below, that allows geological contexts to be classified to determine which mines would be likely to experience such a phenomenon.

#### **2.2.5 Subsidence and settling on stoping**

Until the start of the 2000s, pillar extractions were considered to lead to subsidence in ground that rose to the surface in the months that followed and that after a period of 5 years, no perceptible movement could be recorded (confirmed measurements taken at the surface). However, experience acquired in recent years questions this assumption: today it has been proven that in some circumstances pillar extraction does not lead to surface subsidence during mining operations, but that it may cause earth movements many years after the mining work.

Underground reconnaissance has shown that the old work that was manual or barely mechanized and indicated as having pillars removed on the plans, mining was not systematically continued up to shooting of the residual pillars. The potential effects of pillar extraction not having led to systematic ceiling subsidence is a function of the depth of the mine. For areas near the surface, the existence of a residual void may lead to the formation of a sink hole; the same is true for the rupture of an isolated residual pillar. For deeper areas, sink hole type phenomena are excluded, because the voids cannot reach the surface. However we cannot exclude the possibility that a set of close residual pillars, even confined by the ceiling immediately surrounding them collapsing, do not break progressively. On the surface this would mean slow, small subsidence.

For modern pillar extractions (mechanized mining) we assume that they did lead to caving and subsidence of the entire site. However the subsidence volume at the surface remains lower than the volume removed underground. The maximum subsidence in the centre of the bowl is only half of the void's height. This leads

to disbondments between banks that do not close completely apart from very deep mines. For modern, shallow pillar extractions, a large overload on the surface (large building, etc.) can therefore give rise to settlements of tens of meters.

### **2.2.6 Instability in open-pit mine faces**

After open-cast iron ore mining, unstable cliff faces may subsist. Phenomena such as falling rock, rock slides and slippage may occur. Nevertheless, these phenomena remain marginal in the Lorraine iron ore basin, because there are few open cast mines and they are small.

## **3 General context for post-mining in France**

In France, since the first mining laws in 1791 that set the principle that mines are the property of the nation, then the law in 1810 that founded current law, many evolutions have taken place, in particular for personnel safety, environmental monitoring, abandonment of mines, etc. With the end of mining in the large French mining basins that began in 1990 (coal mines in Nord Pas-de-Calais and the iron mines in Lorraine) the "Post-mining" era began.

Major problems (subsidence, sink holes) that occurred in the Lorraine iron ore basin and affected the safety of persons and property in some cases led France to develop a mining risk management policy.

The law that structures former mine sites was enacted in 1999. It integrated the notion of mine abandonment and mining risk management. It initiated the possibility of a Mining Risk Prevention Plan for town planning, information methods and recognizes that major risks may occur. The state becomes a guarantor for damage caused by the activity of the mine operator when it stops mining or defaults. The Mining Code therefore gives French authorities major operational responsibilities.

Currently, administrative and sovereign control is managed by State Departments and in particular the Ministry of Ecology, Sustainable Development and Energy and its Regional Division (DREAL). Mining expertise is outsourced to an independent entity, GEODERIS, (a French "*Groupement d'Intérêt Publique* [Public Interest Group]" between BRGM and INERIS). BRGM's Department of Prevention and Mine Safety is responsible for safety and operational management of facilities and safety equipment. To complete this approach a scientific interest group (GISOS) with several partners researches in this area.

## **4 Managing future risk**

Subsidence occurring in the iron ore basin between 1996 and 1998 made the authorities take note that these former mines could cause major problems and that it was necessary to assess potential public safety risks. This task was given to GEODERIS.

The considerable extent of the Lorraine iron ore basin, the importance and multiplicity of the identified hazards and the surface challenges meant that a specific hazard assessment methodology had to be defined and put in place. This is how an approach based on the retro-analysis of past events was defined, validated by a Committee of Experts and common to all of the one hundred and twenty towns in the basin.

The hazard maps established are used as base documents for town planning authorities.

### **4.1 Assessing mining hazards**

#### **4.1.1. Information phase**

A first step in assessing mining hazards consists in an information phase. As much data as possible (reports, maps, etc.) is collected on mining activity. This step is crucial since it shapes the rest of the studies. The goal of this research phase is to inventory the state of understanding about the site at the start of the study. It is carried out in two phases.

Document search: in a first phase, the data was collected from concession abandonment or end of work dossiers (DADT) filed at DREAL Lorraine by the mining companies and that contained drawings of the mines that were precise enough (scale 1/5000) to undertake the hazard analysis. However, after having discovered incoherence between the information on the drawings and observations made on the ground, extra research was conducted in departmental archives and mining company archives to find additional information.

Field research: surface reconnaissance to find a maximum of sites that reached the surface (extraction or aeration shafts, access galleries, etc.). Geographic coordinates are taken using GPS and are used to match the underground drawings with the surface features. If the worked areas cannot be found, for shafts that have been filled without traces remaining on the surface, or because of an infrastructure or building that has been constructed on the site, the coordinates stated on the abandonment dossiers are recorded. This step has a twofold objective, since firstly it means that existing mines can be inventoried to assess the associated hazard, and secondly that reference points can be determined, common to the underground drawings and mapping supports (Scan25, Bd Ortho), that are then used to position mining works in relation with surface data.

This information-gathering phase leads to an information map being created that includes all the important information necessary for understanding mining work and assessing hazards.

#### **4.1.2. Determining hazards**

The hazard assessment used a global method to analyse the underground drawings collected during the information phase. This was developed by a committee of experts based on a retro-analysis of past events that occurred in the iron ore basin. The main steps in this method are listed here:

##### Determining and characterizing "homogeneous" areas:

In this step, areas called "homogeneous" in light of a certain number of geological, geotechnical and exploitation criteria have been identified. This analysis was conducted for each seam mined and each interseam.

The natural and mining characteristics of each area identified were then determined from mine drawings and documents on each mine. For each homogeneous area, the following parameters were recorded and/or calculated: gallery size, ore removal percentage, minimum and maximum depths in the area, the size of the seam mined, the presence of adjacent faults or pillar extractions, etc.

Out of the 24,000 hectares concerned, more than 4000 homogeneous areas were identified. All of the data collected is in a database (LorFer) that is integrated in a geographic information system.

##### Hazard assessment for rupture in the mining structure

For each homogeneous area, characteristics are analysed with a view to estimating the predisposition of the mining structure for ruin. According to the nature of the work and the type of hazard that could occur, several criteria are selected.

For room and pillar mines, the stability of pillars is assessed according to the tributary area method. In the past, the long-term resistance of iron ore was assessed. It uses data acquired throughout the mining period and feedback on experience from previous subsidence. It also takes into account ore ageing. From this the following were selected as areas having risk of progressive subsidence: for a single-seam mine, areas with stress greater than 75 bars and for each interseam in a multiple-seam mine, thicknesses less than 7 m.

In a second phase, subsidence and collapse were separated. Analysis of feedback from experience with configurations that lead to subsidence or collapse occurring confirms a difference in the progression mechanisms for these two phenomena. The purpose of this approach was therefore, on the basis of the available information, to define quantitative criteria that exclude a sudden collapse being triggered for a mined area that is judged to be potentially unstable. Therefore two criteria have been defined: one geometric criterion (Figure 4), which illustrates the fragility of mining sites (high level of ore removal,



slender pillars, poor mine superimposition, etc.) and one geological criterion, which characterizes the presence of a steep, thick and strong bank in the overburden.

In a first stage, all of the areas less than 50 m from the surface were selected as sink hole hazards.

Areas with caving prior to 1945 (start of mechanisation in the iron ore basin) were selected as sink hole or subsidence hazards depending on the depth.

A sink hole hazard was identified on shafts that have not been made safe according to the rules of the art.

Finally, open cast mines were selected as having unstable mine faces.

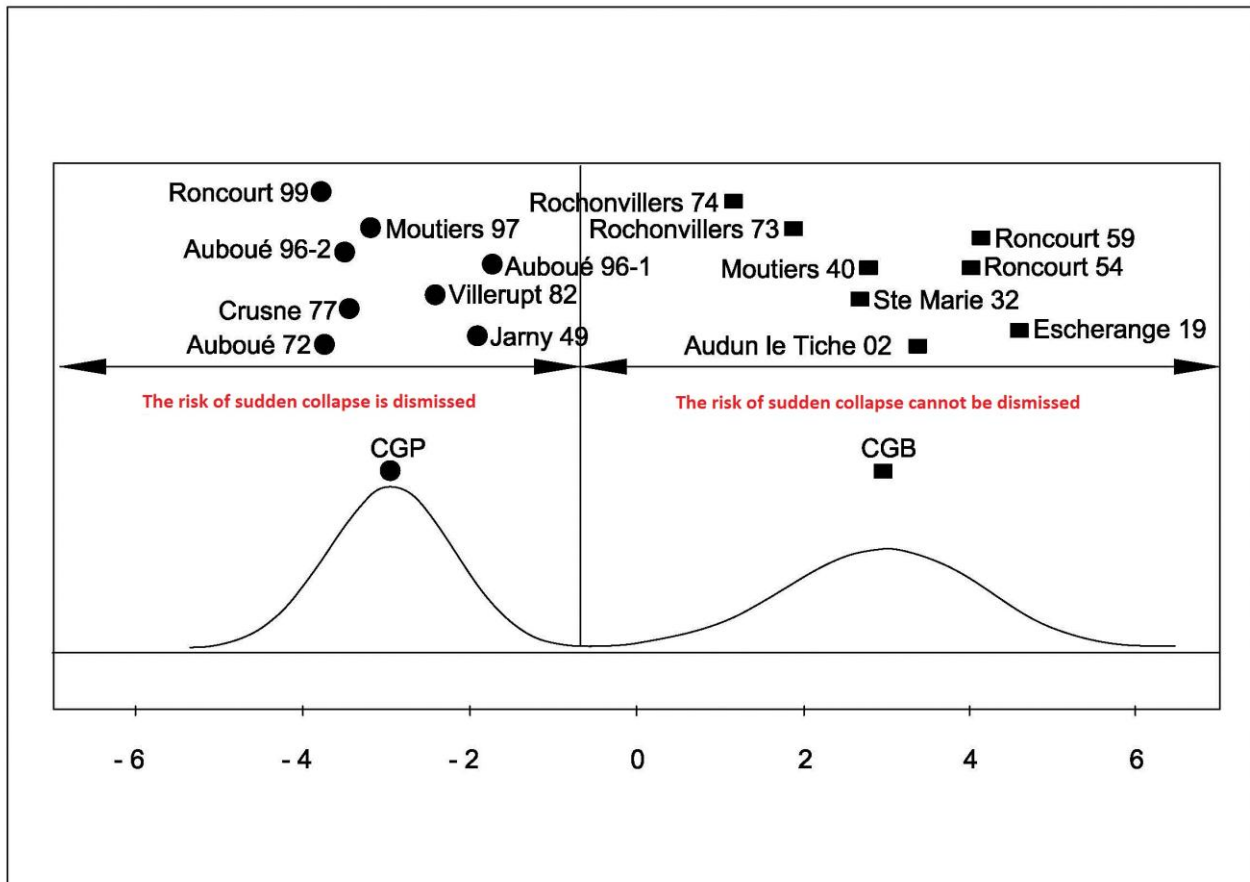


Figure 4: showing a purely geometric criterion,  $f$ , discriminant analysis of 16 separate progressive subsidence events that occurred in Lorraine (on the left) and sudden collapses (on the right). X-axis: the discriminant function  $f$  is graduated from -6 to +6. Y-axis: the probabilities of the value of the discriminant function  $f$  (CGP and CGB are the centres of gravity for the two families) (Josien, 2010). On the left the risk of sudden collapse is dismissed, on the right the risk of sudden collapse cannot be dismissed.

Characterizing the hazard

After having identified the potential hazard areas, the hazard in each area is characterized: this is principally to determine the parameters of subsidence bowls, to assess the risk of sudden collapse for the room and pillar areas selected and to determine the safety radius around the shafts. No specific studies are done first, particularly for areas that can be affected by sink holes. For sudden collapse, only the geometric criterion is studied in the first phase. The geological criteria were assessed in a second phase, only on the areas that presented surface concerns.

### Summarizing and mapping hazards

After the analysis conducted as described previously, a hazards map can be created for the sector. (Figure 5)

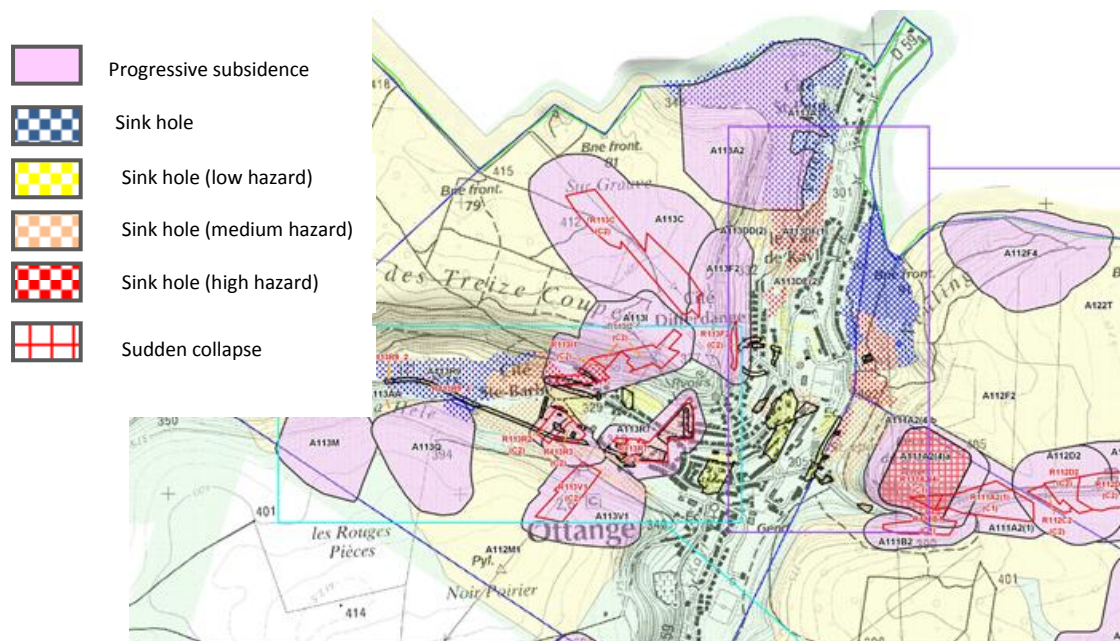


Figure 5: extract from the hazardous ground movement map for the town of Ottange (57) (GEODERIS, 2009)

## 4.2 Managing future risk: the plan for preventing mining risks

The hazards map localizes and ranks the areas affected by potential phenomena. The hazards are classified by several levels, taking account of the nature of the phenomena, if possible the predisposition that they may occur, and their intensity. It does not include the nature of the surface occupation. It converts the forward potential for hazards or harm that the former mining activity may cause objectively, in the sector studied.

The hazard maps should be taken into account for town planning documents to limit new risks caused by new challenges appearing. More restrictive than for developing local town planning documents, mining risk prevention plans (PPRM) have been instituted by the legislator to, among other things, be able to make building permits subject to requirements to prevent damage that could affect construction in case of accidents or mine subsidence. This being the case, above this size, the PPRM and town planning documents make the areas in which no reasonable requirements can be set unsuitable for construction to ensure the safety of persons and property.

Mining risk prevention plans (PPRM) implemented by French authorities pursuant to the law dated 30 March 1999 (art. 94 of the Mining Code), define the areas exposed to mining hazards, taking account of the nature and intensity of the risks. They also establish land-use and town-planning rules.

The phenomena taken into account in them are in particular ground movements, flooding, hazardous gas fumes, land and water pollution.

When mining hazards are known and classified, a PPRM is developed in five phases:

- the Prefecture sets a perimeter where the mining hazards extend or are repeated (since this perimeter may include several towns);
- the instructing department creates it (French *Direction Départementale des Territoires* DDT, supported by DREAL under the prior definition, and which makes the hazard maps available);
- consultation with the towns affected and other departments;

- public survey in the towns affected;
- plan approved by Prefectural decree.

In the Lorraine region, 165 towns are affected by mining hazards and for these, 21 PPRM have been issued for 71 towns.

## 5 Managing current risk

### 5.1 Risk assessment

After having characterized and mapped the hazards, surface risks are analysed to define at-risk areas. This involves identifying the risks located in line with hazard areas. The risk level is obtained by factoring the hazard level and the vulnerability of the challenge, i.e. the severity of the consequences should the hazard occur.

For progressive subsidence hazards, a multi-criteria analysis was conducted, with a view to ranking all of the areas having vulnerable sites determined previously. This ranking takes into account the characteristics of the subsidence bowl (deformation, subsidence amplitude, etc.) and the vulnerability of the site. The site's vulnerability was estimated as a first analysis by a qualitative criterion with five classes (town, village or with area with long buildings and apartment buildings, terraced houses, housing developments or isolated houses, commercial areas) taking account of both population density and sensitivity of buildings to subsidence. From this methodology risk areas can be classified into four classes. Out of the thousands of progressive subsidence hazard areas identified in the iron ore basin, about 370 have buildings on the surface.

For areas at risk of sink holes, taking account of the large extent of shallow areas, the first decision was to define a hazard for all sites at less than fifty meters deep. However, for the sectors where the surface is built up, it was necessary to specify the sink hole hazard. To do this, we had to understand the mines' precise characteristics (height and width of galleries, height and nature of the overlying strata, exact position of shafts). During the first phase of study, this information was not always available. An "underground" reconnaissance was then conducted. Two sorts of investigations were conducted, depending on whether the sites were accessible or not. For the accessible areas, each gallery was visited, the site's state and the geometric characteristics of the galleries (width, height) were recorded as were any instabilities that were observed (start of sink holes, ceiling falling, cracked pillars, etc.). The sites were also surveyed and precise positioning compared to the surface determined.

For inaccessible areas, either because of submergence or because of access problems (walled-off galleries, ceiling falls blocking access, pillar extraction, presence of harmful gases, etc.), sites were drilled into from the surface. This can provide two types of information: when drilling led to a cavity, a tube was inserted to allow a laser or sonar analysis instrument to pass through. Sometimes drilling did not lead to a clearly identified void. In this case, analysis of parameters recorded confirmed that the sector has had its pillars extracted. The operating method to determine the drilling location enables for sure not to drill into a pillar and therefore removes the risk of not detecting the searched cavity.

Once all these operations are complete, the sink hole risk can be studied more carefully and the risk can be assessed on the basis of the vulnerability of whatever is present at the surface. Of about 1800 areas of sink hole hazards identified, 292 have a built up surface (2013 data).

### 5.2 Risk management

The goal of the current risk management policy in France is to preserve the safety of persons.

Risks can be treated by three different means:

- eliminate the challenges;
- remove the hazard by strengthening or filling the cavity;

- monitoring.

France has delegated operational management for risks related to former mines to BRGM (monitoring and treatment).

### 5.2.1. Monitoring

The evaluation of mining hazards, particularly ground movement phenomena, does not enable an occurrence date for instability to be defined. The purpose of implementing monitoring suited to the risk is to monitor change in a phenomenon and to be warned if it is imminent. Therefore monitoring reduces the risk by taking account of the requirements to limit the effects of the phenomenon at the surface and to ensure protection of persons and property.

Monitoring is therefore put in place either while waiting for the risk to be actively dealt with or as a substitute for dealing with the risk. It also means that the phenomenon can be followed to help plan active treatments over time.

Given the large number of hazard areas identified in the Lorraine iron ore basin, it seems difficult to eliminate all the challenges i.e. all the hazards. For hazards that present no imminent danger for people, monitoring is preferred.

In the case of progressive subsidence, microseismic monitoring probes have been developed. This is a microseismic listening technique for noise emitted while mining work is stopped. The purpose is to detect precursor signs for subsidence before it becomes visible. This technique (Figure 6) is suitable for monitoring inaccessible or hazardous mine sites. Currently, about fifty of the built up areas are covered by microseismic monitoring. About 370 progressive subsidence risk areas are identified with built up areas above them on the Lorraine iron ore basin, representing a little more than 1700 hectares.

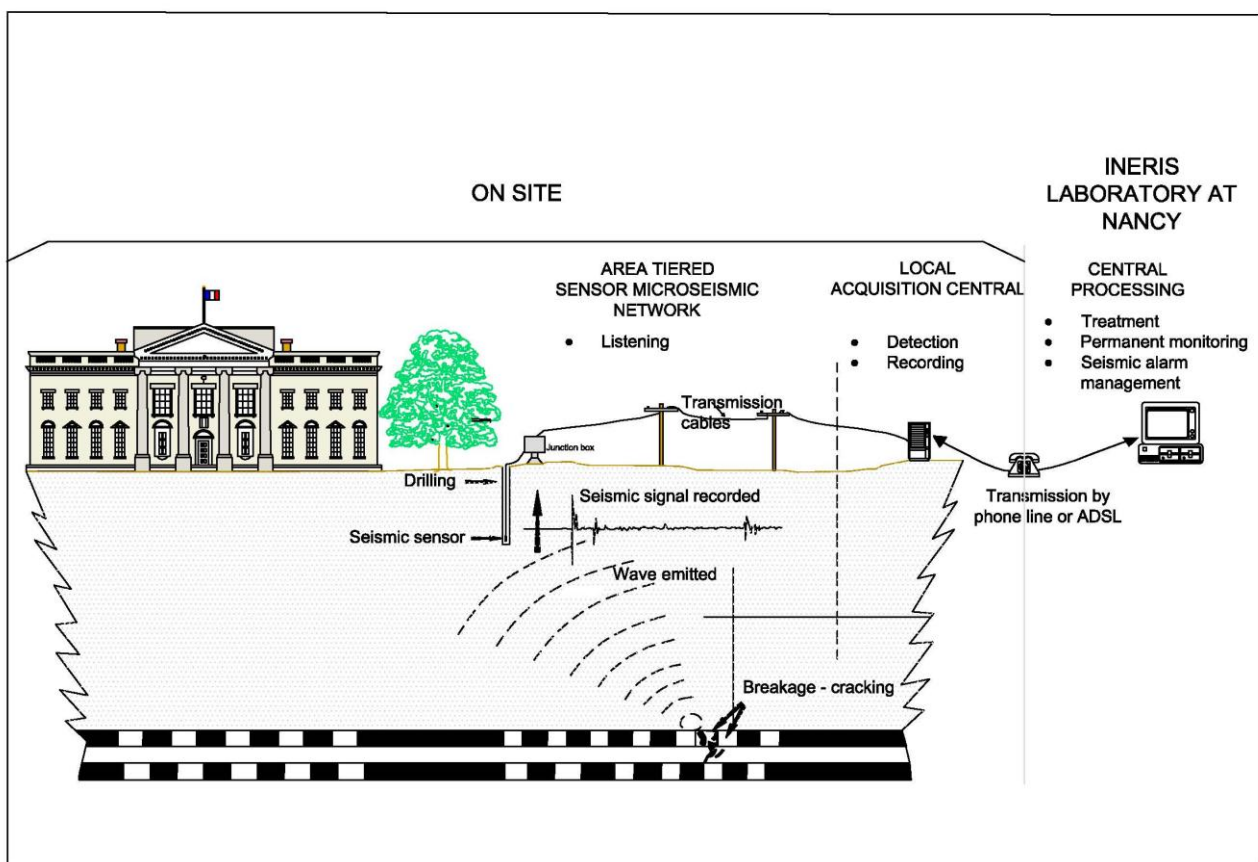


Figure 6: principle of microseismic monitoring (Bennani, 2004)

On the surface sink holes are characterized by the sudden creation of a crater. But this appears and changes slowly underground. The phenomenon can be anticipated by regular monitoring of underground work. When mining work is accessible from underground, it is monitored by visual inspection of the risk area, with particular care taken in sectors located under housing (Figure 7). The frequency of inspections is defined by the degradation of mine sites and generally varies between every one and three years. If change is observed, the frequency may be increased.

When the areas to monitor are not accessible underground, 3D imaging of galleries is used, by laser or sonar via drilling. In addition, video footage and photographs are taken. Monitoring frequencies are set according to the same criteria as for underground inspections.



**Figure 7: visit underground of an area at risk for sink holes (BRGM)**

For the risk of sudden collapse, which is a real danger and difficult for people to predict, monitoring cannot be the long-term solution. Two solutions are therefore being considered: cavity treatment or population expropriation. Regardless of the solution chosen, the period before implementation can be long. And so as not to leave the populations under the threat of such instability, provisional monitoring is considered. This takes account of the depth of the mine, the state of pillar fracturation and mine accessibility. Microseismic monitoring, acoustic auscultation or video monitoring may be used.

### **5.2.2 Removing risk: expropriation of challenges or treatment of mine voids**

When monitoring does not make it possible to control the risk, solutions to treat the risk must be considered.

Article L. 174-6 of the Mining Code sets out that "if mining risks seriously threaten the safety of persons, property exposed to this risk can be expropriated by the State [French authorities], under the conditions set out by the expropriation code for the cause of public utility, when means of safeguarding and protecting populations are more expensive than expropriation".

Accordingly, in such cases, a technical and economic study on filling and in parallel an assessment of the cost of expropriation are conducted. The State then decides on the best solution on the basis of the assessments.

In the Lorraine iron ore basin, six areas at risk of sudden collapse have been expropriated, regarding 113 families in two towns. Only one risk area was filled. It is located in Thil. Mine sites were filled by a flow of fly ash and cement over an area of 26 hectares and affecting 26 families.

Currently, no area at risk of sink holes has been expropriated. A dozen areas at risk of sink holes have been filled, representing about 0.5 hectares. Generally, filling is from the surface from drill holes by injecting concrete (Figure 8). Beforehand, barriers are set up to make the area inaccessible. They are made underground (concrete walls) or by injection from the surface. One area was treated by sand injections (Cité Curel in Moyeuvre-Grande in 1999). This method was chosen because the mine sites were underwater.



Figure 8: injection into the cavity in Franchepré in Moyeuvre-Grande (57)

## 6 Conclusions

Following the stoppage of iron mining operations in Lorraine and the appearance of very serious problems putting people's safety at risk, France has implemented a set of regulatory, technical and organizational measures including:

- developing a method for identifying and assessing hazards and risks suited to the iron ore basin;
- implementing a policy for preventing mining risks integrating requirements for town planning, including, if need be, creation of a PPRM.
- Developing monitoring methods suited to each risk type
- implementing protective measures affecting the safety of persons and property in some cases, including treatment and expropriation.

To implement this global policy, France has relied on its mining expert body GEODERIS, and BRGM, which has operational management in former mine sites.

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