Introduction

The next three articles discuss gases held within salt and is an attempt to address the following questions; 1) What is the scale and location of known rock-bursts/gas-outbursts in salt rock? 2) Where do gases reside in a salt mass at the micro- and meso-scale? 3) What are the gases held in salt? 4) How are gassy salts distributed across various salt deposits across the world (macro-scale) and what are the lithological associations? Topics 1 and 2 are the main focus of the first article, topic 3 mostly in the second, while topic 4, where do gases held in salt generate and reside at the scale of a salt mass or salt bed, is the focus of article 3. Along the way, we shall also discuss whether some of the encapsulated gases in salt can be considered samples of the ambient atmosphere that have been held in brine inclusions since the salt bed was first precipitated? And, as a corollary, we will come to a discussion of how did some of the occluded gases first enter or remobilize through the salt mass during the long history of burial and salt flow (halokinesis) experienced by all ancient evaporite units?

Gases in evaporites can create problems

Various gases such as, carbon dioxide, nitrogen, methane, hydrogen and hydrogen sulfide, can occur in significant volumes in and around domal salt masses or bedded evaporite deposits, as seen in numerous documented examples in mines and drilling blowouts in Louisiana, New Mexico, Germany, Poland and China (Figures 1, 2; Table 1). Gases are held in pressurized pockets in the salt that, if intersected, can create stability and safety problems during an expansion of operations in an active salt mine or during petroleum drilling, especially if the pockets contain significant levels of toxic or flammable gases, sufficient to drive rockbursts or gassy outbursts into the adjacent opening. A gas outburst (or rockburst) is defined as an unexpected, nearly instantaneous expulsion of gas and rock salt from a mine production face, normally resulting in an expanded open cavity in the salt. Outburst cavity shapes are generally metre- to tens of metre-scale combinations of conical, cylindrical, hemispherical, or elongated shapes with an elliptical cross section decreasing...

Figure 1. Salt anomalies and rockburst sites. A) Klowda salt mine, Poland. The black salt is associated with elevated levels of methane and hyrocarbons in inclusions in the salt (after Weseluca-Birczynska and Tobata, 2016). B) Hattorf Mine, Germany, illustrating sulfur-rich salt rock thrown out by a gas outburst (predominantly CO₂) 20 m away from a basalt dike. The original evaporite rock has locally been replaced completely by sulfur. The typical fissility of the gas-bearing salt rock can be seen (Knipping 1989).
in diameter away from the opening (Figure 1). Many mapped examples in salt mines of the US Gulf coast have the shape of a cornucopia (Molinda, 1988).

In the case of blowouts during oil-well drilling, there are two dominant styles of overpressured-salt encounters. The first, and the main focus in blowout discussions this article) is when gas-ky fluid outbursts occur internally in the salt unit as it is being drilled. Generally, this happens on the way to a test a deeper subsalt target, or less often on the way to test as series of intrasalt beds. Once intersected, pressures in such intrasalt pockets tend to bleed off and so decrease in hours to days as pressure profiles return to normal (Finnie, 2001; Warren 2016; Chapter 8). Providing the drilling system was designed to deal with short-term high-pressure outbursts, drilling can continue toward the target. The other type of gas outburst encountered when drilling salt is high-pressure outbursts, drilling can continue toward the target. The other type of gas outburst encountered when drilling salt is high-pressure outbursts, drilling can continue toward the target.

Perhaps one the most impressive examples of this type of blowout, and the ability of evaporite unit to seal and maintain an overpressured subsalt pressurized cell, comes from the Alborz 5 discovery in Central Iran (Figure 3; Morley et al., 2013; Gre- tener, 1982; Mostofi and Gansser, 1957). Earlier wells testing the Alborz Anticline had failed to reach target due to drilling difficulties coming from “an extremely troublesome evaporite section that continually menaced drilling and caused numer-
ous sidetrack operations.” So difficult was drilling through this stressed Upper Red Formation salt unit that it had taken eight months for a previous well to drill through some 170 metres of evaporitic sediments to reach the Qom target. Later wells testing a Qom Fm. target, like Aran-1 to the south of the Alborz anticline, did not intersect thick stressed halite above the Qom Fm., only an anhydrite layer that perhaps was the dissolution resi-dues of former halokinetic salt mass (pers obs.). The discovery well in the Alborz anticline (Alborz 5) had drilled through some 2296 m of middle to late Tertiary clastics and some 381 metres of Oligo-Miocene salines in the lower part of the Upper Red Formation and made up of siliciclastics, banded salt, anhydrite (Figure 3). On its way to the blowout point, the lower part of the well trajectory had penetrated normally to slightly overpressured dirty salt (halokinetic) and then penetrated some 5 cm into the fractured subsalt Qom Limestone (Oligo-Miocene). On August 26, 1956, the entire drill string and mud column were blown back out the hole and many metres into the air. At that time, the mud pressure was 55 MPa (8,000 psi) at a reservoir depth of 2700 m (8,800 ft), a pressure depth ratio of 20.5 kPa/m or 0.91 psi/ft (a lithostatic value!). Over 82 days, the well released 5 million barrels of oil and a large, but unknown quantity of gas before it self-bridged and the flow died on November 18, 1956. The temperature of the oil at the surface was measured at 115°C and at the time of the blowout the mud column density was 2.07 x 10³ kg/m³ (129 lb/ft³)(see Figure 3). This type of subsalt over-pressured gas occurrence illustrates salt’s ability to act as a highly effective seal holding back huge volumes of highly overpressured fluid. Associated occluding processes are discussed in an earlier series of Salty Matters articles dealing with salt as a seal, espe-
cially the article published March 13, 2016.

Gassy salt (knistersalz)
Much of the occluded gas in a salt body, prior to release into a mine opening or well bore, is held within inclusions within salt crystals or in intercrystalline positions between the salt crystals. Gas-entraining rock salt, was known from salt mines of Poland and in East Germany since the 1830s and described as knis-tersalz (literally translates as “cracking salt”). In many mines, walking on knistersalz releases gas as little popping sounds from underfoot. The pressure of the shoe adds a little more stress to an already gas-stressed fragment of salt (Roedder, 1972, 1984).
Dumas (1830) first described such “popping salt from Wieliczka, Poland, and concluded that gas was evolved, presumably from compressed gas inclusions, upon dissolving the salt. Further details on the occurrence were given by Rose (1839). As we shall see, this type of salt can cause serious mine accidents when large volumes of salt explosively and spontaneously decrepitate into the mine openings as rockbursts. Dumas (1830) and Rose (1839) found the released gas from “popping” salt in Germany to be inflammable. Bunsen (1851, p. 251) found 84.6 % CH$_4$ in the gas released during the dissolution of Wieliczka salt, while in many early mines in Germany the occluded gas phase is dominated by nitrogen or carbon dioxide (see Article 2).

Knistersalz will “pop” sporadically once placed in water, releasing pressurized gas bubbles as the salt matrix dissolves. This simple demonstration of gas presence is also the foundation for one method of determining the gas content of a rock salt sample (Hyman, 1982). The sometimes rather energetic “pops” that can occur as gases are released from a gas-enriched rock salt sample attest to the high pressures under which the gases are occluded. Pressures postulated in knistersalz can be near-lithostatic and even higher depending on local stresses, related to the low creep limits of rock salt, particularly around mine openings. According to Hoy et al. 1962, CO$_2$-bearing gas mixtures in the knistersalz of the Winnfield salt dome (Louisiana, USA) is under a pressure of 490 - 980 bar (49 - 98 MPa) at 0°C. Similar values (500 - 1000 bar or 50 - 100 MPa) are given by Hyman (1982) for gas bubbles held in rock salt in various Louisiana salt domes. For example, during exploratory drilling in one such Louisiana salt dome, methane gas was released from the salt under a pressure of 62 bar (6.2 MPa) at a flow rate of 1.2 m$^3$/hr (Iannachione et al., 1984).

Mining causes a pressure drop in the rock salt as it is extracted from a working face and such pressure drops can change the phase of a fluid occluded in salt, or change the solubility of a gas dissolved in such a fluid. Carbon dioxide, in particular, is susceptible to a phase change because its critical point is close to some ambient mining conditions. As long as CO$_2$ is present above 1070 psi (7.4 MPa) and below 31°C (88°F; critical point), it will be in a liquid phase. Such conditions are not typical in salt mines in the US. However, CO$_2$ generally exists as a liquid in rock salt in many German potash mines (Gimm, Thoma and Eckart, 1966). When mining drops the pressure (from lithostatic to near atmospheric) the CO$_2$ phase will change to a gas, causing abrupt expansion. The sudden change also results in a 5 to 6°C cooling, as measured in regions near large outbursts (Wolf, 1966). The solubility of gases dissolved in brine also changes when mining.
<table>
<thead>
<tr>
<th>Location</th>
<th>Rock unit</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle Isle Mine</td>
<td>Louann salt in salt dome</td>
<td>Shortly before 11:00 p.m. on June 8, 1979, a scheduled blast was initiated in the Belle Isle Mine, a salt mine. About ten minutes later a gas explosion occurred, that blew out ventilation controls, including stoppings and doors, and upended trucks and other heavy machinery. MSHA investigators determined that the scheduled, initial blast had triggered a massive “outburst” of about 15,750 tons of broken salt and flammable gases. Included in these gases were methane and minute quantities of other hydrocarbons, which were ignited by electric arcs, sparks, or burning electric cable insulation. (5 killed) ———— A fire occurred on Tuesday, March 5, 1968, at about 11:30 p.m. in the Belle Isle Salt Mine, while 21 men were working underground. There were no survivors; 20 died of carbon monoxide poisoning, and one as a result of massive skull fracture. A subsequent 6-month investigation could not identify either neither the cause of the fire or the point of origin although it appears that the fire originated in the lower part of the shaft at about, or below, the mining level. I is likely an escape of methane from the salt was involved. The cause of ignition could have been an electrical fault, use of an oxyacetylene torch, or frictional ignition of a belt conveyor, but the cited evidence does not clearly favour any one of the three possibilities. Direct property damage was confined to the mine shaft and its equipment. (21 Killed)</td>
</tr>
<tr>
<td>Jefferson Island Mine</td>
<td>Louann salt in salt dome</td>
<td>Were four levels, deepest at 450 m. Inclusions in salt contained sediment, brine and gas. There were several large rockbursts near edge of dome shear zone</td>
</tr>
<tr>
<td>Cote Blanche Mine</td>
<td>Louann salt in salt dome</td>
<td>Gas has also been known to bleed from natural fractures in salt, from blast drill holes, r from undercutting a face in preparation for blasting. In at least one instance where a continuous miner was used, gas was emitted (1,000-8,000 ft³/d) through the face and ribs, migrating primarily along layering within the salt. Detailed mapping also revealed that the zones are well defined, with salt crystal size abruptly increasing upon entry into the zone. The intensity of folding and kinking of the salt layering within the outburst zone also appears to increase. An interbedded sand layer occurring throughout the mine does not appear to be a significant source of methane. However, fine-grained salt may be related to outburst occurrence.</td>
</tr>
<tr>
<td>Weeks Island Salt Mine</td>
<td>Louann salt in salt dome</td>
<td>Two operational levels at 150 m and 250 m. A number of small to medium-size outbursts in shear zones at edge and in centre of dome</td>
</tr>
<tr>
<td>Winnfield salt mine</td>
<td>Louann salt in salt dome</td>
<td>Sublevel, at 190 m, flooded. Main level was 250 m, Inclusions containe brine, CO₂, 10% anhydrite. The five outbursts or ‘blowouts’ occurred within 150 m of the edge of the dome</td>
</tr>
</tbody>
</table>
| Potash mines Carlsbad mining district | Salado Fm Northern Delaware Basin | Dec 13, 1983. Kerr-McGee Mine, 10th ore zone. A mining machine was found 25 ft away from rockburst face. An estimate 15 tons of ore was blown out and a cavity of some 60 ft³ formed, centred on a vertical fracture trending 122°. One fatality. There were other non-fatal gas blowouts in this mine; an earlier one on Dec 13, 1963 and a later one on Jan 23 1964, which blew back a mining machine some 2 feet. The machine operator suffered no serious injuries due to installation, after the Dec 13 rockburst, of a protective steel grid that surrounded the operator’s cage.  
Dec 16, 1973 to Feb 24, 1974. Eddy Mine, North Section. Release of trapped gases via a floor break. Later sample from fissure contained 12% oxygen and 16% methane (likely was nitrogen dominant but this was not measured). On 24 Feb, 1974, and area of bottom, measuring some 230’x230’, fell 30 to 40 feet, after a gas release. At the same time a section of roof, measuring 6’x8’, fell in to the centre of the floor-fall area (Chatuvedi, 1984) |
| Oct 3, 2016, WIPP site. Roof falls. On Sept. 27, 2016, crews discovered a mound of collapsed salt blocks (roof fall) in an entry chamber to Panel 4, a storage area officials say has been filled to capacity since 2010. The rockfall is located well away from the Panel 4 storage site. Due to earlier problems related to a contaminated ventilation system, no one had accessed the area to conduct routine maintenance in the previous six months. On Tuesday, Oct 3, 2016 a second rock fall was found in Panel 3, another restricted area. No maintenance work had been done on bolt heads that secure the salt rock in this are since access to the area was restricted in November 2014 due to a radiogenic release and contamination incident that partially compromised the sites subsurface ventilation system. Gas likely played no major role in the rock falls. The roof is expected to close and collapse over the longterm, so sealing the waste the problem is shortterm due to a lack of access for roof main- tenence (news report <http://www.santafenewmexican.com> last accessed 25 Oct, 2016). |
| Cane Creek potash mine | Salt and potash in Paradox Fm. | Both crude oil and natural gas (methane) were encountered during mining operations. Like brine in the mine that drained without ongoing connection, methane and other hydrocarbons were found only in the MA marker bed lithologies but not within the sylvinite or halite beds. A methane explosion killed eighteen miners on July 31, 1963, and the accident occurred during the development of the incline from the bottom of the shaft to the potash ore zone proper. The explosion occurred 20 minutes after the 2 south face was blasted. The source of the gas is suspected to have been from interbed 3, situated well above the K5 potash zone. (18 killed) |

Table 1. Documented regions in salt basins prone to occasional rockbursts and gassy outbursts (compiled from SaltWork database 1.8)
For example, the solubility of methane in brine is extremely low at atmospheric pressure and so is released as gas bubbles from a brine issuing from rock salt fissures upon mining, as observed in a number of US Gulf Coast salt mines (Iannacchione and Schatzel, 1985).

Pressures released during an outburst result in velocities at the outburst throat which can be very large and locally approach sonic velocities (Ehgartner et al., 1998). Velocities of more than 152 m/sec (500 ft/s) have been recorded in vertical airways some distance from rockbursts in Germany. Velocities at the rockburst site would be even higher. Narrow throat characteristic of some rockbursts can result in throttling. However, associated pressure waves are not strong enough to cause the observed levels of equipment destruction, since they are of a magnitude similar to those found in blasting. Rather, observed damage associated with rockbursts is due to flying debris in the pressure wave as the quantities of rock thrown out by the burst have high kinetic energy (Wolf, 1966).

Table 1. Documented regions in salt basins prone to occasional rockbursts and gassy outbursts (compiled from SaltWork database 1.8).

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<td>Goderich salt mine, Ontario</td>
<td>Salina Salt, Michigan Basin</td>
<td>Large roof outbursts began occurring in November 1986 at Domtar’s Sifto Salt Mine in Goderich, Ontario, Canada, working the bedded Salina A-2 Salt unit. Within three months (1986/87) three gas outbursts occurred. The outbursts, measuring about 13-20 m in diameter, released high concentrations of methane from cavities that extended into carbonate roof units. Spontaneous ignitions of methane gas during an outburst seriously burned a mine technician. The salt extraction is by single level regular room and pillar mining in the stratified salt deposit which leaves a protective rock salt layer towards roof and floor strata. The gas outbursts are related to gas release from pressure pockets due to the close vicinity of roadways excavation, and pressure pockets which are located in the shale formations overlying salt beds. Gas outbursts were followed by a methane flash fire which was ignited during its expulsion.</td>
</tr>
<tr>
<td>Wieliczka salt mine, Permian</td>
<td>Zechstein, Permian</td>
<td>During mining operations, pockets of brine were only encountered within the M4 marker bed, above Salt 5. When encountered, the yield of brine was finite and minimal; a small amount would quickly drain from a cavity. Neither brine nor brine pockets were reported from within halite or sylvinite beds.</td>
</tr>
<tr>
<td>Menzengraben mine, Saxony</td>
<td>Zechstein, Permian</td>
<td>July 7, 1953 the largest rockburst event ever documented occurred, with 70,000-100,000 t of ore being thrown into the mining entries, and one million m$^3$ of gas being released. Three people were killed on the surface (because of small mine openings compared to the gas volume released), and many conveyors and some surface buildings were destroyed (7 killed). This shut the mine down for about three months. On April 17, 1958 an unusual rock-burst appears to have been triggered by surface drilling into the Hessen seam. This may have created crystal fractures, and during subsequent mining aided in causing a large rock-burst which killed 12 miners. During the period 1980-1987 in the Werra district 1,200 rock-bursts were noted, but none caused extensive damage other than the two just noted. (Post April 1958, 12 killed)</td>
</tr>
<tr>
<td>Salzungen Shaft, Permian</td>
<td>Zechstein, Permian</td>
<td>1895: In the Werra potash mining district of central Germany, large amounts of CO2 gases were encountered in 1895 at the depth of 208 m in rock salt when the shaft Salzungen reached that depth</td>
</tr>
<tr>
<td>Volkenrodena mine, Permian</td>
<td>Zechstein, Permian</td>
<td>11 July 1951, Prior to explosion, there had been a 40-hour shut-down with no ventilation, and when work resumed presumably a defective drill cable ignited the methane that had accumulated. (9 dead, 14 injured)</td>
</tr>
<tr>
<td>Aschersleben II mine, Saxony</td>
<td>Zechstein, Permian</td>
<td>1886: the shaft Aschersleben II was flooded when it had reached the depth of 300 m; a pilot hole, drilled from the temporary bottom of the shaft into the underlying Stassfurt rock salt, hit a gas pocket with H$\text{S}$—CH$\text{4}$—N$\text{2}$ gases escaping under high pressure: for two hours. At the same time an NaCl brine was ejected to the height of a “house” by the pressure of the gas mixture. Flow ceased after 2 hours and the shaft was abandoned.</td>
</tr>
<tr>
<td>Leopoldshall III, Saxony</td>
<td>Zechstein, Permian</td>
<td>1887: the shaft Leopoldshall III at Stassfurt, having been sunk through the caprock, hit a pocket containing H2S while sinking to a total depth of 412 m through the Stassfurt rock salt; in 1887, four miners were killed by gas escape, and in 1889, seven more were killed.</td>
</tr>
<tr>
<td>Bouby potash, UK</td>
<td>British Zechstein 3 (Permian)</td>
<td>Rock bursts of up to 1,000 tons of ore have been experienced, and occasionally rock bursts have blown ore in considerable volume clear back to the previous crosscut area. Generally the greatest danger is associated with higher shale contents in the ore, even though the gas is in the halite or sylvinite crystals. New faces are examined prior to working by mine geologist. (Worker John Anderson, 56, killed by a “sudden and powerful release of gas” in Bouby mine early on Friday June 17, 2016)</td>
</tr>
<tr>
<td>Verkhnekamskoe salt mines, Permian</td>
<td>Kungurian potash, Permian</td>
<td>Intersection of a zone a with a volatile gas release, can reduce output by 30%. To minimize the danger advance drilling of gas-draining holes are practiced in troublesome areas, as well as driving entry, ventilation and conveyor tunnels well ahead of mining the rooms in new panels in order to allow them to degas. After a number of accidents, ventilation was improved to maintain H2S levels below 2.1 ppm in the air stream, and the mining plan was changed to not require normal travel in the return airways. Prolonged exposure to even dilute H2S gas had caused irritation to the eyes and mucous membranes of the affected workers.</td>
</tr>
<tr>
<td>Sergipe potash mines, Cretaceous</td>
<td>Aptian salt, Cretaceous</td>
<td>Potential methane problem, gas detectors installed throughout the mine workings</td>
</tr>
</tbody>
</table>
(a blowout), or (3) as the mine or the drill bit enters some other relatively permeable geologic anomaly (Kupfer, 1990).

Gassy outbursts and rockbursts in salt

Outbursts are documented in the U.S., Canada, and throughout northern Europe in various salt and potash mines (Figure 2; Table 1). The salt domes of northern Europe and the US Gulf coast are in particular loaded with pockets of abundant gas inclusions (Ehgartner et al., 1998). Many dangerous pockets of methane and $\text{H}_2\text{S}$ were intersected during the opening of shafts into the domes of Zechstein salts in the Saxony region, Germany and several early potash mines in the area were abandoned because of problems caused by rockbursts and associated gas outflows (Gropp, 1919; Löffler, 1962; Gimm, 1968). Before the current practice of evacuating any gas-prone salt mine prior to blasting, many fatalities resulted from such gas and rock outbursts (Table 1). A significant portion of the deaths was due to secondary factors (post-rockburst), such as methane fires, CO$_2$ suffocation, and H$_2$S poisoning (Dorfert, 1966). Even with the practice of mine evacuation prior to blasting, outburst gases have in some cases filled a mine, blown out of the mine shafts, and caused fatalities at the surface. This was the case in Menzengraben in 1953, as heavier-than-air CO$_2$ gas, released by a blasting-induced rockburst, blew out of the mine shafts for 25 minutes and flowed downhill into a nearby village, where it ponded and ultimately suffocated 3 people in their sleep (Hedlund, 2012).

The most frequent and largest rockbursts and gas outflows from subsurface salt occurred in the Werra mining district in former East Germany. Gimm and Pforr (1964) report that rockbursts occurred every day in the Werra region. If one also includes potash mines in the Southern Harz region, more than 10,000 outbursts were recorded up till the 1960s in the German salt mines (Dorfert, 1966). The 1953 Menzengraben(Potash Mine No. 3) rockburst blew out some 100,000 metric tons of fractured rock salt (approximately 1.6 million cubic feet). This may well be the world’s largest rockburst in terms of cavity size (Gimm, 1968). In an earlier incident in the same region in 1886, the shaft Aschersleben II was flooded with water and gas as it reached a depth of 300 m. A pilot hole drilled from the temporary bottom of the shaft into the underlying Stassfurt rock salt, hit a gas pocket, releasing a combination of $\text{H}_2\text{S}—\text{CH}_4—\text{N}_2$ gases, which then escaped under high pressure for some two hours carrying with it a NaCl brine to the height of a “house” above the shaft floor before the outflow abated. The shaft was abandoned (Baar, 1977).

In 1887 the shaft Leopoldshall III, at Stassfurt, had been sunk through the caprock, and into the Zechstein salt to a total depth of 412 m subsurface, when it hit a gas pocket containing H$_2$S, and four miners were killed by gas escape. Subsequently, in 1889, seven more were killed during shaft construction in the same mine. In 1895, a large volume of CO$_2$ was released from rock salt at a depth of 206 m during the sinking of the Salzungen shaft (Gimm 1968, p. 547). Numerous other outbursts of gas occurred in the same Werra-Fulda district with most mines operating at depths greater than 300 meters, with outbursts responsible for a number of deaths both below and above ground. According to Gimm (1968, p. 547), since 1856, toxic gases were also encountered during the sinking of a number of other shafts in the Stassfurt area. Gropp (1918) documents 106 gas occurrences in German potash mines for the period 1907 to 1917, at depths of ≈300 meters and greater. Many of these gassy encounters caused casualties, particularly in salt dome mines of the Hannover area where several of the potash mines were abandoned due to dangerous gas intersections (Barr, 1977).

Less severe examples of gas outbursts and rockbursts transpired in other salt mines around the world (Figure 2). More than 200 gas outbursts with ejected rock salt volumes up to 4500 tons have occurred in the Upper Kama potash deposits of Russia (Laptew and Potekhin, 1989). Baltaretu and Gaube (1966) reported sudden gassy outbursts in potassium salt deposits in Rumania. Outbursts in Polish salt mines were noted by Bakowski (1966). Potash mines in England and Canada also exhibited outbursts (Table 1; Schatzel and Dunsbier, 1988) with the most recent case being a gassy outburst that caused a fatality in the Boulby mine in June 2016.

Major rockbursts, tied to methane releases, occurred in Louisiana in four of the 5-Island salt mines exploiting the crestal portions of subcropping salt domes (Belle Isle, Cote Blanche, Weeks Island, and Jefferson Island) with the exception of Avery Island. Gassy outbursts, of mostly CO$_2$, also occurred at the Winnfield salt mine, Louisiana (Table 1). Rockburst diameters range from a few inches up to over 50 ft. Cavities heights range from several inches to several hundred feet. Smaller rockburst and cavities in the Five-Island mines were ordinarily not reported (Kupfer, 1990). Only the more gas-inclusion-rich salt decrepitates in these mines, and the concave curvatures of the walls are such that the resulting slight additional confining force from the concavity keeps the remaining salt from decrepitating further (Figures 1; 4; Roedder, 1984).

The larger outburst shapes tended to be cornucopian in shape, whereas the shorter ones were conchoidally shaped with symmetrical dimensions (Figure 4). Outbursts approaching several hundred feet high were documented in the Jefferson Island and Belle Isle mines. The disaster at Belle Isle mine in 1979, in which five miners died, proved that high-pressure methane in large quantities could be released near instantaneously during a rockburst. It was estimated that more than 17,000 m$^3$ (600,000 ft$^3$) of methane was emitted by the 1979 outburst (Plimpton, et al., 1980). At the former Morton mine at Weeks Island, an even larger gas emission apparently occurred in connection with a rockburst. It was estimated that as much as 1,020 m$^3$ (36,100 ft$^3$) of salt was released as 1.4 million m$^3$ (50 million ft$^3$) of gas filled the former Morton Mine (MSHA, 1983). If the limited number of sample points represent a well-mixed mine atmosphere, the gas alone would occupy approximately 17,000 m$^3$ (600,000 ft$^3$) in the salt at lithostatic pressure (Plimpton, et al., 1980).

Outbursts occurred during mining in all three of the mines at Weeks Island - the “old” Morton mine (the site of the now abandoned U.S. Strategic Petroleum Reserve), the Markel mine, and the “new” Morton mine. Perhaps the largest outburst at the “new” Morton mine occurred on October 6, 1982, in the southwest corner of the 1200-ft level, close to the edge of the dome.
A balloon with an attached measuring string is typically used to estimate the height of the major vertical outbursts. A balloon went up more than 30 m (100 ft) into an outburst some 10 m (35 ft) wide (MSHA, 1983). Outbursts in the old Morton mine occurred only in the larger lower level (~800 ft) of the two level mine outside the vertically projected boundary of the upper (~600 ft) level. A similar trend was noted at Jefferson Island where no gas outbursts occurred in the upper level of the mine. The outbursts observed at the Jefferson Island mine were in the same relative position at both the 1300-ft and 1500-ft levels. This is attributed to the near vertical orientation of a very gassy zone of salt (Iannacchione, et al., 1984). Structural continuity (banding) is nearly vertical in many Gulf coast salt dome diapirs, except where the top of the dome has mushroomed. As a result, horizontal runs of outbursts have reportedly been small, and unlikely to connect caverns separated by 100 ft or more (Thoms and Martínez, 1978).

The geometry of the gas pockets is not well known. Thoms & Martínez (1978) argued that prior to the rockburst the gas is concentrated in vertical, cylindrical zones or pockets, which were created and elongated by the upward movement of the salt. Mapping in the Five-Island mines shows that the rockbursts are often aligned along structural trends. At Winnfield (Hoy et al., 1962), and possibly at Belle Isle (Kupfer, 1978), the outbursts occur close to the edge of the dome. In other cases (e.g., Cote Blanche and Belle Isle) the outbursts follow structural trends such as shear zones within the dome (Kupfer, 1978). In all cases, there is an association between methane gas occurrence and other anomalous features such as dirty salt, sediment inclusions and oil or brine seeps (see article 2).

Rockbursts are not limited to gassy intersections in domal salt. High-pressure pockets of inert gas, typically nitrogen, are documented in bedded potash mines (Carlsbad, NM), and combustible gases (methane) and fluids (brine and oil) in potash mines in Utah (Djahanguiri, 1984). The Cane Creek potash mine (Utah), exploiting halokinetic salts sandwiched by the bedded formations of the Paradox Basin, had a history of fatalities and extensive equipment damage as a result of rockbursts (Westfield, et al., 1963). In contrast, no gassy outbursts were reported during the construction and operation of the Waste Isolation Pilot Plant in the bedded salts of southeastern New Mexico. During WIPP construction, routine drilling ahead of the road-header checked for gas, but found very little (Munson, 1997).

In my opinion, some gas pockets in domal salt can be related to the diagenetic process creating a caprock, where methane and H_2S are typical byproducts. In others, the gases are related to the burial history and recrystallisation (partially preserving primary nitrogen), while in yet others, the gas release is related to heating and alteration especially of the hydrated salts (hydrogen) and associated fracturing related to igneous intrusion (CO_2). In
some cases, gases were encountered in fracture systems of cap anhydrite close to the top or edge of the salt dome; such fracture systems apparently had connections to the groundwater as the gassy outbursts were followed by water of varying salinity. In other cases, fracture systems headed by a gas cap connected the expanding mine to overlying aquifers and ongoing salt dissolution was facilitated. But, in most cases of rockburst located within the interior of a salt mass, the majority of the intersected gas pockets are isolated, as once the burst occurred most cavities tended to receive little if any subsequent recharge, so gas and brine outflow rates tended to decrease to zero across hours to days (Loffler, 1962). The relationship between the type of gas, its position in the salt, and possible lithological associations are documented and discussed in detail in articles 2 and 3.

The physics that drives rock and gas outbursts in an expanding mine-face or shaft is relatively straightforward. In the petroleum industry, it constitutes a process set that is already well documented as the cause of many salt–associated gassy blowouts such as Alborz 5 (Figure 3; Warren, 2016 – Chapter 8 for detail on pressure distribution in and about a salt mass). Oilfield blowouts associated with salt occur when pore pressures in fluids in the drilled rock approach or even exceed lithostatic and the weight of mud in the approaching borehole is not sufficient to hold back this overpressured fluids entering and escaping up the borehole (Figure 3). Spindletop and other famous caprock blowouts in the early days of salt dome drilling in Texas and Louisiana are famous examples of this process (Figure 5). Ehgartner et al. (1998) argue that the same pressure release occurs as an expanding mine face approaches a gassy zone in the mined salt. Once the pressure is reduced by the approach of the mine face, the release of gas formerly held in place by lithostatic pressure within a homogeneously stressed salt mass will release, the enclosing rock salt will lose cohesion and so a rockburst (gas outburst) occurs (Figure 6).

How is the gas held and distributed within salt at the micro and mesoscale (microns to metres)?

That free gas and gas in inclusions occur simultaneously in salt masses is undeniable, numerous examples come from salt mines and salt cores (Table 1). Gases are held in evaporite salts in three ways (Hermann and Knipping, 1993); 1) Crack- and fissure-bound gases, 2) Mineral-bound gases, a) intracrystal, b) intercrystal, and 3) Absorption-bound gases. Type 1 occurrences, as the name suggests, are defined by gas accumulations in open fractures and fissures, typically in association with brine. Some occurrences are tied to pressurized aquifers, others are isolated local accumulations within the salt. Intracrystal gas occurs as bubbles, some elongate, some rounded in brine inclusions that are fully enclosed within a crystal (typically halite). At the micro (thin section–SEM scale), intracrystalline gases typically form as a few to aggregates of small bubbles, arranged along crystallographic axes or planes, with bubble diameters in the range 1 to 100 µm. Intercrystalline gases occupy the boundary planes of crystals in contact with one another, that is intercrystalline gases occupy polyhedral porosity. According to Hermann and Knipping (1993), up to 90% of the mineral-bound CO₂ gas mixtures in the salt rocks of the Werra–Fulda mining district is likely intercrystalline, and the remaining 10% is intracrystalline. Adsorption bonding is likely an independent form of gas fixation in salt. Adsorptive bonding describes the ability of solids, especially clays, and crystalline compounds to store gas on their surfaces in the form of layered molecules, most would term this a subset of microporous gas storage in a shale.

[i]The stresses in and around and in salt structures can be high and troublesome to stabilize, even today and is an indication of the ongoing dynamic nature of salt flow and recrystallisation in the subsurface. Therefore, if borehole fluid pressure is lower than salt strength during drilling, stress relaxation may significant-
ly reduce open-hole diameters. In some cases, relaxation causes borehole restrictions even before drilling and completion operations are finished and casing has been set.

References


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