SALT-INDUCED GROUND MOVEMENTS IN LORRAINE, FRANCE

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Summary: This article uses examples to describe the typology of salt-induced ground movements in Lorraine, France, over two centuries of salt production. This typology, which distinguishes between settling, sinking (at differing rates) and localised and generalised collapse, represents one of the tools to be used to draw up maps of areas exposed at risk of ground movement in salt-bearing areas.

1. Introduction

Lorraine, a region located in northeast France, is the country's largest salt production area, with three salt basins: the Dieuze basin, the place where rock salt was discovered in France in 1819, the Sarralbe basin and the Nancy basin (Figure 1). Only the Nancy basin is still in production.

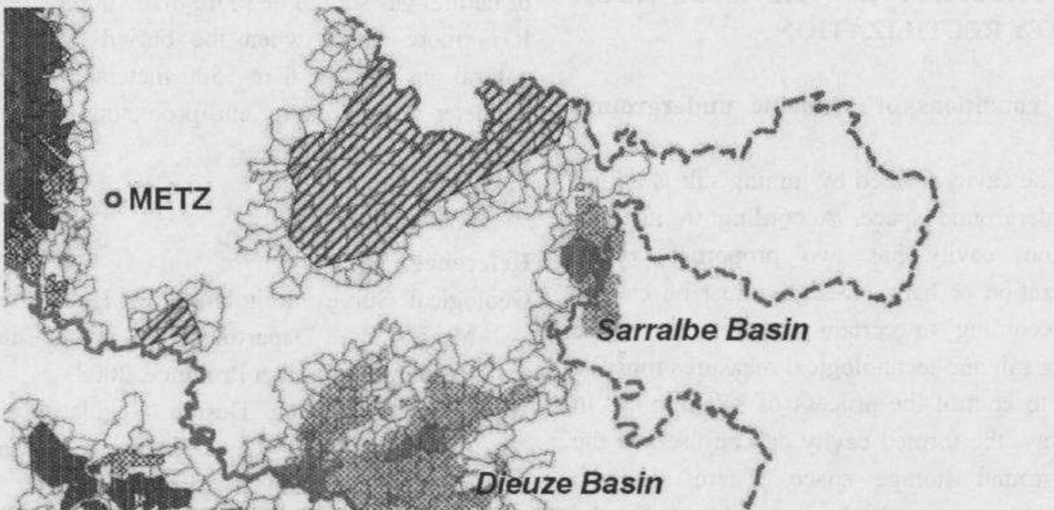

Figure 1. Map of salt basins in Lorraine (in green; areas in red and blue correspond to the coal basin and the iron basin respectively).

The salt produced is bedded salt belonging to the Middle Muschelkalk in the Sarralbe basin and to the Lower Keuper in the other two basins. Figure 2 shows a simplified geological cross-section of Lower Keuper in Lorraine and of the terrain above it in the areas where salt is produced (depth of extraction does not exceed 250 m). It will be noted that apart from the stiff layer of Beaumont Dolomite, located in the Middle Keuper, the terrain above the salt formation is fairly soft.

AGE		FORMATION	THICKNESS			LITHOLOGY
LIAS		Promicroceras Clay	~25 m	~30 m		Mudstone
		Gryphaea Limestone	~15 m			Marl and Limestone
UPPER KEUPER	Rhetian	Levallois Clay	~10 m			Mudstone
		Rhetian Sandstone	~20 m			Fine-grained Sandstone, Siltstone
	"Marnes Irisées Supérieures"	Upper Variegated Clay	25 to 35 m	40 to 45 m		Mudstone (+ Limestone, Dolomite, Gypsum)
		Chanville Clay	10 to 15 m			Mudstone (+Dolomite, Gypsum)
MIDDLE KEUPER "Marnes Irisées Moyennes"		Beaumont Dolomite	5 (to 10 m)	20 to 30 m		Dolomite (Top : Anhydrite)
		Middle Variegated Clay	~5 m			Mudstone
		Reed Sandstone	~10 m			Fine-grained clayey Sandstone or Mudstone
LOWER KEUPER "Marnes Irisées Inférieures" (Lower Variagated Clay)		Anhydrite Marl / Estheria Layer	5 to 20 m	30 to 50 m		Mudstone (+ Anhydrite, Dolomite, Gypsum)
		1st unit	20 to 40 m	100 to 150 m	Salt-bearing formation	80% Salt +Mudstone, (Anhydrite)
		2nd unit	~25 m			40% Salt, + Mudstone, (Anhydrite)
		3rd unit	~25 m			60% Salt +Mudstone, (Anhydrite)
		4th unit	~25 m			Mudstone, little Salt, (Anhydrite)
		5th unit	~30 m			50% Salt +Mudstone, (Anhydrite)
		Pseudomorphoses Sandstone	~25 m			Mudstone (+Dolomite, Anhydrite)
LETTENKOHLE		Upper Dolomite	2 to 5 m			Dolomite

Figure 2. Geological profile of Lorraine Keuper

Industrial salt production began since its discovery, initially using traditional mines. Five mines were opened: Vic-sur-Seille and Dieuze mines in the Dieuze basin; and the Saint-Nicolas, Rosières-aux-Salines and Einville mines in the Nancy basin. The Saint-Nicolas and Rosières mines were subsequently merged to create the Varangéville mine, still in production, which has a production capacity of 600,000 tonnes per year. Pumping of brine at the salt roof developed in the second half of the 19th century. Apart from very locally, this was abandoned for good in the 1960s, giving way to modern methods of solution mining. Current production of salt through solution mining in the Nancy basin is in the region of 3 million tonnes/year.

Salt production often causes ground movements and these ground movements may continue or occur long after the end of production. Lorraine is no exception to this rule.

Optimum use of former salt production areas requires an evaluation of ground movements which could occur in the future. To obtain the resources to map the 'ground movements' hazard resulting from salt in Lorraine, GEODERIS has created an inventory of types of ground movement caused by salt in Lorraine, based on a historical study of salt production and related incidents or accidents.

This article presents this inventory, using as a basis the typology used in France for mining hazard maps (*PPRM : "Plans de Prévention des Risques Miniers"*). This typology distinguishes between settling, sinking, local collapse and global collapse. A specific paragraph is devoted to each of these types of ground movement.

2. Settling

Settling designates a slow movement of the ground, resulting not from the extraction or dissolution of material but from the compaction of a soft massif (heap of granular material) or affected by underground works (caved terrains).

There is only one known case of settling in Lorraine: the progressive compaction of backfill, undoubtedly due to the effect of its own weight, poured into craters created on the surface by the collapse of salt caverns. This type of movement is illustrated by Figure 3.

Figure 3. Settling of backfill of a crater created by the collapse of a solution mining cavern. Nancy basin

3. Sinking

Sinking is a slow movement of the ground, progressive and flexible, originating in underground works and causing the formation of a depression trough whose edges are marked by a lack of significant rupture. The dimensions of this depression may be very variable, as we shall see.

3.1. Sinking due to solution mining

Sinking in salt-bearing areas is due mostly to dissolution of salt at the top of the salt formation.
This dissolution may be natural and may result in the presence, at the top of the salt, of brine constituting what is normally referred to as salty aquifer. In this case, the phenomenon is geological in nature and the removal of the salt, and the sinking this causes, are generally imperceptible on a human level.

The first salt production using wells in Lorraine was developed from the 1870s. It consisted of removing brine by pumping from existing salty aquifer, a practice called wild brining. This removal had the effect of activating circulation of the salty aquifer and thus led to dissolution and sinking.
However, in the Dieuze basin, this type of production did not lead to any perceptible surface movement. This is explained by the fact that material removed (30,000 tonnes of salt/year at the most) has never exceeded the natural production of the salty aquifer, estimated to be 50,000 tonnes/year. As a result, the material removed has never attracted fresh water to vicinity of the wells. Dissolution occurred in the areas where fresh water entered the salty aquifer, far from the area exploited, and affected such a large surface area that it was manifested by very slight ground movements (Feuga, 2004).
This was not the case in the Nancy and Sarralbe basins where, with greater amounts of brine removed than could be provided by the salty aquifer, fresh water from shallow aquifers was attracted to the base of the wells. This fresh water circulated between the terrain and the casing which was not cemented to the ground. Thus a solution cavern was created in the salt around the well, and this ultimately crumbled (Figure 4). It must be noted that this cavity could only affect the area immediately surrounding the well. In fact, fresh water and brine do not mix in subsoil. As brine is denser than fresh water, fresh water has a tendency to float above the brine, meaning that dissolution tends to spread horizontally rather than vertically.

The emergence of a sink resulting from crumbling of the cavity created and the size of this sink was clearly related to the thickness and strength of terrain above the salt.
The amplitude of sinks of this type could greatly exceed one metre. The observations we might make today on sites over a century old reveal that the diameter of the collapse sink could reach 10 m (Figure 5). This size limit was certainly not the result of the existence of a physical limit to the mechanism of dissolution of the salt but, more probably, due to the fact that after a limited number of collapses, repairs to the casing became impossible and the well was simply abandoned.

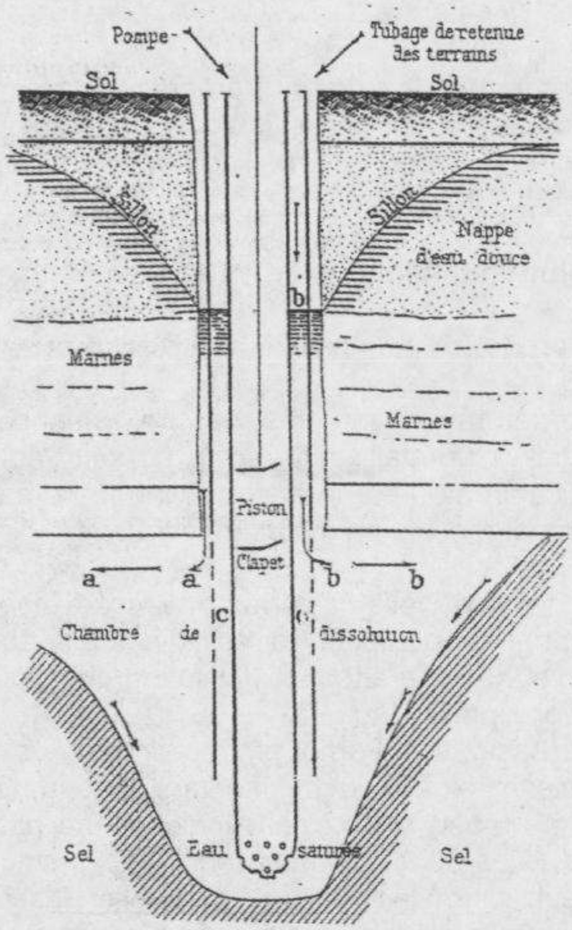

Figure 4. Production of brine by pumping at the top of the salt with the formation of a dissolution cavity at the base of the well (excerpt from Bailly, 1904)

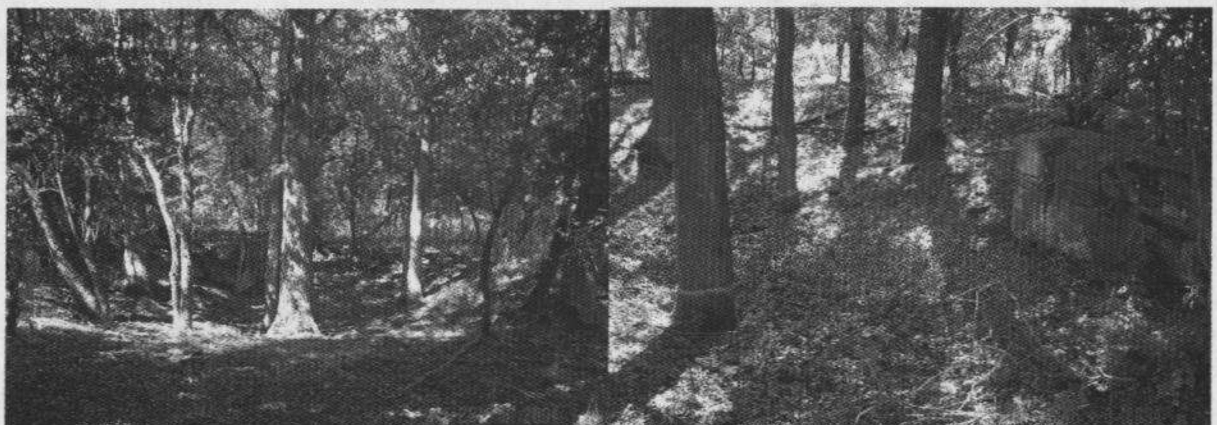

Figure 5. Collapse sink around a former well to extract brine from the salty aquifer, Nancy basin

Dissolution caused by drawing off brine at the top of the salt was not always limited to the area immediately surrounding the wells but could affect a large area. In this case, if the terrain covering the salt (overburden) was sufficiently flexible, it would cave in at the rate of the removal of the salt. A large surface area could be affected, as seen in Figure 6.

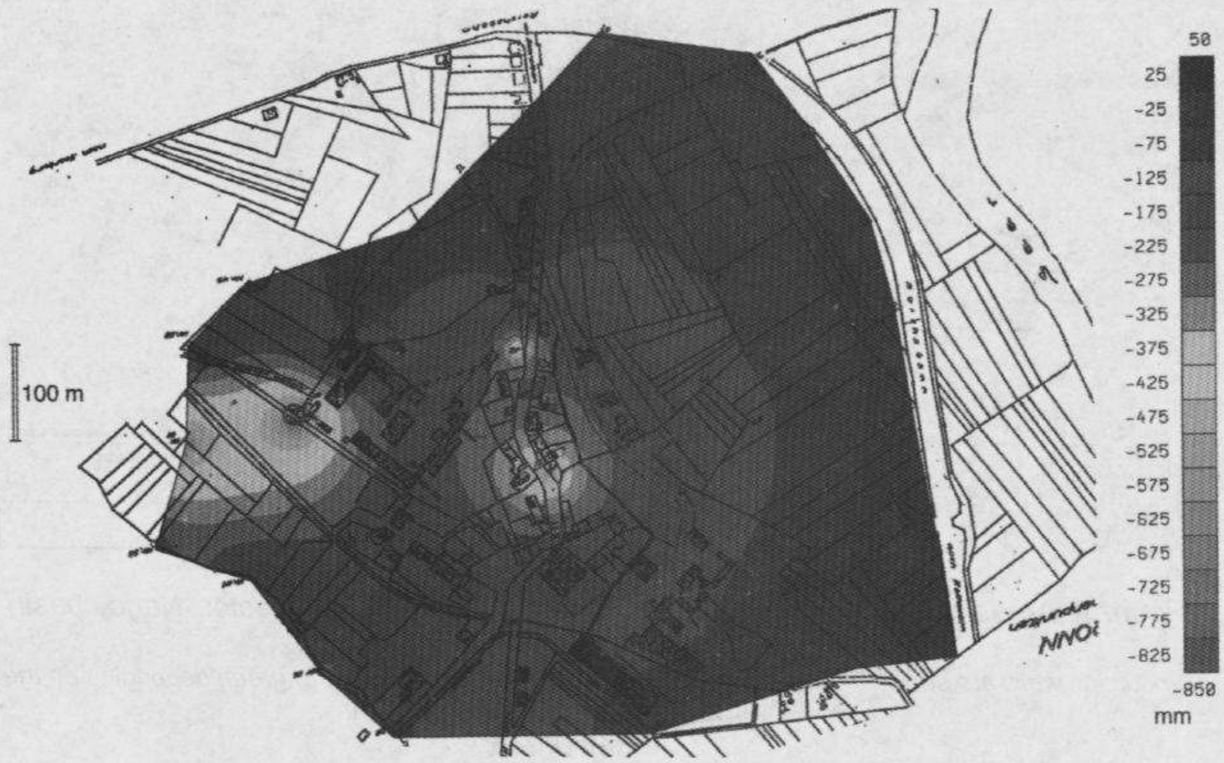

Figure 6. Example of large collapse sink resulting from pumping brine at the top of the salt, Sarralbe basin (CSME– École des Mines de Paris document)

Regarding the speed of sinking, one might refer to the example currently being measured in the only area still practising this method of production in Lorraine: Very locally, this reaches 50 mm/year, with annual production just above 20,000 tonnes of salt.

Distribution in sink troughs depended upon the location of wells, the quantity of brine removed from each of them, the nature of overburden and the relative content of salt, depending upon the place, at the top of the salt formation exposed to dissolution. As a result, this could be very irregular, as demonstrated by Figure 7.

The stiff and continuous layer constituted by Beaumont Dolomite, located in the overburden around 60 metres above the salt is, as a result of erosion, rarely present in the lower regions where former production in the Nancy basin was concentrated. In the few areas in which it is present, brine production by pumping at the top of the salt could cause a much faster type of ground movement than the ones just mentioned. In this case, this stiff layer might not weaken at the same rate as the removal of salt. A void which was relatively shallow but over a large area could therefore develop beneath this layer until, once a maximum limit had been reached, it broke suddenly on the periphery of the void, the terrain above it falling with it. Only one case of this type has been heard of in Lorraine. It affected the former Art-sur-Meurthe saltworks in

the Nancy basin. On 9 November 1876, at 15:00 hours, the soil at the saltworks began to sink without breaking and in a regular fashion, making an ellipse of 140 x 170 m, stabilising at around 22:00. The movement covered a depth of 0.80 m at the centre of the sunken area.
Figure 8 provides a historical picture of the event.

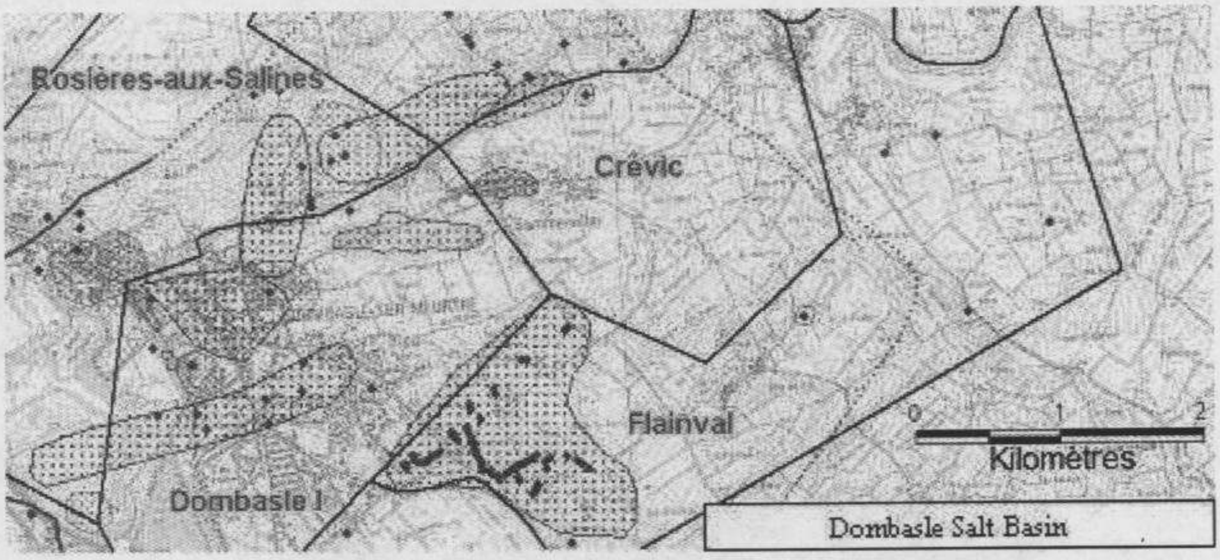

Figure 7. Areas of historic sinking in the Dombasle-sur-Meurthe sector, Nancy basin (INERIS document).

Production wells are shown in red. Areas of sinking are shown in blue, red or green depending on the source of information.

Figure 8. Representation of the area affected by the rapid sink on 9 November 1876 at the Art-sur-Meurthe saltworks (DRIRE archives, Lorraine)

The reason that the rupture of Beaumont Dolomite caused not a sudden collapse but a sinking of the soil surface was rightly imputed by the *Service des Mines* (the French Department of Mines) at that time to the fact that this layer lay upon a 'great mass of water, which had no egress other than via two very narrow wells'. The Beaumont Dolomite sheared off on the periphery of the solution mining cavern but without fragmenting, the much less resistant overlying marly layers followed the movement and the section as a whole worked like a piston, expelling the water through the wells. It was the presence of water, or rather brine, in the Art-sur-Meurthe solution mining cavern which explains why a failure mechanism which, in other contexts, could have caused a sudden collapse of the soil surface, caused a less sudden movement above this cavity, a movement which might be termed 'rapid sinking'.

The experience showed that in Lorraine, in the vast majority of cases, sinking linked to brine pumping at the top of the salt decreased rapidly before disappearing completely in the few years following the cessation of pumping. In some cases, however, residual sinking has occurred a very long time after the cessation of pumping. Although the salty aquifer may return to natural functioning after extraction has ceased, and in this sense is determined by factors no longer linked to human activity, and although it may appear that the quantity of salt dissolved annually returns after production to a level comparable to the level before production, it does not return to its original condition. The underground environment has in effect been changed by production. As a result, the 'natural' functioning of the salty aquifer may involve, locally, dissolution and thus sinking which cannot be compared to any dissolution and sinking which occurred prior to production. Thus in the Nancy basin there are several fairly large areas continuing to experience significant sinking, reaching up to 30 mm/year, several decades after the end of removal of brine from the salty aquifer (Figures 9 and 10).

Figure 9. Area of active sinking, Nancy basin (INERIS document)

Production by pumping brine at the top of the salt gradually gave way to solution mining of the salt formation in Lorraine as elsewhere. This development occurred mainly between the beginning of the 20th century and the 1960s. At the same time as this technological change, production, in the Nancy basin, gradually abandoned the highly populated valleys of rivers Meurthe and Sânon, moving further north to the Haraucourt plateau. The great difference between these two contexts, apart from the greater depth of salt beneath the plateau (over 200 m) compared with that beneath the valleys (50 to 100 m) is that the stiff and resistant layer of Beaumont Dolomite, generally absent from valleys, is omnipresent beneath the plateau. Salt-extraction companies exploited the first three units of salt there, creating cavities with a height of up to 60 metres if you take account of the insoluble matter deposited at their base.

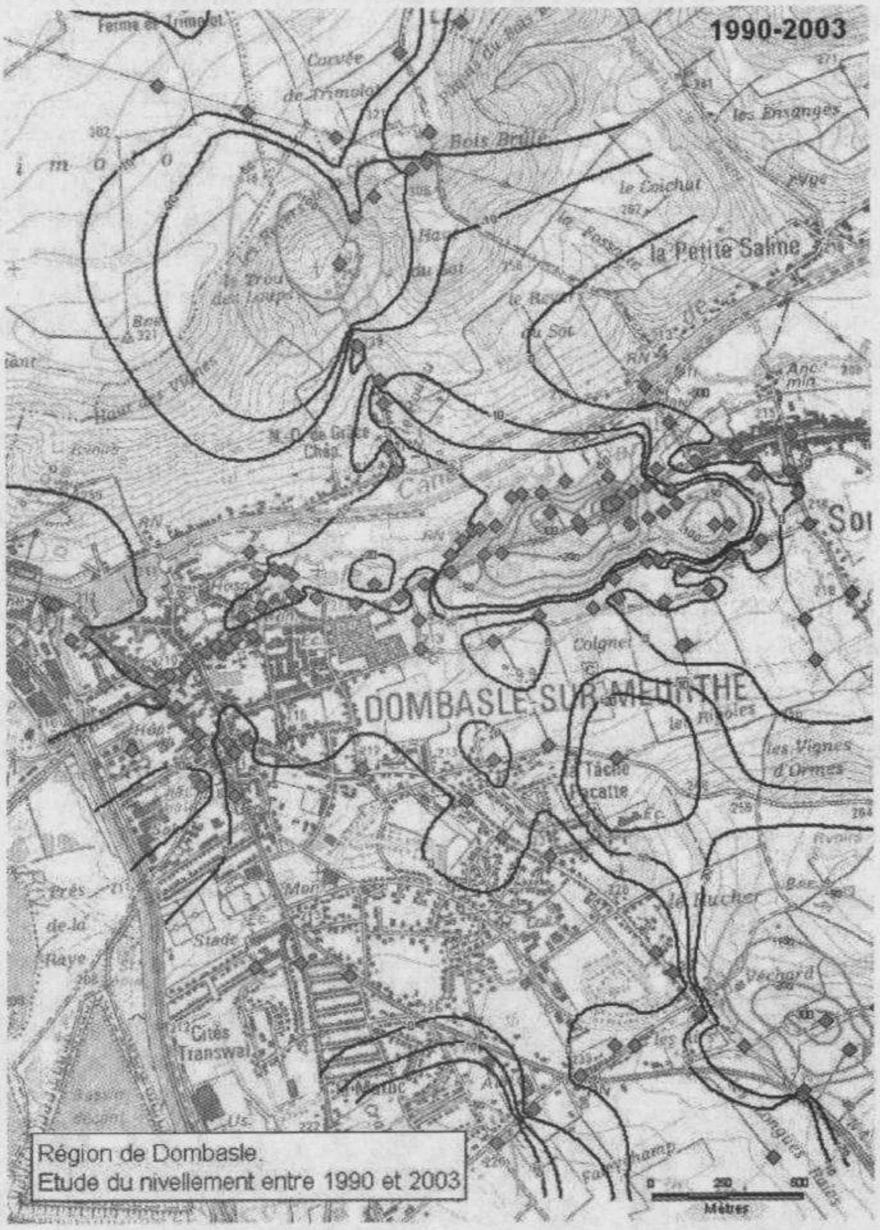

Figure 10. Sinking (in mm) in the Dombasle region (Nancy basin) between 1990 and 2003 (INERIS document)

Exploitation ceased in this area in the early 1960s. The green squares represent bench marks.

A protective layer of salt 5 to 10 m in thickness remains at the top of the cavities, to prevent any stoping of the marl overburden, which is much less resistant than salt. In these conditions, calculations show, and experience confirms, that cavities of a diameter of up to 80 m are stable over the long term. Such cavities cause a slight sinking of the soil surface, inherent in the operating methods and presenting no worrying features. This sinking is due to two phenomena: elastic deformation of the layers covering the cavities, and salt creep, which is normally manifested by the progressive closure of the caverns and particularly by a slow and regular shortening of the 'pillars' of salt left between them. In the Nancy basin, the speed of sinking resulting from creep in areas exploited by large cavities is very low.

The most critical situation, in terms of sinking in solution mining areas, is where, as a result of production, aquifers overlying the salt find themselves in communication with the salt. Such communication may be created when a solution cavity, such as has just been described, collapses and creates a chimney which could extend to the open air. In such a case, a connection is made between the fresh water of the aquifers and the brine present at production level. The altitude of this interface, after stabilisation, depends on the local hydrogeological context. If this interface is below the salt level, fresh water comes into contact with salt and causes it to dissolve. In the case where the dip of the top of the salt is very small or null, this dissolution is little active since the layer of saturated brine it creates remains beneath the fresh water and protects the salt from further dissolution. This is not at all the case when the top of the salt has a dip. In this case, the fresh water, flowing above the brine, has a tendency to flow up dip, which can cause dissolution and therefore sinking at significant distances from collapsed areas. This phenomenon was described in Franche-Comté, in terrains of the same age and of the same type as those in the Nancy basin (Feuga, 2005). A similar case has been recorded in this basin where, at the beginning of the 1980s, a whole development in the town of Saint-Nicolas-de-Port had to be abandoned due to large scale rapid localised sinking (the speed reached 50 mm/month; Figure 11).

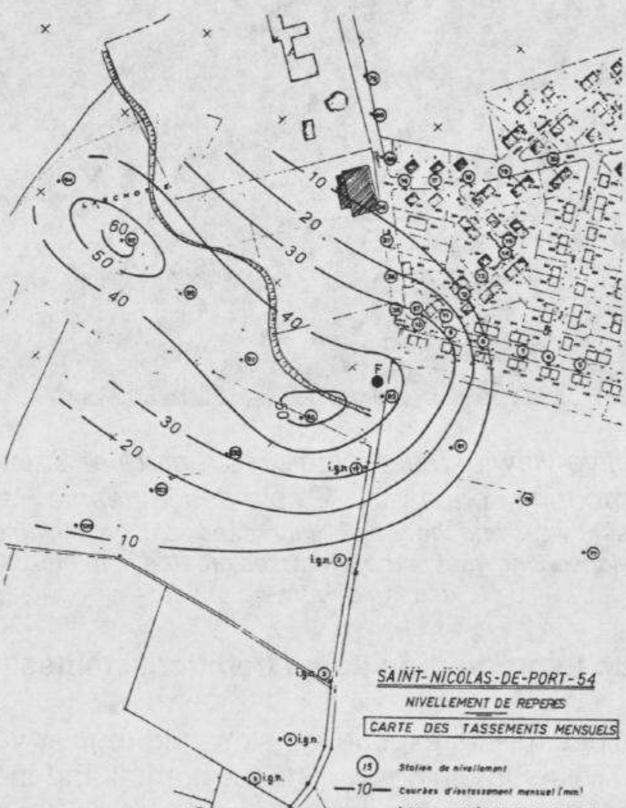

Figure 11. Sinking in December 1984, in mm, in Saint-Nicolas-de-Port (BRGM document)

This sinking was attributed to two main factors: the presence, on the neighbouring concession, of several collapse chimneys (the nearest of which was, nevertheless, 600 m from the sinking area), and the existence of a significant geological flexure, placing the level of the top of the salt beneath the development around 80 m higher than its level beneath the concession (Figure 12).

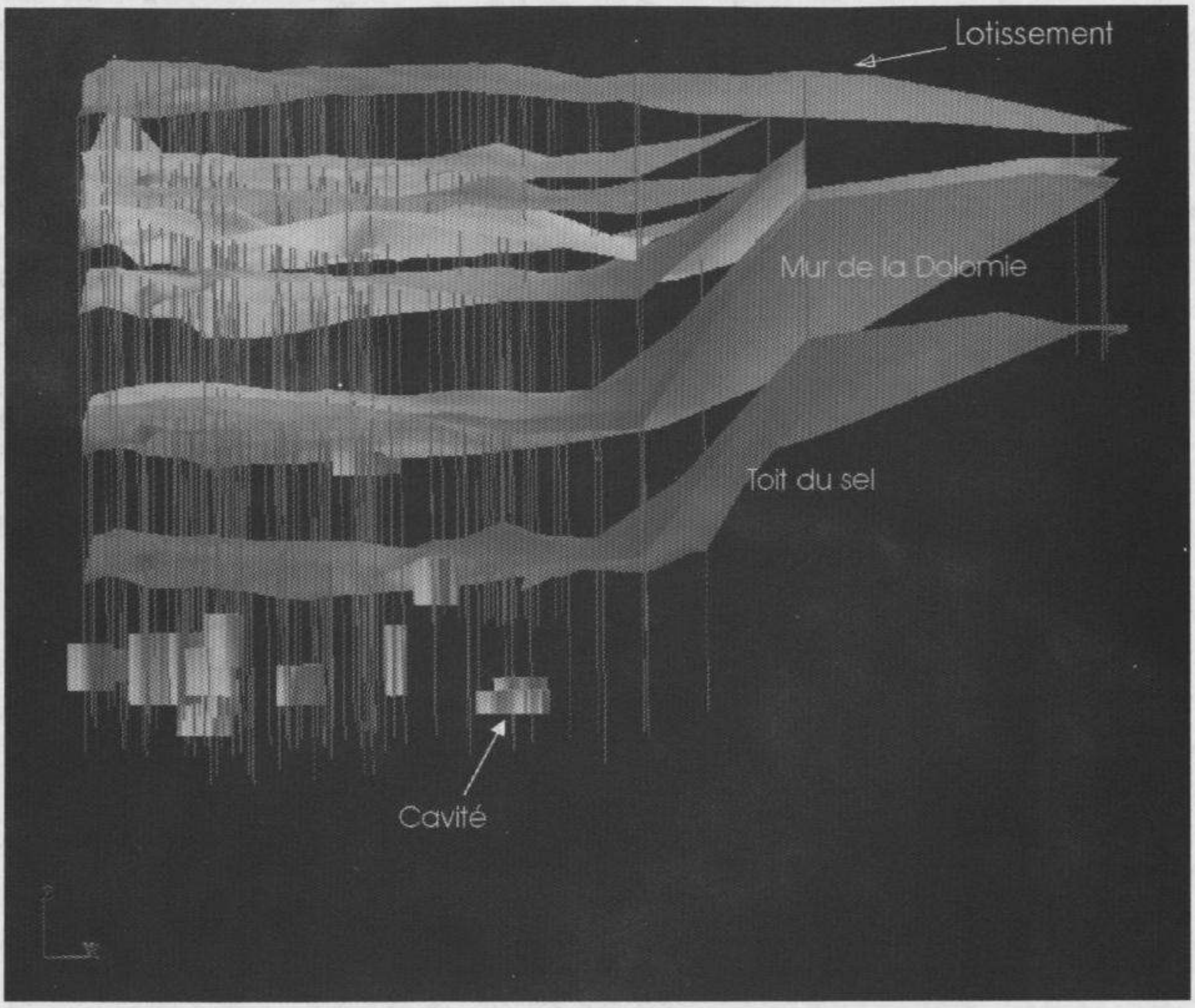

Figure 12. Perspective view of the geological structure at Saint-Nicolas-de-Port and of the neighbouring concession (École des Mines de Paris document)
The red lines represent wells and the grey cylinders the solution mining cavities created by the exploitation. As they collapsed, several of these cavities created communication links between the salt and the underlying aquifers

3.2. Subsidence due to production using traditional mines (dry mining)

In room and pillar mines, pillars experience slow and regular vertical shortening as a result of salt creep. This shortening, which is a normal and inevitable phenomenon, has an effect on the soil surface by way of subsidence on the same amplitude when the mine covers a large area.
Above the Varangéville mine, still in production, the rate of subsidence of the soil surface is around one tenth of a millimetre per year above the area of the modern mine whose extraction ratio was 37% (depth of 150 m). The rate is several mm/year above the old areas, deeper and with an extraction ratio of 75%.

3.3. One special case: Sinking due to a deep, poorly cemented well

Situations in which a deep well links a saturated aquifer situated beneath a salt formation with aquifers overlying the salt, can cause serious accidents as borne out by international literature (Morisseau, 2000; Johnson, 2001). If the well is badly cemented or if it was abandoned without the appropriate treatment, the water from deep below flows to the surface through this well, due to the difference of hydraulic head between the deep aquifer and the shallow ones (in the hydrogeological context of Lorraine, the head of deep aquifers is generally higher than that of the shallow ones). As it crosses the salt formation, the water dissolves salt, creating voids which may cause sinking on the surface or even, in the most serious cases, collapse. There is a very large aquifer in Lower Triassic Sandstone (LTS) in Lorraine, several hundred meters beneath the Keuper salt.

While there is no known example of the phenomenon referred to above in the Nancy basin, there is one in the Dieuze basin: the Brejcha well, bored in 1906-1907 to supply water from the LTS to Dieuze chemical plant. In 1924 this well caused sinking and damage to the plant's buildings. To put an end to the sinking, the well had to be abandoned and very carefully sealed.

4. Local collapse

Collapse is defined as a rapid movement of the soil surface, characterised by the sudden appearance of a depression, often called a crater, whose edges are marked by clear breaks. Collapses occurring above salt solution mines may be distinguished from those occurring above traditional mines by the fact that they are in general much slower. While the latter last only a few seconds and are accompanied by a real seismic tremor, the duration of collapses above salt solution mines often take hours. As we saw in paragraph 3.1, with the collapse in 1876 at Art-sur-Meurthe, this can be explained by the fact that these cavities are generally filled with brine and the evacuation of this brine through wells in communication with the cavity which collapses or through the ruptures appearing in the overburden takes some time. More than the duration of the phenomenon, it is therefore the morphology of the depression created (the presence of clear breaks) which allows sinking to be distinguished from collapse in salt-bearing areas.

Local collapse is small-scale collapse, where the crater diameter varies from several metres to a few dozen metres.

4.1. Local collapse due to solution mining

There are no known cases in Lorraine of local collapse which could be directly attributed to the crumbling of a solution mining cavity. Due to its dissolution by surface water, in Lorraine there is no salt less than 50 m beneath the soil surface. A cavity in the salt must, therefore, be at a depth of at least 50 m. Given the nature of the terrain covering the salt, for such a cavity to cause a movement reaching the surface, it must be large in size and, in these conditions, the crater created on the surface itself is large in size and part of the generalised collapse described in paragraph 5.

However, there is a lot of gypsum in the Anhydrite Marls covering the salt. This gypsum is often karstified and may reveal caverns large enough to crumble, and, given their lack of depth, give rise to surface sinkholes. This phenomenon occurs extremely frequently in Lorraine and is totally independent to salt. But exploitation of the latter, through pumping brine from the salty aquifer, may trigger some of these collapses. Voids in the gypsum are filled with water from the water table with which they communicate. The tapping of brine from the salty aquifer causes a piezometric depression in the groundwater which spreads to the overlying aquifers, and the pressure of water filling the voids in the gypsum falls. If these voids are verging on instability, this reduction in support provided by the water pressure is sufficient to provoke collapse. It is probably this mechanism which is behind many small collapses affecting the Paris-Strasburg railway between Dombasle and Varangéville at the end of the 19th century (Figure 13). After the end of exploitation of the Dombasle salty aquifer, the frequency of these collapses reduced significantly.

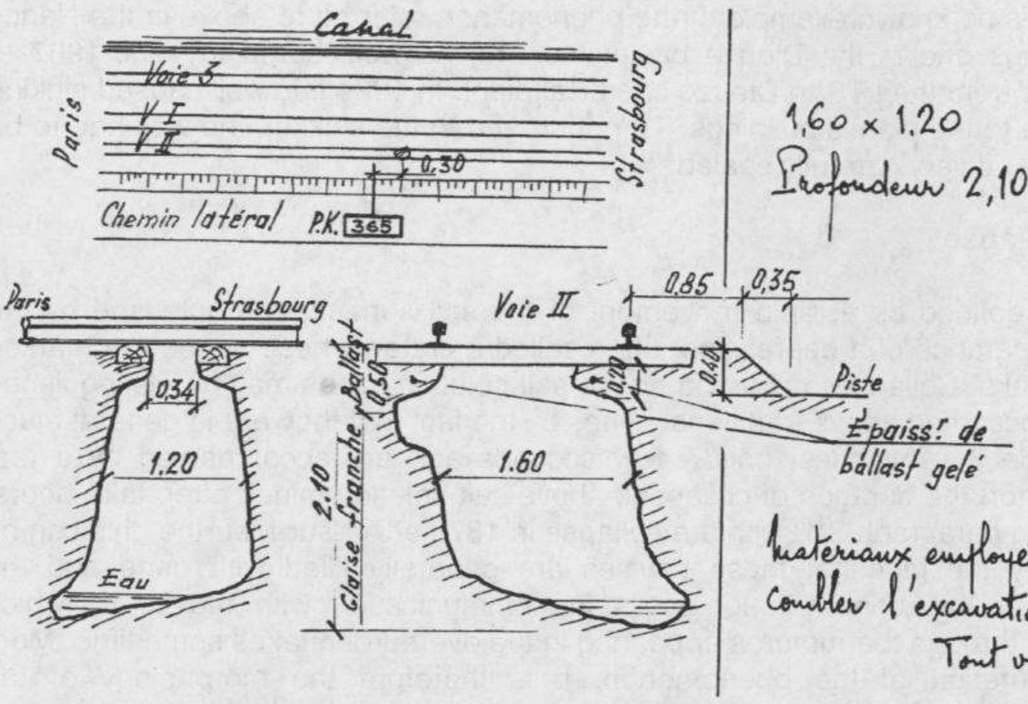

Figure 13. Diagram of a local collapse above a gypsum lens, beneath a railway (Dombasle region, Nancy basin. DRIRE, Lorraine archives)

Another example of this type of collapse may be found at Dieuze, where flooding of the mine, occurring in 1864, caused drawdown which dried some agricultural wells and was marked by the appearance of three local collapses (sinkholes) up to 1 km from the mine.

There is a case of local collapse above a solution mine in Lorraine which cannot be explained by this mechanism. This is the case of well no. 7 at Dieuze. In 1951, during development work to improve communications between this well and the salty aquifer, a local collapse with an initial diameter of 1.5 m appeared 16 metres from this well. The cause of this collapse, which was not repeated, was not identified, but all explanations given referred to the hypothesis of a particular underground structure in the area surrounding the well.

It should be noted that there are no known cases in Lorraine of collapse of the head of a salt production well. Given the high diameter of these wells, which can exceed 0.5 m at their upper end, this type of incident cannot be ruled out but if this is the case there is no trace in the archives.

4.2. Local collapse due to traditional salt mining

Given the depth of traditional salt mines in Lorraine and the nature of their overburden, the phenomenon of chimneying of underground collapsed materials of limited dimensions is not possible. Thus there is no phenomenon of subsidence above Lorraine salt mines as occurs frequently above iron mines in this region.
The only local collapses are due to old poorly plugged mine shafts. The most characteristic example of this was the sudden appearance in 1974 at Vic-sur-Seille, in the Dieuze basin, of a swallow-hole 4 m in diameter and several dozen metres deep, corresponding to the collapse of the plug which had been placed over the Becquey shaft, one of the three shafts belonging to the oldest salt mine in France, abandoned since 1825.

5. Global collapse

The general characteristics of a collapse in a salt region were described in paragraph 4. A global collapse can be distinguished from a local collapse by its extent, which can reach several hectares. The depth a global collapse may be very variable, from several tens of metres to a hundred metres.

5.1. Global collapse due to solution mining in the heart of a salt formation

Solution mining at the top of the salt cannot give rise to global collapse. Even if the extent of the area affected by solution mining is a large one, the void created is low in height and, furthermore, in Lorraine, in most of the areas in which this type of production was practised, the flexible nature of the overburden means that this sinks at the same rate that dissolution takes place, that is, slowly and progressively. In the worst case scenario, in contexts of this type there could occur a rapid widespread sinking like the one occurring at Art-sur-Meurthe in 1876 (paragraph 3.1).
However, solution mining within a salt formation creates large cavities which, from the moment they reach a critical dimension, may collapse, particularly if a sufficiently thick protective layer of salt is not left at roof level. The collapse of these cavities often has major consequences on the surface.
We should distinguish two cases here:

- Former, involuntary collapses, for example the dozen between 1950 and 1970 in Nancy basin. These collapses are poorly documented;
- Voluntary collapses. There are two types. Either they are an integral part of the exploitation method (the 'intensive method' practised by the Solvay company – Figure 14 and 15), or they involve cavities which have become too big and are threatening collapse, and thus the operator decides to cause a collapse for preventive purposes (Buffet, 1998, Jeanneau, 2005) (Figures 16 and 17).

Figure 14. Aerial view of deliberate collapse craters at Haraucourt in 1977 (IGN document)

Figure 15. Cerville deliberate collapse, one day after its appearance on February 13, 2009

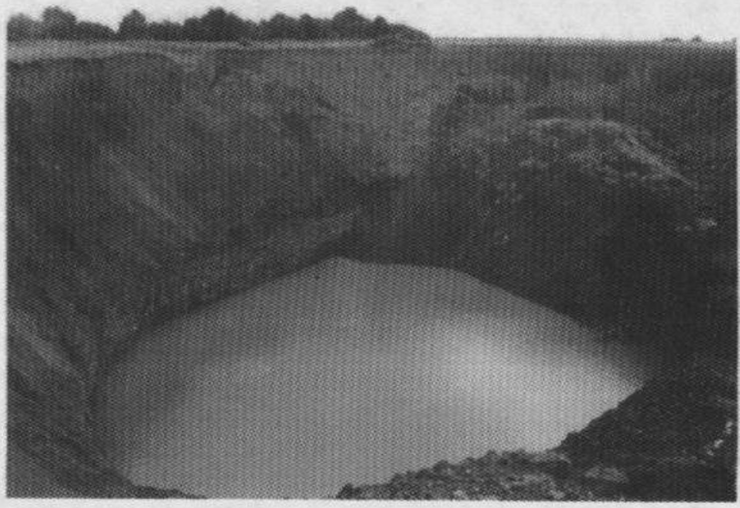

Figure 16. Collapse caused by SG4-SG5 cavities at Gellenoncourt in 1998 (CSME & École des Mines de Paris document)

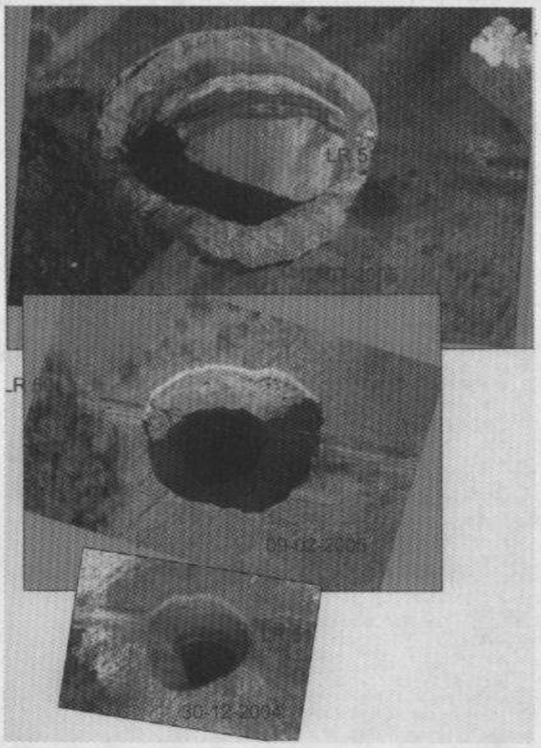

Figure 17. Development over time of the deliberate collapse of cavities LR50-51 at La Rape (Rhodia-CIM document)

While the result of these collapses (the craters) is well known and quite comparable to the global collapses which can occur in other contexts (but generally far greater in depth as a result of the greater thickness of salt exploited), much less is known about the dynamics of their movement. What appears certain is that these collapses are neither instantaneous nor sudden and that their duration is undoubtedly minutes or even hours rather than seconds, as a result of the time needed for the brine to leave the cavity. Even when it is air and not brine which is present in the cavity the phenomenon is not instantaneous and the air space also appears to have an effect of slowing movement.

5.2. Global collapse due to traditional mining (dry mining)

The only known accident of this type in Lorraine was the sudden collapse of the Saint Maximilien district on 31 October 1873 at the Saint Nicolas mine, Varangéville, in Nancy basin (Figure 18). The mechanism behind this collapse, identified from the first visits to the place of the accident by M-A Braconnier (1873), from *Service des Mines* (the French Department of Mines), was re-examined by Bérest et al. (2008b) and appears to be the only one of its kind. The operator created slots in the room face with high-pressure jets of water to facilitate blasting, which was carried out with the use of explosive powder. The water used, whose collecting system appears to have been insufficient, lay stagnant in the mine galleries, causing rapid degradation of the mechanical characteristics of the floor marls, very sensitive to water due in particular to their salt and very finely separated anhydrite content (Boidin, 2007). The bearing capacity of the pillars reduced progressively in significant proportions. The accident occurred when, as a result of the expansion of the district, the overburden, comprising a layer of salt 70 m in thickness, could no longer be supported by the pillars, and sheared apart over the entire periphery of the district, causing a sudden punching of the floor by the pillars, including the large central pillar protecting the shaft.

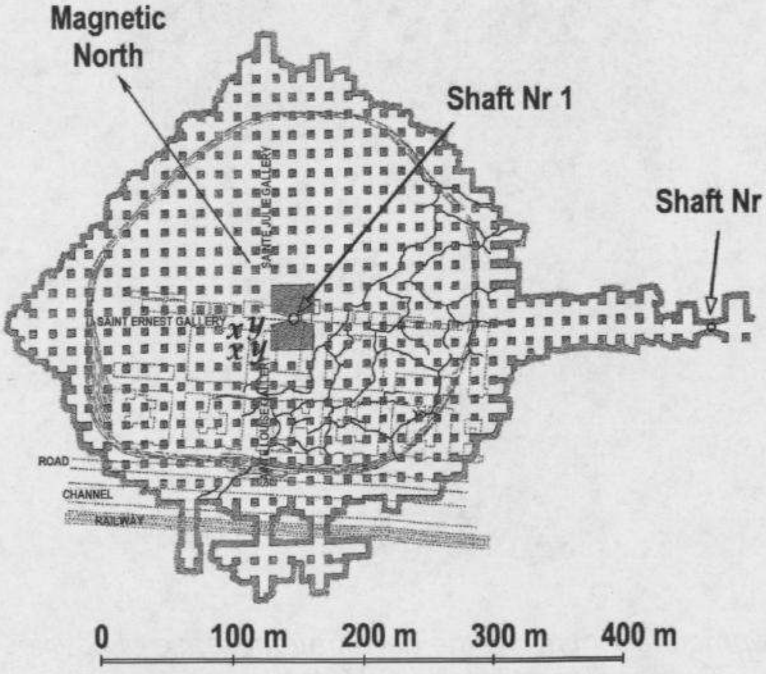

Figure 18. Map of the Saint-Maximilien district which collapsed in 1873, showing the tension cracks on the surface outlining the collapsed area (after Braconnier, 1873 modified)

The collapsed district, nearly circular in shape, measured around 300 m in diameter and the maximum vertical amplitude of the collapse on the surface was 3.30 metres, with galleries of 5.5 m in height and an extraction ratio of 82%. It is important to note that while the collapse area had been outlined on the surface by very visible tension

cracks, there was, however, no relative vertical displacement (steps) noted along these cracks.
This means we can classify this accident among global collapses, and it is the suddenness (duration of a few seconds, seism felt 15 km from the place of the accident) and not the shape of the depression produced on the surface which makes it a classic collapse sink.

5.3. A collapse which didn't happen: Dieuze, 1864

The most serious accidents to occur across the world in salt or potash mines were on most occasions due to water ingress or were accompanied by water ingress which made the catastrophe worse.
Fortunately, no such events have ever occurred in Lorraine, and yet...
The Dieuze mine, opened in 1826, with a gallery height of 4 m and a depth of 120 m, worked the same layer of salt as the Saint-Nicolas-Varangéville mine which we referred to in paragraph 5.2. The extraction ratio varied from 80 to 90%. On 8 February 1864, following the collapse of an underground dissolution cavity in contact with one of its wells via its access gallery, the mine was filled with water or rather with saturated brine from the abundant salty aquifer above the mine. Following an unsuccessful month-long attempt to control the flood, the mine had to be abandoned on 7 March 1864. The only significant ground movements to accompany this accident were local collapses at a distance from the mine, of pockets of gypsum dissolution indicated in paragraph 4.1 which were only an indirect consequence, as we have seen. Studies, in particular the survey of earlier works and an examination of these by sonar, were carried out in 2002 to evaluate the stability of the mine (Feuga, 2003). These showed that it was in an extremely stable condition.
How did the Dieuze mine, filled with brine, one century and a half after the event, manage to be in such good condition when the Saint-Maximilien district of the Varangéville mine, which was in apparently very similar condition, collapsed fifteen years after production commenced as a result of water damage to a wall identical to that in the Dieuze mine?
Bérest et al. (2008a) considered this question and showed that two main points distinguished the two mines:

- Firstly, the brine entering the Dieuze mine was saturated, which was not the case with the water soaking the floor of the Saint-Maximilien district. Now, Boidin (2007) showed that if, as a result of their salt content, the marls of this floor were very sensitive to water not saturated with salt, they were not damaged by contact with saturated brine;
- Secondly, the Dieuze mine (width: 130 m) was much narrower than the Saint-Maximilien mine (300 m). The weight of the overburden therefore was supported much more by the abutments than it was at Varangeville. As a result, and also due to the support provided for the roof of the mine by the brine filling it, the pillars of the Dieuze mine had a far smaller load than those in the Saint-Maximilien district. This state of affairs is sufficient explanation on its own for the stability of the Dieuze mine.

6. Conclusion

As we have seen, although the geological structure is very simple there, incidents and accidents occurring in Lorraine over nearly two centuries of salt production provide a fairly representative sample of what can happen in many salt basins elsewhere in the world.

The typology of ground movements which has been identified following this historical examination represents one of the tools used to identify the type, amplitude and dynamics of ground movements the different areas of salt-bearing regions in Lorraine are likely to experience in the future, in particular according to the method of production and the geological and hydrogeological context.

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