Salty Matters

John Warren - Saturday, December 31, 2016

Gases in Evaporites: Part 3 of 3: Where do gases generate and reside at the scale of a salt mass or salt bed

So far we have looked at gas distribution and origins in evaporites at micro and mesoscales and have now developed sufficient understanding to extrapolate to the broader scale of architecture for a large body of salt in an evaporite. We shall do this in a classification framework of extrasalt versus diagenetic periphery versus intrasalt gas in a halokinetic salt mass (Figure 1)

Extrasalt gas and brine intersections

This type of gas intersection is perhaps the most damaging to a salt mine operation and tends to occur when a gas release is encountered in an expanding mining operation, or a drill hole, that lies near the salt body edge and intersects nonsalt sediments. Extrasalt fluids can be either normally pressured or overpressured depending on the connectivity of the plumbing in the extrasalt reservoir. Salt because of its excellent seal potential tends not to leak or leak only slowly, so facilitating significant pressure build-up (Warren, in press)

The gas inflow from this type of extrasalt breach in a salt mine is typically accompanied, or followed by, a brine release that sometimes cannot be plugged, even by a combination of grouting and brine pumping. Brine inflow rates in this scenario tend to increase with time as ongoing salt dissolution is via ongoing undersaturated water crossflows and the mine or the shaft is ultimately lost to uncontrollable flooding of gas blowouts in an oil well with poor pressure control infrastructure and planning. This type of edge intersection is why a number of early attempts to construct shafts for potash mines in western Canada failed in the middle of last century. It is why freeze curtains are considered the best way to contract a shaft for a potash mine. Examples of this type of gas/brine intersection are usually tied to telogenetic

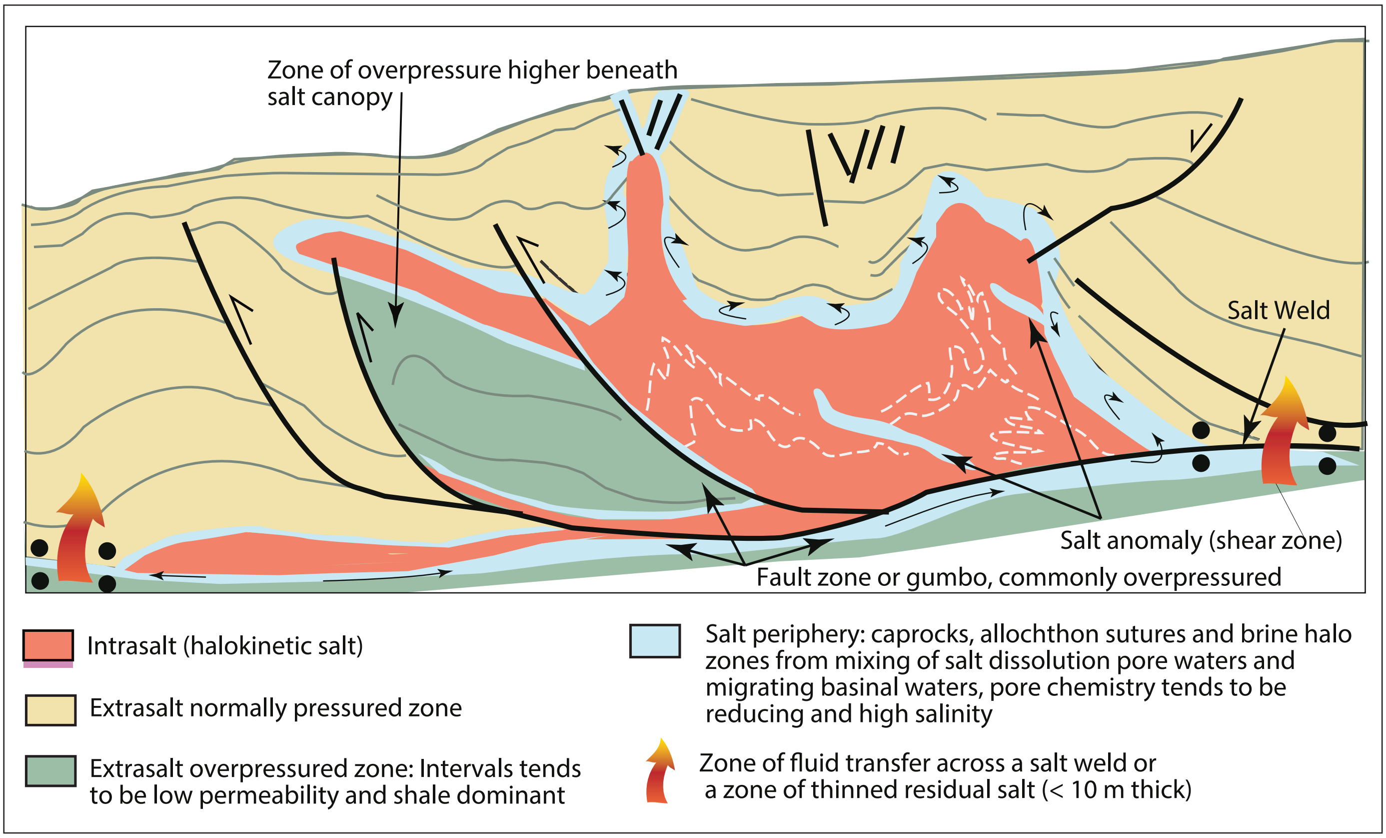

Figure 1. Zones of intrasalt, peripheral and extrasalt emphasising positions where gassy salt is likely in a halokinetic framework (modified from Warren, 2017)

fluid entry from substantial aquifer reservoirs outside the main salt mass and are discussed in detail in Warren, (2016, Chapter 13) and as a type of salt anomaly association discussed in Warren (in press).

The extrasalt source and potential inflow volume of this form of gas (mostly methane and co-associated brine) is largely tied to maturity of hydrocarbon source rocks located external to the salt mass in both suprasalt and subsalt positions (Figure 1). In the past, unexpected extrasalt intersections of pressurised gas reservoirs during oil well drilling lead to spectacular blowouts or "gushers", especially in situations where the salt held back a significant volume of fluid held in open fractures beneath or adjacent to a salt seal (Table 1). The fluid-focusing effects of suprasalt dome drape and associated extensional falling and gas leakage also mean "gas clouds" are common above salt domes (Warren, 2016, in press). Low σ_{hmin} leads to upward gas migration through fracturing (Dusseault et al., 2004). So, in the supradome extrasalt position, simultaneous blowout and lost circulation conditions can be encountered, as well as the problem of severely gas-cut drilling fluids. The volumes of gassy liquids held in pressurised extrasalt reservoirs can be substantial so blowouts or "gushers" can be difficult to control, as was the case with the world-famous subsalt Qom (1956) and suprasalt Macondo (2010) blowouts (Table 1). Methane and gassy liquids generated by organic maturation tend to be the dominant gases found in this situation.

Caprock and other salt periphery-held gases

This style of gas occurrence is in part related to gases sourced in maturing extra-salt sediments but also taps gases that are the result of the diagenetic processes that create caprocks. Caprocks are alteration and dissolution haloes to both bedded and halokinetic salt masses and so are distinct gas reservoirs compared to extrasalt sediments (Warren, 2016; Chapter 7). They are compilations of fractionated insolubles left behind at the salt dissolution interface as the edge of halite mass liquefies. Accordingly, caprocks are zoned mineralogically according rates of undersaturated fluid crossflow and in part responding to variable rates of salt rise and resupply. Anhydrite (once suspended in the mother salt) accretes at the dissolution front. Ongoing undersaturated crossflow at the outer contact of the anhydrite residue carapace alters anhydrite to calcite via bacterially- or thermochemically-driven sulphate reduction, with hydrogen sulphide as a by-product. Additional sulphate reduction can occur in the extrasalt sediment both at or near the caprock site, but also deeper or more distal positions in the extrasalt, so sulphate reduction can be a major source of the H_2S gas found in the salt periphery. H2S can also migrate in a c from sulphate reduction in maturing sediments located some depth below the salt.

Dissolution that facilitates caprock also drives the creation of vugs and fractures in the caprock, and is one of the primary controls on reservoir poroperm levels in various caprock oil and gas reservoirs discovered in the 1920s in the US Gulf Coast. Methanogenic biodegradation of the same hydrocarbons, which facilitate sulphate reduction, can generate CO_2 in the caprock and extrasalt sediments (Clayton et al., 1997)

Many salt mine problems in Germany in the early days of shaft sinking for salt mining were related to unexpected shallow gas outflows confronted within caprock-hosted gas-filled vugs and fractures encountered by the mine shaft on the way to a potash ore target (Gropp, 1919; Löffler, 1962; Baar, 1977). Likewise, the highly unpredictable distribution of gases in the shallow caprocks and salt peripheries of the US Gulf Coast were the cause of some spectacular blowouts such as Spindletop (1901) (Table 1). Because the volume of held liquids is more limited in the vugs and fractures in a caprock compared to fractured subsalt reservoirs, the rate of fluid escape in a "caprock-fed" gusher tends to lessen and even self-bridge more rapidly than when salt is sealing a fractured overpressured subsalt reservoir (days or weeks versus months). As such these intersections, if isolated from extrasalt reservoirs as not such a problem in the drilling of oil wells. In simpler, less environmentally conscious, early days of oilwell drilling in East Texas in the 1920s, "gushers" were often celebrated, tourist spots and considered a sign of the potential wealth coming to the country being drilled.

Intrasalt gas

This type of accumulation/intersection is often described as an intrasalt gas pocket and is typified by a high rate of gas release, that in a mine is accompanied by a rockburst, followed by a waning flow that soon reaches negligible levels as the pocket drains (see article 1 in this series). Intrasalt gas pockets can create dangerous conditions underground and lives can be lost, but in many cases after the initial blowout and subsequent stabilisation, the mine operations or oil-well drilling can continue. Gas constituents and relative proportions are more variable in intrasalt gas pockets compared to gases held in the extrasalt and the periphery. Extra-salt gases are typically dominated by methane with lesser H_2S and CO_2, periphery gases by H_2S and methane, while intrasalt gases can be dominated by varying proportions of nitrogen, hydrogen or CO_2. Methane can be a significant component in some intrasalt gas pockets, but these occurrences are usually located in salt anomalies or fractures that are in current or former connection with the salt periphery.

Gas types and sources at the local and basin scale

The type of gas held within and about a salt mass in a sedimentary basin is broadly related to position in the mass and proximity to a mature source rock. Herein is the problem, most of the gases that occur in various salt-mass related positions (intrasalt, extrasalt and periphery) can have multiple origins and hence multiple sources.

Accumulations of gas with more than 95 vol.% N_2 are found in most ancient salt basins and the great majority of these accumulations are hosted in intersalt and subsalt beds, with the gas occurring in both dispersed and free gas forms in the salt, as in many Zechstein potash mines of Germany and the Krasnoslobodsky Mine in the Soligorsk mining region of Russia (Tik-

Date	Location	Detail	Gas position	Other
1815	Kilbock Creek, Ohio, USA	Joseph Eichar and his team were digging west of the town of Wooster, Ohio, when they struck oil.	Extrasalt: suprasalt (bedded)	Blowout resulted from an attempt to drill for bedded salt, not for oil
January 16, 1862	Shaw Gusher, Oil Springs, Ontario, Canada	Hugh Nixon Shaw using a springboard to chip through rock, created Canada's first oil gusher (located on Gypsie Flats Road). It shot oil from over 60 metres (200 ft) below ground to above the treetops at a rate of 3000 barrels per day.	Extrasalt: suprasalt (bedded)	Possibly world's first oil gusher when actually drilling for oil. Gushers of last century largely indicate cable-tool drilling rigs that lack an ability to control pressure via mud weight.
January 10, 1901	Lucas Gusher, Spindletop in Beaumont, Texas, USA	Spindletop blew when at a depth of 1020 feet. Initially, six tons of four-inch drilling pipe shot out of the ground and several minutes later, a stream of oil blew out over 100 feet in the air. The well blew some 100,000 barrels (16,000 m3) per day at its peak, but soon slowed and it was capped within nine days. Within 9 months, 64 more wells were completed into the Spindletop caprock, each producing a gusher.	Periphery: caprock, diapiric	The word "gusher" comes from the Icelandic word"geysir"and means or "one who rages." The Spindletop well tripled U.S. oil production overnight and marked the start of the Texas oil industry
May 26, 1908	Masjed Soleiman in Meidan Naftoon region, Iran	Masjed Soleiman No. 1 well blew out at about 1180 feet, sending a column of oil 50 feet above the drilling rig.		This blowout marked the first major oil strike recorded in the Middle East
February 9, 1915	Cerro Azul No. 4, near Tampico	On Feb. 9, the well took a gas kick and water forced its way out of the hole. The next day, crews heard a deep rumbling and the ground began to shake. Suddenly, the drill line shot out of the hole, smashing the top of the derrick. Seven hours later, oil spouted out and formed a geyser nearly 600 feet into the air. By Feb. 15, flow was estimated at 152,000 barrels of oil per day. Workers capped the well on Feb. 19. Nearly six years later, the well had produced more than 57 million barrels of oil.	Extrasalt: subsalt (bedded anhydrite)	Though production has dropped off considerably, the well is still producing 100 years later.
October 16, 1927	Baba Gurgur, Kirkuk, Iraq	Gusher spouted more than 130 feet into the air at a rate of 95,000 barrels (15,100 m^3) a day. The spraying oil threatened local inhabitants and there was a risk of oil polluting waterways. The decision was made to build a series of dams about a mile apart to hold back the oil. One night, gas collected in a depression near the worksite, killing two drillers and three Iraqi workers. It took 10 days to close the valve. The company attempted to pump the oil back into the ground, but most of it was set ablaze. Work on removing the oil was completed on Christmas Day 1927.	Extrasalt; subsalt bedded	The Kurdish name Baba Gurgur roughly translates to "The Father of Flames." The well is located 2 kilometres from the site of the "eternal flame" that has burned for at least 4,000 years. Some believe the flame is the basis for the Biblical fiery furnace mentioned in The Old Testament's Book of Daniel.
August 26, 1956	Qom, Central Iran	The Alborz 5 well blew near Qom, Iran 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!). The uncontrolled oil gushed to a height of 52 m (170 ft), at a rate of 120,000 barrels (19,000 m3) per day. The gusher was closed after 90 days' work supervised by Bagher Mostofi and Myron Kinley. 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.	Extrasalt: Subsalt (halokinetic); Fractured carbonate, low matrix storage	The largest known 'wildcat' oil gusher, worlwide
June 23, 1985	Tengiz field in Atyrau, Kazakhstan	A 4209-metre deep well (well #37) blew out and the resulting 200-metre high gusher self-ignited two days later. Oil pressure up to 800 atm and high hydrogen sulfide content had led to the gusher being capped only on 27 July 1986. The estimated total volume of erupted material was 4.3 million metric tons of oil, 1.7 billion m^3 of natural gas, and the burning of the gusher resulted in 890 tons of various mercaptans and more than 900,000 tons of soot being released into the atmosphere. The initial explosion killed one man while the self -gnited flare was one the longest-burning in the century-old history of the Russian-Soviet oil industry	Extrasalt: Subsalt bedded	High levels of H2S amd mercaptans meant it was one of the most toxic blowouts in the history of the oil industry. . It took Moscow six months to even report the existence of the blow-out, even though a 200-meter-high column of fire was visible from 140 km.
December 23, 2003	Luojiazhai gas field, East Sichuan Province, China	A major blowout of sour (H2S-rich) gas in a well being drilled into the lower Triassic anhydrite-sealed Feixianguan Fm reservoir occurred when well LJ16H reached a depth of 4049.68 m. The resulting uncontrolled gas escape led to the death of 243 persons At the time of the blowout, the well had a formation pressure of about 40 MPa and was approximately 23% overpressured. Most of the H2S is the result of subseal thermochemical sulphate reduction of dispersed anhydrite,	Extrasalt: Subsalt bedded anhydrite seal, reflux dolomite, leached and fractured carbonate resevoir	Deaths were mostly caused directly by the accidentally emitted H2S ponding on the landscape and turning 10 square miles into a "death zone."
April 20, 2010,	Macondo Prospect, Offshore Gulf of Mexico	The largest underwater blowout in U.S. history with a fireball from the explosion that could be seen 40 miles away. Associated explosion killed 11 crew and destroyed the Deepwater Horizon, a mobile offshore drilling platform owned by Transocean and under lease to BP at the time of the blowout. While the exact volume of oil spilled is unknown, estimated at between 35,000 to 60,000 barrels (5,600 to 9,500 m3) of crude oil per day. Both the blowout preventer and blind shear ram failed, leaving the well on the sea floor gushing for 87 days. The well was capped on July 15, 2010 and successfully sealed off from all flow into the sea on August 4, 2010 by a "static kill" (injection of heavy fluids and cement into the wellhead at the mudline). The U.S. government estimated the total discharge at 4.9 million barrels of oil.	Extrasalt: Suprasalt dome (halokinetic)	Largest anthropogenic marine oil spill in history. One possibility explaining well failure emerged through documents released by Wikileaks discussing a similar incident that had occurred on a BP-owned rig in the Caspian Sea in September 2008. Both cement plugs were perhaps too weak to withstand the pressure because they were composed of a concrete mixture that used nitrogen gas to accelerate curing.

Table 1. Some of the larger extrasalt and salt periphery blowouts. This table complements the rockburst (intrasalt) blowout table in article 1 of this series (published October 30, 2016)

homirov, 2014). Nitrogen gas today constitutes around 80% of earth atmosphere where it can result from the decay of N-bearing organic matter (proteins). Ultimately, nitrogen speciates from aqueous mantle fluids in oxidised mantle wedge conditions in zones of subduction and in terms of dominance in planetary atmospheres it indicates active plate tectonics (Mikhail and Sverjensky, 2014). Nitrogen in the subsurface is large unreactive compared to oxygen and so tens to stay in its gaseous form while oxygen tens to combine into a variety of minerals. When held in a salt bed, nitrogen can be captured from the atmosphere during primary halite precipitation and stored in solution in a brine inclusion so creating a dispersed form of pressurised nitrogen. When buried salt recrystallizes during halokinesis, with flow driven by via pressure solution, inclusion contents can migrate to intercrystalline positions and from there into fractures to become free gas in the salt.

Methane gas captured in and around a salt mass as both dispersed and be gas typically mostly comes from organic maturation. The maturing organic matter can be dispersed in the salt during primary halite precipitation, it can be held in intersalt source beds (as in the Ara Salt of Oman), or it can migrate laterally to the salt edge, along with gases and fluids rising from more deeply buried sources. Thus, the presence of oil, solid bitumen and brine inclusions, with high contents of methane in halite, does not unequivocally point to the presence of oil or gas in the underlying strata, it can be locally sourced from intersalt beds as in the Ara Salt. However, a geochemical aureole can be said to occur if hydrocarbons in the halite-hosted inclusions can genetically be linked with reservoired oil or gas. The presence of methane in salt anomalies in Louann Salt mines in the US Gulf Coast and some mines in Germany is likely related to organic maturation of deeply buried extrasalt source rocks with subsequent entrapment during halokinesis and enclosure of allochthon-suture sediments.

Hydrogen sulphide gas (H_2S) is a commonplace free gas component in regions of bacterial and thermogenic sulphate reduction. Like methane, much of its genesis is tied to organic maturation products (and sulphate reduction processes), and like methane, it can be held in salt seal traps, or in peripheral salt regions, or in intrasalt and intersalt positions and like metyhane if it escapes and ponds in an air space its release can be deadly (Table 1; Luojiazhai gas field, China). Because both bacterial and thermochemical sulphate reduction requires organic material or methane, there is a common co-occurrence of the two gases. Caprock calcite phases are largely a by-product of bacterial sulphate reduction, so there is an additional association of H_2S with caprock-held occurrences. This form of H_2S, along with CO_2, created many problems in the early days of shaft sinking in German salt mines. More deeply sourced H2S tend to be a production of thermochemical sulphate reduction in regions where pore fluid temperatures are more than 110°C.

Detailed study of CO_2 and its associated geochemical/mineralogic haloes shows much of the CO_2 held in Zechstein strata of Germany has two main sources; 1) Organic maturation and 2) carbonate rock breakdown especially in magmatic hydrothermal settings (Fischer et al., 2006). The organic-derived CO_2 endmember source (with $\delta^{13}C$ near -20‰) is present in relatively low concentrations, whereas large CO_2 concentrations are derived from an endmember source with an isotope value near 0‰. Although the latter source is not unequivocally defined by its isotopic signature, such "heavy" CO_2 sources are most likely attributed to heating-related carbonate decomposition processes. This, for example, explains the CO_2-enriched nature of salt mines in parts if the former East Germany where Eocene intrusives are commonplace (Shofield et al., 2014).

Hydrogen (H_2) gas distribution as a major component varies across salt basins and is especially obvious in basins with significant levels of carnallite and other hydrated potassic salts. This association leads to elevated radiogenic contents tied to potassic salt units, with hydrogen gas likely derived from the radiogenic decomposition of water (see article 2 in this series). The water molecules can reside in hydrated salts or in brine inclusions in salt crystals.

Summary

Various proportions of gases (N_2, CH_4, CO_2, H_2S, H_2) held in salt as dispersed and free gas occur in all salt basins. But at the broad scale, certain gases are more common in particular basin and tectonic positions. Methane is typically enriched in parts of a basin with mature source rocks, but can also have a biogenic source. Likewise, H_2S is tied to zones of organic breakdown, especially in zones of either bacterial or thermochemical sulphate reduction. CO_2 can occur in salt in regions of organic degradation, but is most typical those of parts of a salt basin where igneous processes have driven to thermal and metamorphic decomposition of underlying carbonates (including marbles). Nitrogen because of its inert nature is a commonplace intrasalt gas and comes typically from zones of organic decomposition with dispersed nitrogen becoming free gas with subsequent halokinetic recrystallisation. Ongoing salt flow can drive the distribution of all dispersed salt stored gases into free gas (gas pocket) positions.

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