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Cases, causes and classifications of craters above salt caverns

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Based on the description of a dozen of cases, this paper suggests a categorization of craters formed above brine-production caverns for “piston” and “hourglass” types. The deliberate creation of three craters in Lorraine (France) above the Keuper salt formation is described first. After the cavern roof reaches the top of the salt formation, stoping takes place. A rigid cylinder of rock (a piston) drops abruptly in the cavern, experiencing no deformation and creating vertical crater edges. In the same mining district, a room-and-pillar panel collapsed abruptly in 1873. Multiple pieces of evidence have proven that, here again, no deformation occurred in the cylinder that dropped into the mine. These examples prove that cavern drop is more abrupt when the cavern is filled partly with air, as less brine must be evacuated from the cavern during collapse. The Haoud Berkaoui (Algeria) and Bereznikovsky (Russia) craters also belong to the piston type; less information is available. The main features of the piston mechanism can be captured by a simple model: failure takes place when vertical shear forces along the cylinder edge, plus cavern internal pressure, are not able to balance cylinder weight. This model suggests that the contour of the crater must be a circle and that collapse is easier when the ratio between cavern radius and cavern depth is larger. This may explain why no example of a collapse above a hydrocarbon storage cavern is known: in most cases, this ratio is very small. Three sinkholes formed above salt caverns leached out from the Hutchinson salt formation in Kansas (USA) epitomize the hourglass type. Here, again, stoping occurs until the cavern roof reaches loose sediments at shallow depth. A sinkhole grows when sediments flow to a central hole to fill the cavern underneath, generating an upward flow of brine to the sinkhole. Such a phenomenon also can occur in a salt dome. At Bayou Choctaw (Louisiana, USA) a brine cavern rose through the caprock, allowing loose shallow sediments to flow to the cavern. At Bayou Corne (near Napoleonville in the same state), a cavern was within a short distance from the flank of a dome; a 1500-m-deep breach was created, and loose sediments in the dome sheath, accumulated during geological times, filled the cavern—a process that lasted more than one year and created a sinkhole at ground level. In both cases (piston and hourglass) lakes form in the crater and gravity-driven waves are observed. Sinkhole creation can be prevented when the distance between the cavern roof and the salt top (or dome flanks) is large enough and when the ratio between cavern radius and cavern depth is small enough.

1. Introduction

For this topic, a few introductory definitions are needed. A *subsidence bowl* is a trough observed at ground level above any underground opening. Its vertical profile is smooth, and its slope is several mm/m or less. In some instances, folds and vertical fractures, implying a discontinuity in horizontal displacements, can be observed at ground level. A *crater* is generated by downward vertical displacement of a piece of rock (the “*piston*” model, Fig. 1) or an inward horizontal displacement of loose materials toward a central hole at ground level (the “*hourglass*” model, Fig. 1). A discontinuity in vertical displacements by several meters or dozens of meters (a “step”) can be observed at the edge of a crater. A *sinkhole* is defined less clearly; it encompasses both craters and subsidence bowls with large slopes.

Millions of craters or sinkholes have been created worldwide during geological times. Natural sinkholes result from the collapse of overburden rocks above karstic voids created through the dissolution of limestone (sometimes of gypsum or chalk) by swift running water; or through the washing of loose shallow materials through fissures and caves, a process named *suffusion*.^{1,2} In this paper, it is suggested that a similar classification (“*piston*” and “*hourglass*”) applies to sinkholes created above caverns leached out from salt formations for brine production or hydrocarbon storage.

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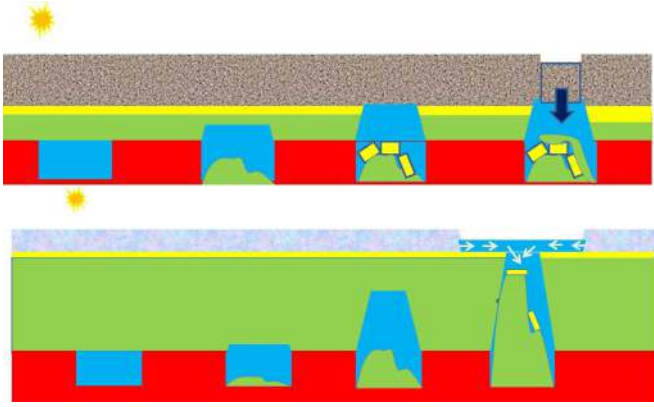


Fig. 1. The piston model (top) and the hour-glass model (below).

2. The piston model

2.1. Three craters in Lorraine

2.1.1. The collapse of a cavern of the 2100–2200 lines at Cerville-Buissoncourt, France

At Cerville-Buissoncourt in Lorraine, France, the Solvay Company operates a brine field according to the *intensive* method, whose objective is to achieve high extraction ratios. Two parallel borehole rows, or “lines”, slightly more than 1-km long, oriented South-North, are drilled; along each line, the distance between two boreholes is 50 m. Water is injected in the first borehole of each of the two lines; water leaches out the salt formation; and brine is withdrawn from wells located several hundreds of meters away from the injection wells. A cavern develops below the two first wells. When this cavern reaches the “critical” horizontal dimensions, known from experience, injection stops. The brine level then is lowered in the boreholes to decrease cavern pressure by pumping, which leads to cavern collapse.

Gisos, a scientific consortium, monitored the evolution and collapse of a cavern created during the 2002–2003 period at the end of the 2100–2200 lines.^{3,4} The stratigraphy can be described as follows.⁵ From 0–123 m, a succession of marls, limestones, sandstones, marly anhydrite whose strength is low. (The sandstone layer is called the Rhetian aquifer.) From 123–132 m, a competent anhydrite/dolomite layer (Beaumont Dolomite). From 132–183.5 m (top of the salt formation), poorly consolidated anhydritic marls. Below 183.5 m, the Keuper salt formation.

High-resolution micro-seismic probes were set above the brine field in cemented boreholes at depths from a few meters to 125 m—the depth of the Dolomite layer. A subsidence-survey system, including 17 targets along a line above the cavern at ground level, was scanned every 20 min by an automatic tacheometer; resolution in the vertical displacement measurement was ± 3 mm. This system was complemented by a GPS monitoring system. An extensometer set in a drill hole measured the relative displacements of several points set at different depths from ground level to the Beaumont Dolomite layer. Five piezometers measured the water head in the Rhetian aquifer, 60 m above the Dolomite layer. In addition, Solvay ran gamma-ray logs on a regular basis to assess cavern roof depth and measure brine pressure (or the brine/air interface depth) in the boreholes of the two lines. This monitoring program of a salt cavern collapse was probably the most comprehensive ever conducted.

At the end of 2004, solution mining through the two first boreholes of the two lines was completed, and a sonar survey was performed. The horizontal dimensions of the cavern roof were $180 \text{ m} \times 40\text{--}50 \text{ m}$, a size known to be critical. In the eastern part of the cavern, below line 2200, the roof of the cavern had reached the top of the salt formation at a depth of 183.5 m; in the western part, a 10-m-thick salt roof remained

(Fig. 2). From 2004 to May 2007, solution mining took place in the northern part of the two lines, 200-m away from the “critical” cavern. Three small micro-seismic swarms, less than 24-h long, were observed in 2007 (they might have been generated by failure of thin interbedded anhydrite layers during stoping); three major crises (The number of events was larger by one order of magnitude than during small swarms.) took place in April 2008. Gamma-ray logs proved that cavern roof had risen by 30 m in 5 months, from February 2008 to May 2008; the cumulated volume of marl that collapsed to the cavern bottom during stoping was estimated to be $500,000 \text{ m}^3$. Seismic events took place at the cavern walls and roof but also below and above the Beaumont Dolomite, especially in the easternmost part of the cavern.

Leveling had shown no significant movement before March 2008, when a cumulated 10-mm vertical displacement was observed that included a sudden movement by 3.5 mm in 24 h on March 31. On April 4, the brine level rose by 13 m in a “downstream” well of the line, 1200 m away from the collapsing cavern; it took 8 h for the brine level to return to its initial volume (see Section 2.2.2). It was clear that the mechanical system existing between ground level and the salt top had been disturbed greatly. At the cavern top, brine pressure was 0.9 MPa. For safety reasons, no further gamma-ray logs were run.

The cavern roof ultimately reached the Beaumont Dolomite, below which it cleared a $60\text{--}80,000\text{-m}^2$ area. It was decided to lower the brine levels in the wells to trigger cavern collapse. Brine extraction began on February 10, 2009. At the end of the second day, 34 h before the final collapse, the brine level had dropped by 50 m (a brine pressure drop of $\Delta P = 0.6 \text{ MPa}$); brine pressure at the cavern top was 0.2 MPa. In³ multiple evidence are presented that there was, at this stage, a first failure of the Dolomite layer: roof sagging, differential subsidence between ground level and Dolomite layer, and sudden rise of the brine level in the wellbores. “... [$\Delta V =$] $12\,500 \text{ m}^3$ of brine had to be pumped to break the Dolomite”.⁶ Brine volume was $V \approx 3 \times 10^6 \text{ m}^3$ (the exact figure is unknown), the apparent compressibility was $\beta = 7 \times 10^{-4}/\text{MPa}$ —i.e., greater by one order of magnitude than the typical compressibility of a cavern, which is $\beta = 4\text{--}5 \times 10^{-4}/\text{MPa}$, proving that rock mass was deeply disturbed. At this stage, however, the Dolomite layer did not fall at the cavern bottom. Twenty hours before the final collapse, the Dolomite layer sagged by 0.5 m. At this point, sensors in the layer were lost, and the brine level rose again abruptly. Daupley et al.⁴ suggest that the 120-m-high, 150-m-diameter cylinder of rock did not drop abruptly as a monolithic block, as no violent brine outflow was observed during the collapse. However, the air/brine interface rose to ground level in the remote wells of the line; rather, at the bottom of the cylinder, slices of rock broke and dropped to the cavern bottom, lowering the height of the rigid cylinder, which allowed the cavern roof and brine to rise to ground surface until a cylinder (a “piston”), whose height had decreased to be less than 120 m, dropped abruptly (Fig. 3).

2.1.2. The SG4-5 collapse at Gellenoncourt, France

The Compagnie des Salins du Midi et Salines de l’Est (CSME) operates a brine field at Gellenoncourt in Eastern France, a few kilometers from Cerville-Buissoncourt. Salt top is 217-m deep, instead of 183.5 m at Cerville-Buissoncourt. The following description is based on.⁷ At that time, in this field, several drill holes, 280- to 300-m deep, were connected through hydro-fracturing to form “panels”. Water then was injected in a well and flowed through several caverns before being withdrawn from an “extractor” well. When caverns grew, a 10-m thick salt layer was left below the top of the salt formation whose role was to prevent direct contact between cavern brine and overlying argillite layers, which are known to be prone to weathering when in contact with brine, a characteristic feature of most argillaceous overburdens above bedded-salt formations. Beginning in summer 1967, water was injected in the SG4 and SG5 wells, and brine was withdrawn from the SG1 well. In July 1971, it appeared that SG5 roof was 2 m below the top of the salt, much less than the recommended 10-m thickness. It was

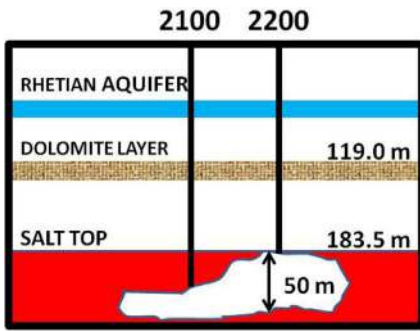


Fig. 2. The vertical cross-section and horizontal contour of the cavern at the end of 2004.



Fig. 3. The crater at Cerville-Buissoncourt six months after the collapse. (Acknowledgement: Solvay).

decided to inject water through other wells to prevent further dissolution at the SG4 and SG5 roofs; however, during its travel to the SG1 well, unsaturated brine crossed through these two caverns, leading to additional (although slow) cavern growth.

In 1982, it became clear that SG4 and SG5 had coalesced and that the SG4-5 cavern roof had reached the top of the salt. From 1982–1992, the company monitored the two caverns through frequent sonar surveys and gamma-ray logs. After 10 years, in October 1992, a cavern-roof rise was observed. Three months later, the roof ultimately reached the Beaumont Dolomite layer, an 8-m thick competent layer, located 70 m above the top of the salt formation (Fig. 4, top). As a consequence of stoping, an area ($25\text{ m} \times 75\text{ m} = 1875\text{ m}^2$) was cleared below the Dolomite layer. Collapse was feared. It was decided to lower cavern pressure using two submerged pumps to trigger a preemptive collapse. Reflecting benchmarks were set at the SG4 and SG4 wellheads; they were scanned every 15 min by a theodolite to detect possible vertical movements. On October 1995, the level of the air-brine interface in the wells was lowered to -146 m and -221 m , successively: at the cavern roof, below the Dolomite layer, air pressure had become atmospheric (Fig. 4, top), but nothing happened. It then was decided to enlarge the lower part of the cavern by injecting water in the cavern. (Air was left at cavern top.) A total water volume of $300,000\text{ m}^3$ was injected.

The collapse took place on March 4, 1998, at 5:30 a.m. The leveling system provided no warning, strongly suggesting that a rigid block had dropped abruptly. While no brine blowout was observed, the air in the cavern was compressed and blew out from the cavern through the crater edges. The resulting ground-level crater contour took the shape of an ellipse, whose axes were 65 m and 90 m , and whose walls were steep (Fig. 4, bottom). Below was a 120-m high, 50-m in diameter chimney created during the collapse.

2.1.3. The LR51 collapse at La Rape, France

Since 1880, Novacarb has operated a brine field in the La Rape area, a few kilometers from Gellenoncourt. Overbrining led to the creation of several sinkholes. The most recent is the LR51 crater, which is described in more detail in.⁸ LR51, which had been connected hydraulically to a line of brine caverns, was operated from 1971 to 1993. Water was injected in the neighboring LR53 and LR54 caverns. Here, again, the 10-m thick salt layer left at cavern roof below the top of the 160-m -deep salt formation was leached out. After 1993, injection stopped, but the cavern roof migrated through the 50-m -thick marls/anhydrite layers above the salt formation, reaching, some $3\text{-}1/2$ years later, the Beaumont Dolomite at a depth of 110 m . As a consequence of stoping, a 4000-m^2 area was cleared below the Dolomite. It was decided to trigger cavern collapse. From December 2001 to April 2002, brine was pumped out from the neighboring LR43 and LR44 caverns, and the brine/air interface dropped to the level of the top of the salt formation. Again, leveling provided no alert. During the overnight of December 15–16, a crater abruptly appeared. Its diameter was 25 m (much smaller than the diameter of the zone cleared below the Dolomite), and its depth was 95 m . The “chimney” formed during the collapse was “quite circular” and “quite vertical”.⁸ Three months later (March 2005), the initially circular contour had evolved to a $62\text{-m} \times 53\text{-m}$ ellipse, and the chimney bottom was 66-m deep (Fig. 5).

2.2. Lessons drawn from the Lorraine cases

2.2.1. Stopping

In the Gellenoncourt, La Rape and Cerville-Buissoncourt cases, when solution mining is completed, cavern size and depth cannot lead to a sudden collapse, as the overburden is reinforced by a competent layer 8- to 9-m thick, $60\text{--}70\text{ m}$ above the initial cavern roof, the Beaumont Dolomite (and by several thinner anhydrite layers), which prevent failure from propagating from the cavern roof to ground level. The cavern, whose internal pressure is low, generates bending of these stiff layers, hence horizontal tensile stresses. However, at this initial step, as argillite is still present below the layers, these additional stresses are small when compared to anhydrite and dolomite strength. The cavern roof must rise before the overburden is able to drop. This happens when, at the end of the leaching period, the cavern roof reaches the top of the salt formation, allowing direct contact between brine and marls or argillites, which are abundant in the overburden. (In many countries, recent regulations require a minimum salt roof thickness above any salt cavern.⁹) Boidin¹⁰ described the lithology of the 60- to 70-m -thick interval separating the top of the salt formation from the Beaumont Dolomite. It is composed of a dozen interbedded anhydrite and argillite layers, through which the cavern roof rises step by step. The argillite layers weather when in contact with saturated brine, a progressive physico-chemical and mechanical process.¹¹ Based on the interpretation of the sonar surveys run in the caverns during stoping,

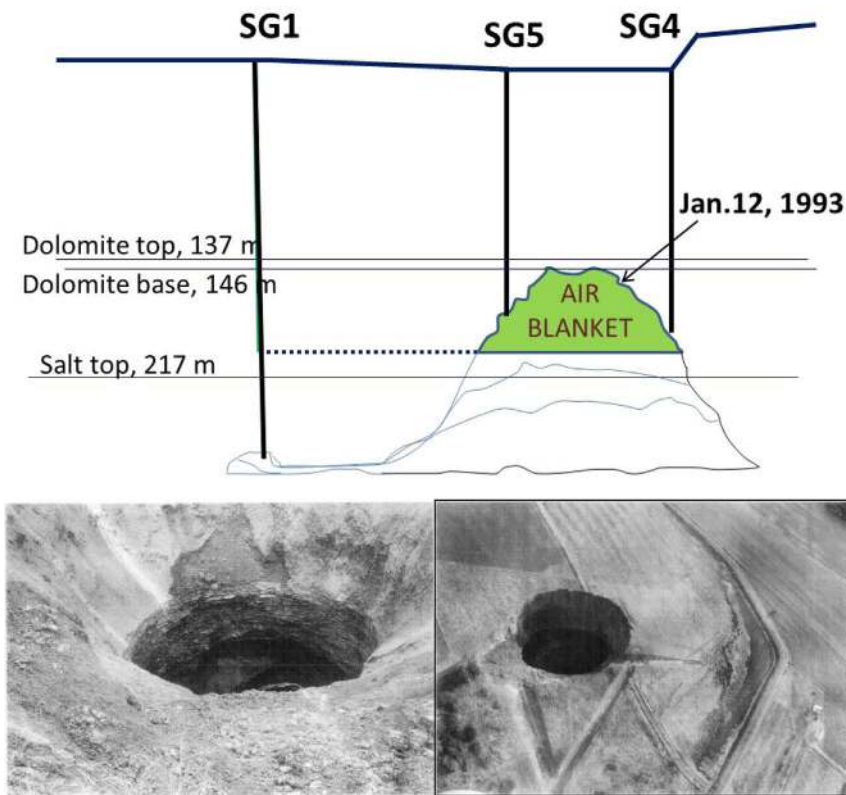


Fig. 4. Vertical cross-section of SG4-5 (top) after air injection; (below): the crater on March 8, four days after the collapse (left) and on March 29 (right).⁷

the following description is proposed in.¹⁰ When the cavern roof reaches an un-fractured anhydrite layer, roof rise stops, sometimes for several months. Argillite weathering continues, and a larger area is cleared progressively on the lower face of the anhydrite layer. The anhydrite plate sags under the weight of the overburden. Above the contour of the cavern roof, bending moments in the anhydrite plate increase, and tensile stresses are generated on the edge of its upper face and at the center of its lower face. Ultimately, the anhydrite layer experiences tensile failure, stripping an argillite layer which, in turn, weathers when in contact with brine. Remarkably, this process is not observed in *all* the anhydrite layers,¹⁰ probably because some of them are pre-fractured and are not able to hinder roof rise. This process lasted 10 years at SG4-SG5, and more than 3 years at LR51 and 2100–2200.

Ultimately, the cavern roof reaches the competent Dolomite layer. The areas cleared below this stiff layer were 1875 m² (SG4-SG5, Gellenoncourt), 4000 m² (LR51, La Rape) and 8–10,000 m² (2100–2200, Cerville-Buissoncourt). Stress conditions were not severe enough for the Dolomite to break. Brine pressure, which supports the

Dolomite from below, must be lowered through brine withdrawal. In the case of LR51 and SG4-5 caverns, a brine-air interface developed below the cavern roof, air pressure was atmospheric beneath the cavern roof, and the Dolomite layer broke. In the case of the 2100–2200 cavern, brine pressure was lowered, but no air was present at cavern roof, and cavern collapse was less abrupt (see Section 2.2.2). When a large enough area is cleared below the Dolomite layer and pressure is lowered in the cavern, this stiff layer sags and tensile stresses develop, as explained above, ultimately leading to Dolomite failure. This tensile-failure mechanism was described in other salt formations.¹² When a breach is created in the Dolomite layer, a cylinder of rock above this hole can drop into the cavern. Note that chimney diameter was 25 m at La Rape (however it doubled during the three months following the collapse), 50 m at Gellenoncourt and 150 m at Cerville-Buissoncourt. These differences might be related to the size and shape of the cavern underneath, as well as to the size of the breach initially created in the Dolomite layer.

Remarkably, salt mechanical behavior plays no role in these

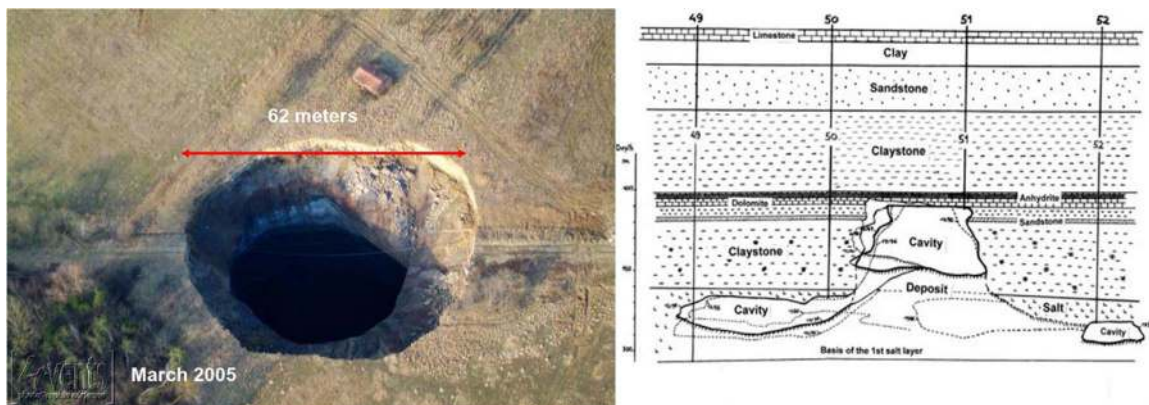


Fig. 5. The LR51 crater in March 2005(left) and cavern shape evolution.⁸

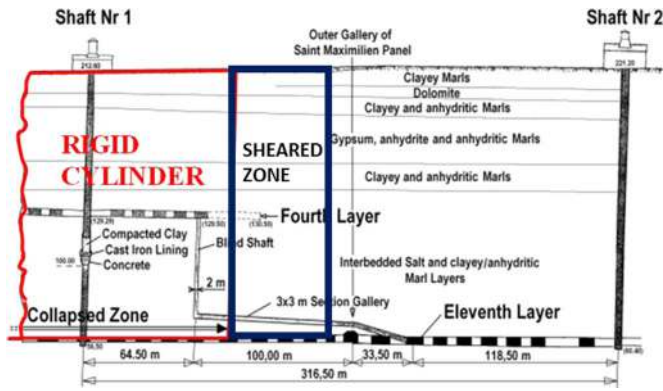


Fig. 6. Vertical cross-section showing a part of the rigid cylinder (whose axis of symmetry is shaft n°1) that dropped into the Saint-Maximilien panel.¹⁶

collapses. At such depths, creep closure is exceedingly slow. (Creep closure rate was measured in a 250-m deep cavern belonging to the Gellenoncourt brine field; it was less than 10^{-5} /year).¹³ It must be mentioned that not all salt caverns whose roofs reach the top of the salt formation lead to the formation of a crater. When cavern diameter is small, stoping comes to an end before the Beaumont Dolomite layer is reached by cavern roof, or the area cleared underneath the Dolomite layer is not large enough for a breach to be created. When cavern height is small, bulking of roof debris fallen at cavern bottom may stabilize the cavern.

2.2.2. The role of fluids during cavern collapse

In the cases of the La Rape and Gellenoncourt caverns, a large amount of air had entered the cavern before the collapse, although brine had been left at the cavern bottom (see Fig. 4). The collapse was fast and abrupt — there was no forerunner. For instance, at Gellenoncourt, no detectable subsidence was observed even 15 min before the collapse. When the overburden collapsed, less room was left for air in the cavern, and its pressure increased, at least when the vertical displacement of the piston of rocks was large enough. There was no report that a large amount of fluids was expelled from the neighboring wells (SG1 on Fig. 4). Rocky blocks, whose weight could reach several kilograms, were found at ground level near the crater edge⁷; they had been carried away by the air flow expelled from the cavern. When a cavern is filled with brine rather than air, one can expect that an overburden collapse would be less abrupt. When the cavern is tight, or almost perfectly tight, an abrupt collapse of the overburden is highly unlikely: even a very small cavern-volume loss generates a significant brine-pressure increase, which makes the cavern more stable than it was before the volume loss. (Cavern compressibility is $\beta = \Delta V/V\Delta P$, where $\beta = 4 - 5 \times 10^{-4}/\text{MPa}$ is typical). For a collapse to occur, some kind of hydraulic connection between the cavern and ground level or a permeable aquifer layer must be created. In the case of the Cerville-Buissoncourt borehole line, on April 4, 2008, a swarm of seismic events was recorded, it “led to a spectacular variation in the brine level of more than 13 m downstream from the cavern, i.e., more than 1200 m away”, a pressure increase by 0.16 MPa (³, p. 143). The brine level “returned to its initial value nearly 8 h later”. It is likely that in March-April 2008, the overburden over the cavern roof became deeply disturbed, and the cavern was no longer tight. It is possible, for instance, that a (slightly) permeable connection had been created between the cavern and the Rhetian sandstone aquifer, located 50 m above the Dolomite layer. It also must be noted that, before the collapse, which took place in February 2009, the water head in the Rhetian aquifer was consistently decreasing, clear proof of a hydraulic connection with the cavern (Xavier Daupley, personal communication). During the final collapse, piston drop is slowed by the increase of cavern brine pressure, and by the viscous and friction shear forces generated by the cylinder drop,

which apply on the cylinder edge. It is likely that, in most cases, brine pressure increases to high values. During the piston drop, upward vertical fractures open as brine enters the discontinuities created along the edge of the cylinder. If this general picture is correct, roof collapse would be a combination of (purely mechanical) shear failure and hydraulic fracturing.

2.3. The collapse of the Saint-Maximilien panel

A collapse may occur even when cavern roof does not reach the top of the salt formation. In the same mining district as Gellenoncourt, Cerville-Buissoncourt and La Rape, a dry mine had been opened at Varangéville in the eleventh layer.¹⁴ In the case of a mine (when compared to a cavern), much more information is available, especially after the collapse. The extraction ratio was higher than $\tau = 85\%$ and panel diameter was more than 300 m. In this area, the Beaumont Dolomite layer is shallow and fractured — it is not the competent layer described above. On October 31, 1873, the Saint-Maximilien panel of the Varangéville salt mine, at a 160-m depth below ground level and at a 100-m depth below salt top, suddenly collapsed. Witnesses reported that the collapse took “two seconds”. (This is a characteristic feature: collapse is swift and abrupt when the underground voids are filled with air rather than brine; see Section 2.2.2). A subsidence bowl had formed at ground level.¹⁵ Inside the central part of the bowl, whose radius was 80 m, ground remained flat and horizontal; it had subsided by 3.3 m. (Mine-room height was 5.5 m.) Shaft n°1, along the axis of symmetry of the collapsed block, was intact (Fig. 6). The collapsed panel was visited by the miners. The roof was intact. The pillars had not broken out, even at the panel edge. They had punched the marly floor, which was known to weather when in contact with brine and water, which were abundant in this mine. A smaller panel had been mined in the 4th salt layer since 1855, 87 m above the main panel. The collapse generated no or minor damage in this panel, which remained intact.

The weakest part of the ceiling-pillars-roof system was the ceiling. Collapse happened when the pillars punch the ceiling, the roof and the pillars remaining intact. Let σ_{max} be the maximum vertical stress that the ceiling can withstand without being punched. This maximum value is a constant when pillar shape is fixed (it is independent of pillar size). S is the horizontal area of the mine. The maximum vertical force that the ceiling can withstand is smaller than $(1-\tau)S\sigma_{max}$. It is proportional to the mine horizontal extension, which makes this case somewhat similar to the case of a cavern: there exists a critical value of the mine extension such that collapse cannot be avoided, see Section 3. This collapse of the Saint-Maximilien panel epitomizes the piston model. Facts clearly suggest that a cylinder of ground above the central part of the 11th layer panel, including shaft n°1 and the 4th layer panel, approximately 160-m high and 150-m in diameter, dropped by 3.3 m, as a monolithic block, experiencing little or no deformation. Severe strains were localized in an approximately 160 m \times 250 m circular crown around this rigid cylinder. The absence of any water flow to the mine following panel collapse—a fact that remains true 150 years after the accident—also is remarkable: it means that a thick salt roof left above the mined voids is able to accommodate relatively large vertical displacements (as large as 3.3 m) and shears without experiencing fracturing. One can speak of an “aborted” crater: the mine panel was not high enough to allow very large vertical displacements of the rigid cylinder. This is a favorable circumstance which, in most cases, is not met in a solution-mined cavern several dozens of meters high.

2.4. The Haoud Berkaoui crater

The Haoud Berkaoui salt cavern was created inadvertently as a poorly abandoned oil-exploration well allowed soft water to circulate through a thick salt formation located between a lower-lying prolific aquifer layer, of Albian age, with a high water-head, and an upper-lying aquifer layer.¹⁶ The Albian aquifer is artesian; its natural hydraulic



Fig. 7. The 70-m deep, 200-m wide crater, at Haoud Berkaoui, Algeria.¹⁶

head is larger than the hydraulic head of the shallow surface aquifer by 2.5 MPa. Although hydrogeological conditions allowing ascendant water flow from the artesian aquifer to the surface aquifer were present, the thick impermeable layers located below and above the salt formation, whose top is 450-m deep, prevented the creation of such an upward water flow for millions of years.

In 1978, an exploration well was drilled to a deep oil reservoir and stopped at a depth of 2500 m. There was no casing in the lower section of the well. Well abandonment was inadequate, and water began flowing from the Albian aquifer to the surface aquifer, leaching the salt formation and progressively creating a large cavern. Water flow increased as cavern size increased and head losses decreased. The cavern reached a second well at a distance of 80 m from the abandoned well, leading to a second well loss in March 1981. The cavern collapsed in October 1986. The cavern diameter and water flow rate at that time were estimated to be 300 m and 2000 m³/h, respectively. The crater was estimated to be 200-m wide and 75-m deep (see Fig. 7) with a perfectly vertical edge. It is highly likely that a cylinder of rock (a “piston”) that experienced no, or small, deformation, dropped abruptly into the cavern underneath.

2.5. An exotic case of air behavior during piston collapse

In the 3rd Bereznevskiy mine in Russia,¹⁷ a potash bed was mined out at a depth of 425–435 m. On January 11, 1986, a jet of brine developed in a panel. It is believed that a pre-existing fault reopened to allow shallow soft water to develop a funnel to the mine. The inflow of water sharply increased on March 8—an evolution typical of salt mine floods.¹⁸ The 15 million m³ of mine voids were filled with brine by the end of April 1986. Overlying layers fell in the mine above which a cavern grew; its roof rose to ground level. On July 1986, the cavern roof was ~ 50 m below ground level; it was filled with a mixture of air and inflammable gas released from salt layers by dissolution. At midnight on July 24, the cavern collapsed in a violent explosion: rock blocks, some of them 100 kg in weight, were ejected, and flashes of light were observed. This last circumstance led the authors¹⁷ to propose the following mechanism: the overburden dropped into the cavern and compressed the inflammable gas mixture, which was ignited by sparks generated by shocks between rock blocks and metallic parts, such as in an internal combustion engine. The crater was 200 m deep.

3. A mechanical interpretation of the “piston” model

3.1. Sinkhole contour is circular

In the five examples described above, the crater contour is circular. The same can be said of most *natural* sinkholes. Two examples (among thousands) are described below.

The Great Blue Hole (Belize)¹⁹ is an offshore sinkhole, almost perfectly circular in shape, 318 m across and 124 m deep (Fig. 8, left). It

was formed in four stages by the collapse of karstic caves during quaternary glaciations when sea level was low. (Karstic caves grow when they are fed by meteoritic waters.) The four stages were dated precisely through isotope analysis of stalactites found at depth in the hole. A sinkhole 20 m across and 30 m deep (A depth of 100 m also has been reported.) appeared abruptly in Guatemala City in 2010, a few days after an eruption of the Pacaya volcano and a tropical storm²⁰ (Fig. 8, right). Guatemala City is built on a low-density, unconsolidated volcanic ash deposit. This loose material erodes and becomes dissolute easily. It is believed that large underground voids had been formed by water leaking from sewers. Widening of the underground voids by torrential rains and clogging of pipes and drains by volcanic ashes resulting from the eruption may have been triggering factors.²⁰ These two “natural” sinkholes — and thousands of sinkholes worldwide — share a couple of characteristic features with the piston craters described above. The sinkhole edges are vertical, suggesting that a vertical cylinder of rock dropped abruptly in an underlying cavern whose underground contour encompassed the contour of the sinkhole. In addition, their contours also are almost perfectly circular. A tentative explanation is provided in the next Section.

3.2. Why sinkholes contours are circular

This Section presents a discussion of the mechanical equilibrium of an arbitrary vertical cylinder of rocks whose bottom and top are at the cavern roof and at ground level, respectively. H , S and P (Fig. 9) are the height, the horizontal cross-sectional area and the perimeter of the contour of the cylinder, respectively (when the contour is a perfect circle, $P = 2\pi R$ and $S = \pi R^2$). Three vertical forces act on the cylinder. The weight of the cylinder is a downward force, $S\gamma_R H$, where γ_R is the average volumetric weight of the overburden and typically is $\gamma_R = 22\text{--}25$ kPa/m. At the bottom of the cylinder, an upward force applies. This force is SP_c , where $P_c = H\gamma_c$ is the pressure of the fluid at the cavern roof. When the access well is opened and filled with saturated brine, $\gamma_c = \gamma_b = 12$ kPa/m; when the top of the cavern is filled with air at atmospheric pressure, $\gamma_c = 0$; when brine level is lowered in a borehole, $0 < \gamma_c < \gamma_b$. The sum of these two forces must be balanced by the sum of the (vertical) shear forces, or σ_{nz} , that apply on the edge of the cylinder:

$$(\gamma_R - \gamma_c)HS = P \int_0^H \sigma_{nz}(z) dz \quad (1)$$

Assume, now, that shear stresses must remain smaller than some upper bound; for instance the rock mass is homogeneous and the Coulomb failure criterion applies—i.e., $|\sigma_{nz}| < C + |\sigma_{nn}| \tan \varphi$, where σ_{nz} is the shear stress, and σ_{nn} is the normal stress. C (cohesion) and φ (friction angle) are two constants. Equilibrium is impossible when

$$(\gamma_R - \gamma_c)HS > P \int_0^H (C + |\sigma_{rr}(z)| \tan \varphi) dz \quad (2)$$

Note that in the case of the Saint-Maximilien panel (not discussed here), equilibrium was impossible when

$$\gamma_R HS > (1 - \tau)S\sigma_{max} + P \int_0^h \sigma_{nz}(z) dz \quad (3)$$

An assumption must be made to compute $\sigma_{rr}(z)$. The simplest consists of assuming that it is equal to the geostatic pressure, $|\sigma_{rr}(z)| = \gamma_R z$, leading to

$$(\gamma_R - \gamma_c)S < P(C + \gamma_R H \tan \varphi / 2) \quad (4)$$

When $S = \int_{\Omega} d\Omega$ is fixed, the minimum of $P = \int_{\partial\Omega} ds$ is reached when

$$\delta S + \lambda \delta P = \int_{\partial\Omega} (1 - \lambda/R(s)) \vec{n} \cdot \delta \vec{M} ds = 0 \quad (5)$$

where λ is a Lagrange multiplier, $\delta \vec{M}$ is an arbitrary displacement of the boundary, and $R(s)$ is the radius of curvature of Ω , from which it



Fig. 8. Examples of circular sinkholes: the Great Blue Hole, Belize¹⁸ (left); the Guatemala City 2010 Sinkhole (Photograph by Moises Castillo, AP, Google, Guatemala City sinkhole, November 6, 2015¹⁹).

can be inferred that $R(s) = \lambda$ is a constant and Ω is a circle. In other words, the rigid cylinder (the “piston”) is more likely to have a circular cross-section, the shape such that the ratio between the lateral surface and the volume of the cylinder (i.e., the ratio between the cylinder weight and the sum of the shear stresses applied on the lateral surface) is minimal, and Ω is the largest circle that can be inscribed in the cavern-roof footprint. When Ω is a circle, $P/S = 2/R$, and equilibrium is impossible when

$$(\gamma_R - \gamma_c)R > 2C + \gamma_R H \tan \varphi \quad (6)$$

Even if several simplifying assumptions were made (the constants of the Coulomb criterion are the same in the whole rock mass, and virgin horizontal stresses are not modified by cavern creation), Eq. (6) captures two main features drawn from actual observations: a crater is more likely to appear when the cavern is shallower and when its horizontal dimensions are larger.

3.3. Why storage caverns are stable

Eq. (6) allows defining a cone (when γ_c is fixed): a cavern is unstable when it is not contained inside this cone. The values of C and φ in Eq. (6) are difficult to assess. These constants, which, in fact, are averages of the cohesion and friction angles of a variety of layers in the cavern overburden, clearly are site-specific. However, it is interesting to compute orders of magnitude. The first task is to define R and H . Are they the radius and height of the chimney (which can be measured after the collapse), or are they the radius and depth of the cavern roof when leaching was completed (which are more significant when the topic is collapse prevention)? In Table 1 the values of several parameters are

listed. It must be kept in mind that St-Maximilien is not a brine cavern. These values cannot pretend to be exact (in several cases, information is scarce); however, they provide orders of magnitude. They do not contradict the suggestion made in²⁰ according to which no sinkhole can be created above a cavern whose R/H ratio is much smaller than $1/3$, a value that is consistent with these figures.

It is interesting to compare these figures with those encountered in hydrocarbon storage caverns. Hundreds of storage caverns are operated worldwide. In a liquid storage cavern, $\gamma_c = 12$ kPa/m; in gas storage caverns, the equivalent gradient, γ_c , is smaller than 12 kPa/m. No such cavern is known to have collapsed. (Spalling, sloughing, roof fall and creep closure are known to have occurred.) In most cases, the R/H ratio is smaller by one order of magnitude than the $R/H = 1/3$ value mentioned in.²⁰ Note however that this figure was based on collapses which occur when cavern roof had reached the top of the salt formation. The Saint-Maximilien case proves that generalized collapse is more difficult (cavern diameter must be larger) when cavern roof is several dozens of meters below the top of the salt formation, probably because salt is able to accommodate relatively large strains without breaking.

4. The hourglass model

4.1. Kansas sinkholes

Stratigraphy of the area near the city of Hutchinson, Kansas can be defined as follows.^{22,23} Sands and gravels with a thickness of 60 ft (18 m) are found first; these often are saturated with water to form the Equus bed aquifer. Directly beneath them is the Ninnescah Shale, composed of alternating beds of red and light gray shale, silty shale, and

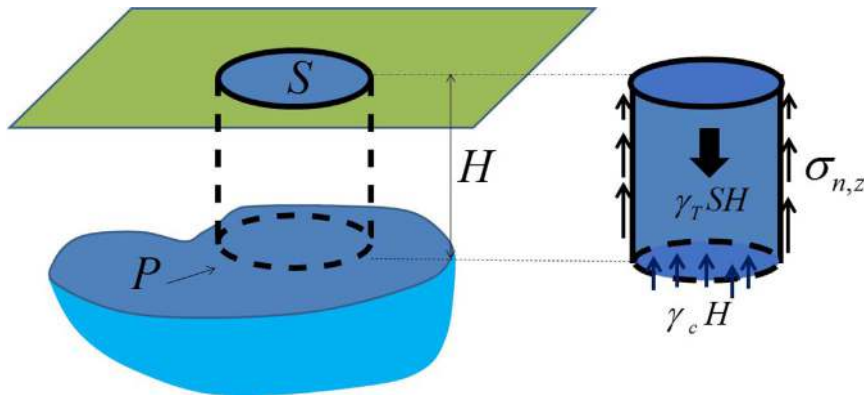


Fig. 9. An arbitrary contour, area S , perimeter P , is drawn above the H -deep cavern. Equilibrium of the cylinder results from the effects of rock weight ($\gamma_T S H$), brine pressure at cylinder bottom ($\gamma_c H$) and shear forces ($\sigma_{n,z}$) on the cylinder edge.

Table 1
Parameters of several piston collapses.

	Fluid at cavern top	Collapse duration	Final Roof depth	Area cleared At cavern top	Max. Diameter below salt top	Chimney diameter
St-Maximilien	Air	2 s	160 m			150 m
Cerville	Brine	1 day	120 m	8–10 000 m ²	180 m	150 m
Gellenoncourt	Air	< 15 min	146.5 m	1875 m ²	180 m	64–90 m
La Rape	Air	< 15 min	110 m	4 000 m ²	95 m	25 m ^a
Berkaoui	Brine	?	< 450 m?	?	300–400 m?	200 m

^a And 50 m three months after the collapse.

siltstone (Small veins of gypsum may be present.) and the Wellington Shale, composed chiefly of silty gray shale, with some interbeds of limestone and gypsum. Beneath the shales, at depths ranging from 400 ft to 525 ft (120–160 m) below ground level (bgl) is the top of the Permian Hutchinson Salt Member, which has a thickness of approximately 350 ft (105 m).

Brine wells have been operated in this salt formation since the late 1880s. Before the 1979 regulations were enforced, no salt roof was left at the cavern top, exposing the shale layers to water or brine, which resulted in shale layers weakening and sloughing. Stopping can be active for several decades and sometimes results in sinkhole formation.

4.1.1. The Cargill plant sinkhole

On the morning of October 21, 1974, it was observed that the surface was subsiding in an area south of the Cargill salt plant located in the east part of the city. Railroad tracks crossing the site were left suspended in midair²² (see Fig. 10). By noon, the growing crater had a diameter of 200 ft (60 m). Settlement continued until the afternoon of October 23, when the crater stabilized at a diameter of about 300 ft (90 m), with edge walls nearly vertical. The maximum depth of water was measured to be 37.5 ft (11.5 m) bgl. In November 1975, one year later, the Solution Mining Research Institute (SMRI) drilled ten holes, two on the banks of the sinkhole and eight from a barge. The nearly flat bedrock surface (at the top of the Ninescaw shale) was reached by seven wells at depths near 70 ft (21 m) bgl [and 50 ft (15 m) below water level, which is 21 ft (or 6.4 m) bgl]. Three boreholes near the center of the pond in the deepest water failed to encounter the shale bedrock, which had collapsed in the cavern below. (Because of technical limitations, holes could not be deeper than 70 ft (21 m) below water level — i.e., 90 ft (27 m) bgl.) The average diameter of the central collapsed area was estimated to be 110 ft (33 m), much smaller than the sinkhole diameter. The sinkhole resulted, in sharp contrast with the Lorraine examples described above, from a *horizontal* displacement of a volume of 90,000 cubic yards (68,000 m³) of loose sands and gravels



Fig. 10. Cargill salt plant, Hutchinson, Kansas, 1974.²¹ (Some 14 h after the collapse, the sinkhole diameter was 200 ft.) (Photograph by Hutchinson News, October 21, 1974.).

toward a central hole. It appeared that in this area, where many brine wells were operated at shallow depths of 400–750 ft (120–225 m) using the dissolution gallery method, a salt cavern had been over-brined. The span capabilities of the overlying rock layers had been exceeded, leading to progressive collapse of the overlying rocks until the uppermost bedrock ledge was breached, permitting sands and gravels to flow to the underground cavern. At that time, this explanation was tentative, as investigation drill-holes were not deep enough to reach the cavern.

4.1.2. The Carey salt well #19 sinkhole

Carey salt well # 19 was abandoned in 1922. On the evening of January 3, 2005, a sinkhole developed rapidly around the wellhead.²³ Its depth was 45 ft (13 m), and its horizontal maximum diameter was 210 ft (63 m). Fig. 11 (left) is a view to the south that includes the sinkhole, a pre-existing brine pond and a railroad track within 34 ft (11 m) of the sinkhole edge. Well #19 casing can be seen on this figure, standing vertical in the N-W part of the sinkhole, clearly suggesting that no rigid rock cylinder had fallen. (The well casing should have dropped accordingly.) This was confirmed by a deviated well and a sonar survey performed in the upper part of the cavern (Fig. 11, right). The cavern bottom was 155 ft (46 m) below water (180 ft or 54 m bgl), much higher than salt-top depth. Over more than 80 years, the cavern had progressed upward through stopping till it reached the water-saturated sands and gravels that flowed into the cavern as through an hourglass.

These two examples (Cargill plant and Carey # 19 well) clearly cannot be explained by the piston model. Sinkhole formation can be divided into two steps. During the first step, not very different from the Lorraine case, the rocks overlying the cavern progressively collapse until the cavern roof reaches and breaches the last competent layer underneath the shallow loose materials of the Equus bed aquifer. During the second step, shallow loose materials flow to the breach, similar to sediments in a submarine landslide; the flow is horizontal in most of the sinkhole and is relatively slow. (In the Cargill case, it took two days to reach the final stable shape of the crater.) One may ask why no rigid piston drops before cavern roof reaches bedrock top. A complete explanation would require a precise comparison of the mechanical and physico-chemical behavior of the Lorraine and Kansas layers above the salt formation. It is clear that, in Lorraine, the overburden above the salt formation is reinforced by the competent Dolomite layer. Fig. 11 suggests that, in Kansas, the stopping process is such that when cavern top rises, cavern diameter strongly decreases, leading to more stable caverns.

4.1.3. The Panning sinkhole

A slightly different case also was described in.²² On April 24, 1959, at 9:05 a.m., dust, mud and dirt were seen being blown into the air from an old well. “A cone-shaped 40-ft (12-m) deep, 75-ft (23-m) across, sinkhole was forming in loose sand and gravel with large flows of water rushing in. It rapidly grew to 200 ft (60 m) in diameter in 3 h. The eye-witnesses estimated ... it was 100 ft (30 m) deep” (²², p.33; see Fig. 12; the wellhead is clearly visible, standing at the left side of the central lake), suggesting that water was flowing into an empty underground cavern. By the evening, the crater diameter reached 300 ft (100 m), and the water level was 50–60 ft (15–18 m) below the surface. Three days later,

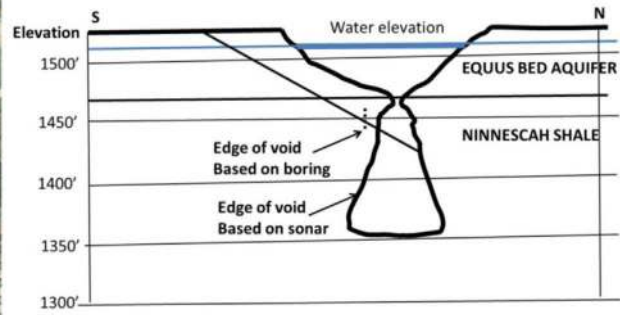


Fig. 11. Well # 19 sinkhole view and vertical cross-section, after.²¹ A deviated well and a sonar survey proved that sediments flowed into the cavern through a narrow central hole.

the sinkhole size had not changed significantly, but the water level was 11.5 ft (3.5 m) below grade. Walters postulated the following sequence of events.

In 1938, the 11 A borehole was drilled into the Arbuckle oil-bearing formation; the production casing was set at a 3268-ft (1000-m) depth. Oil was produced from 1938 to 1943, but in 1946 – 1949, 11 A was converted to a brine disposal well to the depleted Arbuckle. The tubing was removed in 1949; from 1949 to 1958, brine was disposed directly down the casing. Casing leaks permitted access to the salt face for unsaturated brine flowing to the Arbuckle aquifer. A large cavern, more than 300 ft (90 m) in diameter, was created. It was filled progressively with falls of shale interbeds and roof shales. The salt top is 975-ft (290-m) deep. The void migrated upward to the Stone Corral anhydrite, whose depth is 465 ft (142 m) (²² p. 57), and the subsidence began at ground level. In January 1959, the derrick was removed, as it tilted dangerously. On April 14, 1959, the well was plugged and the void, now relatively shallow, was isolated both from the near surface and the Arbuckle formation. Ten days later, on April 24, “the uppermost keystone bedrock at a depth of 106 ft [32.3 m]”²² fell in the cavern, generating both a flow of sand, gravel and water to the cavern and a gas (water vapor?) blow-out from the cavern. Walters suggests that well plugging severed the hydraulic connection between the cavern and the shallow Equus bed aquifer: the brine level dropped in the cavern to reach pressure equilibrium with lower aquifer layers, situated above the Arbuckle aquifer. The cavern roof was left unsupported from below, leading to void at the cavern top. This is what makes this case unique but somewhat similar to the La Rape or Gellenoncourt cases described above.

4.2. Hourglass sinkholes in salt domes

The examples described above are related to bedded salt formations. As mentioned by Neal et al.,²⁴ “relatively few caverns in domal salt have failed completely”. Two reasons can explain this. Domal salt caverns often are elongated cylindrical caverns, with a high H/R ratio. In most cases, a thick salt roof is left between the cavern roof and the dome cap rock, which is composed of relatively strong rocks. Two examples are provided below. In the first, the cap rock was breached during brining. In the second example, a breach was created at great depth between the cavern wall and the dome flank.

4.2.1. The Bayou Choctaw Cavern 7 sinkhole

At Bayou Choctaw, Louisiana Cavern 7 was being operated for brine production in 1954. At that time, cavern control was poor. No salt roof was left, and the cavern “... was leached completely through the cap rock” (²⁴, page 1). In January 1954, “... it did not take more than about a day and an 800 ft [250 m] diameter sinkhole formed” (²⁴, page 1). Few details are available; it is likely that loose shallow sediments filled the cavern through a breach created in the caprock at cavern top.

4.2.2. The Bayou Corne sinkhole

On August 3, 2012, a sinkhole was discovered in the swamp near Bayou Corne in Assumption Parish, Louisiana. The description below focuses on geo-mechanical aspects (This description benefited from many discussions with colleagues from the Bayou Corne Commission, mandated by the State of Louisiana, and from information provided by CB&I, a consulting company; however, the views expressed here reflect the opinions of the author). Numerous gas bubbles had been observed

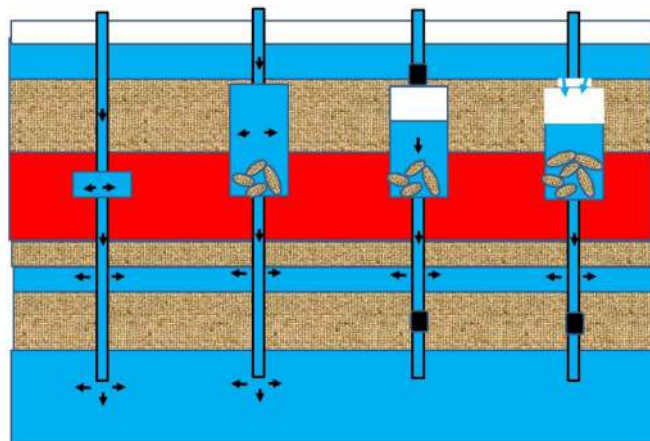


Fig. 12. Panning Sinkhole, Kansas, left [Photo taken on April 24, 1959, by Larry Panning²¹] and tentative explanation of the final collapse, after²¹: water pressure and water level dropped in the cavern after plugging severed the hydraulic connection between the cavern and the shallow aquifer, leading to final collapse.

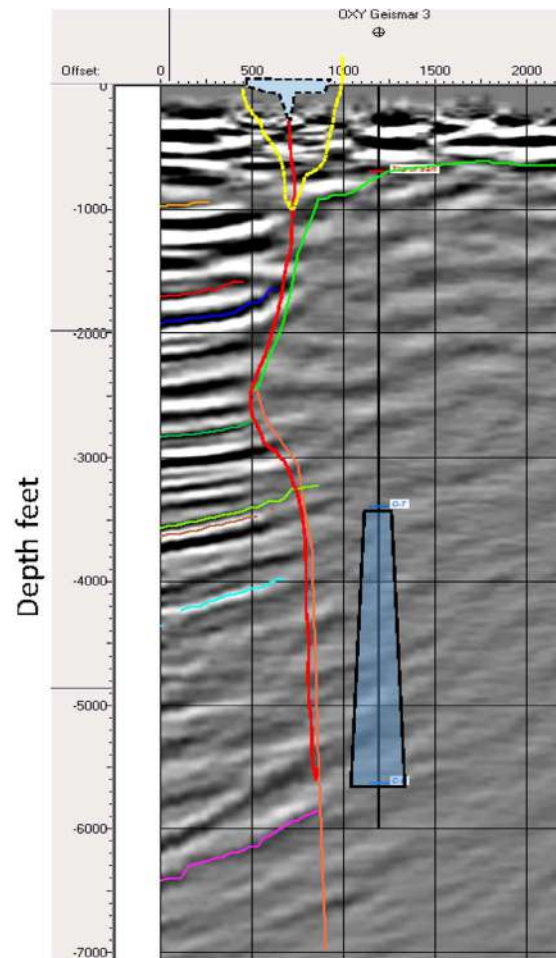
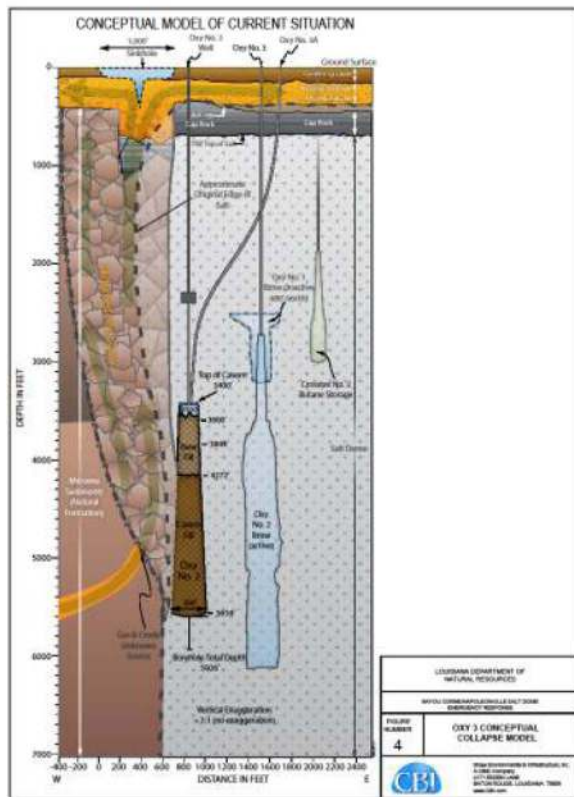


Fig. 13. Initial conceptual model of the Oxy3 cavern showing the sinkhole, the flank of the salt dome, the 5000-ft (1600-m) deep breach, and the Oxy3 cavern, 90%-filled with sediments (Source: CB&I) and a recent interpretation (Acknowledgement: Kevin Hill, 2015.)

as early as May 31, and tremors had been felt since June 8. The sinkhole was within a short distance from the footprint of the Napoleonville salt dome, where dozens of caverns had been leached out. It quickly was suspected that the sinkhole was related to Oxy3, an elongated axisymmetric cavern which, as established by a 2007 sonar survey, had a height of 2200 ft (670 m). Cavern radius was 100 ft (30 m) near the cavern roof at a 3395-ft (1050-m) depth; it was about 150 ft (45 m) at its widest point (near the cavern bottom, see Fig. 13 which displays a conceptual model by CB&I and a recent interpretation by Kevin Hill). In 1982, when the well associated with the cavern was permitted, it was thought that the edge of the dome was at least 1000 ft from the cavern. Vertical seismic profiles and more recent 3D seismic profiles showed that the salt wall between the dome edge and the cavern wall was much thinner than previously believed. In addition, a tightness test performed before abandoning the cavern in 2010 (at which time, cavern volume was approximately 23 million bbls or 3.7 million m³) proved that the cavern was not able to sustain high brine pressures, clear proof of existing leak pathways. It was inferred that the salt wall had breached inward, allowing sediments to flow down from ground level to the cavern through the newly created breach and, on their way to the cavern, to disrupt gas-bearing sedimentary layers, generating tremors, gas bubbles in the swamp and, ultimately, sinkhole creation.

These events prompted a variety of actions. The sinkhole was fathomed and its bottom changes surveyed, and a comprehensive micro-seismic array was set for tremors monitoring and localization. A relief well, Oxy3A, was spudded and re-entered the cavern on September 24, 2012. This allowed performing a sonar survey, wire-line bottom tags and, when the well was shut in, wellhead pressure measurements.

Measurements pointed to the fact that a plug of sediments, overlain by sludge (a mixture of oil and sediments?) was slowly and consistently rising in the cavern as sediments entered the cavern and sinkhole size was increasing. When Oxy3A was shut-in, brine pressure at cavern top built up to a level such that the loss of volume resulting from piston rise was balanced by the loss of brine flowing downward through the porous piston. Sediments flowed from the sinkhole to the cavern as a highly viscous material through a Disturbed Rock Zone (DRZ) along the dome edge. However, this flow through the U-Tube was not frictionless as occasional “stick-and-slip” phenomena (Terje Brandshaug, personal communication) resulted in small tremors and waves at the sinkhole surface. In February 2014, sinkhole dimensions were 600 m in the NE-SW direction and 460 m in the E-W direction. The sinkhole volume was estimated to be 65% of the 2010 cavern volume, and wire-line tags suggested that the slurry above the sediments had reached the cavern top. The breach in the salt wall is likely to have occurred in the lower part of the cavern, where salt-wall thickness was minimal. A remarkable event occurred in April 2014. A cypress root, tangled around a logging tool, was recovered from the Oxy 3 A relief well. This strongly suggested that material from the ground level had been given time to reach the cavern before the top of the sediments in the cavern reached the upper part of the breach. In other words, the volume of the DRZ is roughly equal to the volume of the cavern below the top of the breach, and the average diameter of the DRZ is significantly smaller than the diameter of the cavern (which is 150 ft or 45 m in the lower part of the initial cavern).

These facts raised a puzzling problem. How did a 1000–1500 m cylinder of rock with an average diameter of a few dozen meters drop

Table 2
Sinkholes classification.

	Country	Geological Formation	Breach depth	Stoping	Fluid at cavern top	Cavern or Mine	Sinkhole Type
St-Maximilien	France	Keuper	160 m	No	Air	Mine	Piston
Cerville	France	Keuper	120 m	Yes	Brine	Cavern	Piston
Gellenoncourt	France	Keuper.	146.5 m	Yes	Brine	Cavern	Piston
La Rape	France	Keuper	110 m	Yes	Brine	Cavern	Piston
Haoud Berkaoui	Algeria	Senonian	450 m?	?	Brine	Cavern	Piston
Bereznikovskiy	Russia	Lower Permian	50 m	Yes	Air + CH ₄	Mine	Piston
Cargill Plant	Kansas	Hutchinson	21 m	Yes	Brine	Cavern	Hour-glass
Carey #19	Kansas	Hutchinson	16 m	Yes	Brine	Cavern	Hour-glass
Panning Well	Kansas	Hutchinson	30 m?	Yes	H ₂ O vapor?	Cavern	Hour-glass
Bayou Choctaw	Louisiana	B.C Dome	180 m?	?	Brine	Cavern	Hour-glass
Bayou Corne	Louisiana	Napoleonville Dome	1500 m	Likely	Brine	Cavern	Hour-glass

into the cavern along the dome edge? This is not consistent with Eq. (5) unless it is accepted that the cohesion and friction angle in this cylinder are quite small, or even zero. The opinion of the author is that, at the edge of the dome, a sheath composed of loose and soft sediments was formed during geological times (the product of early natural dissolution of the flank domes). This remarkable configuration allowed loose sediments to flow through the DRZ, as through an hourglass of unusual size and shape, to the 23-million-bbbls cavern until completely filled.

4.3. The role of cavern fluids

In these hourglass cases, sinkhole contours were approximately circular, as in the rigid-cylinder (“piston”) cases. However, the reason here is that the horizontal flow of sediments to the hole at the center of the sink tends to be axisymmetrical.

In principle, the volume of sediments flowing downward into the cavern must be balanced by an equivalent volume of brine flowing upward from the cavern to the sinkhole (and/or to sedimentary layers at the dome flank, in the case of the Bayou Corne sinkhole). In the case of the Cargill crater, “samples of the water in the sinkhole taken October 22, 1974 [the day after sinkhole creation] ... had a chloride content of 89,000 ppm”²²; two weeks later, the chloride content was 1525 ppm — in other words, a slug of brine was displaced to the sinkhole “but substantially dissipated within two weeks”.²² One might expect that such two-way flows of sediments and brine generate no, or a small, change in the crater water level. However, this was not true in the case of the Panning sinkhole. Walters suggested that a vacuum was created in the cavern after the well was plugged and abandoned: room was made available for a downward flow of water to the cavern that did not need to be fully balanced by an upward flow.

5. Waves in the crater lake

An additional comment can be made; it is common to both the piston and the hourglass models. Water-filled craters, as any lake, are the seat of tidal waves. These waves are essentially gravity-driven, and their period depends on the size and the shape of the crater bottom. In most cases, their amplitude is too small to be detected; however, at Bayou Corne, these tidal waves were clearly visible; they were triggered by landslides at cavern bottom as sediments entered the DRZ, or by gas “burps” rising from deep sedimentary layers. In the case of an idealized perfectly cylindrical lake of radius \bar{R} and depth \bar{h} , the period of the fundamental mode, such that the fluid surface sways from one side to the other, is $T \approx 2\pi\bar{R}/1.834\sqrt{g\bar{h}}$ ²⁵ (SI units are used). For instance, if $\bar{h} = 90\text{m}$ and $\bar{R} = 150\text{m}$, $T = 35\text{--}40\text{ s}$, the kind of periods observed at Bayou Corne. Such periods also were observed immediately after the cavern collapse⁶ at Cerville-Buissoncourt, where $\bar{h} = 40\text{ m}$, $\bar{R} = 150\text{m}$ and $T = 20\text{ s}$. However, these waves can be coupled, more or less strongly, to waves generated in the system composed of the underground cavern and the conduit that links the cavern to the crater. In the

case of the Cargill sinkhole, “a rolling motion associated with the water contained in the sinkhole”,²² p. 19, was observed; this motion quieted when nearby wells were shut down. (The cavern below the sinkhole communicated with many interconnected caverns.) The period of the first eigenmode of such a water-filled underground void system is much longer when it is linked to the ground surface through opened wells,²⁶ a circumstance that may have played a role at Bayou Corne.

6. Results and discussion

Analysis of a dozen cases in France, Algeria, Russia, Kansas and Louisiana (Table 2) strongly suggests that two types of mechanisms can lead to the creation of a sinkhole above a salt-production cavern: the piston type (A cylinder of rock drops abruptly into the cavern without experiencing deformation.) and the hourglass type (Loose sediments flow to the cavern and fill the cavern through a breach.) These mechanisms are somewhat similar to those that lead to sinkhole creation above karsts (collapse and suffosion). A couple of differences are worth mentioning. In bedded-salt caverns, weathering of the marly overburden by saturated brine and stoping are, in most cases, an essential part of the collapse process. This process is relatively slow (taking years or decades), and an over-brined cavern can remain stable until the weathering process is completed. Such a configuration may not exist in the case of a karst void, as carbonate or gypsum dissolution is exceedingly slow. At a large scale, piston collapse can be described as shear failure—a mechanism that explains why crater contour is circular. However, at a smaller scale, tensile failure of stiff layers or even hydro-fracturing (when the brine pressure of the cavern becomes larger than geostatic pressure due to piston displacement) might be effective mechanisms. The Bayou Corne case (in which sediments flow from ground level to a breach in the salt flank at a depth of 1500 m) remains puzzling; further evidence of the formation of a loose sheath at geological time scales is needed.

It is difficult to draw definite conclusions when prevention, monitoring or mitigation is concerned: each geological configuration must be discussed on a case-by-case basis. However, a few important lessons can be drawn. In bedded-salt formations, a salt roof must be left between the cavern top and the overburden to prevent weathering of the marly overburden. In domal salt formations, some distance must be left between the cavern and the dome caprock or flanks to prevent breach creation and a flow of loose sediments to the cavern. A maximum radius/depth ratio can be defined, above which the rock cylinder above the cavern cannot be stable. Such a ratio has been respected empirically in salt caverns used for hydrocarbon storage, as no collapse case is known.

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