Salty Matters

John Warren - Saturday Dec 19, 2015

Salt as a Fluid Seal Article 1

Introduction

In the next few articles, I plan to discuss salt's ability to act as a fluid seal in a variety of halokinetic settings, as well as looking at the nature of the sealing salt. Of particular interest are formative mechanisms driving textural and permeability variations in zones that typify the salt side of the sealing boundaries in sub-vertical salt stems versus the lower contact transitions in sub-horizontal allochthons. In the first few articles, we shall focus on local-scale scenarios and salt seal textures, including situations where salt has leaked, and the intercrystalline or tetrahedral/polyhedral pores contain fluid or mineralogical evidence of leakage and crystal boundary dissolution. Within the salt mass, this is usually indicated by occurrences of "black" or "dark" salt in anomalous salt zones, some of which are intersected by workings in a number of salt mines. In contrast, in most oil exploration scenarios we only have wireline signatures to interpret the deeper and typically offshore seal horizons. Following on from that discussion, we shall look at more regional examples of cross-formational leakage. Finally, we will discuss implications of possible leakage in terms of understanding and predicting outcomes with respect to both waste storage and hydrocarbon sealing

"Black" or "dark" salt in anomalous salt zones

The geological term "black salt" covers a variety of salt textures and associated mechanisms of formation. The term "black" salt also has a non-technical culinary association ([1]kala namak) but, other than in the footnote, I will not discuss it further in this series of articles. The geological descriptor "black" or "dark" salt is widely used in the US salt mining industry as a pointer to possible zones of current or past natural fluid entry into the salt mass. Colouring fluids can be brine, oil or gas, often with solid impurities dominated by shale, anhydrite or calcite-dolomite. These intrasalt "black" or "dark" salt zones in a mine were also referred to as "shear" zones and considered pointers to what are often unstable regions, liable to fluid entry, gassy outbursts and roof or wall collapse. "Shear", "black" and "dark" salt zones are better described under the broader term "anomalous salt" zones, many of which were or are in fluid contact with the enclosing non-salt sediment mass (Kupfer, 1990).

In a somewhat related fashion, the term "black salt" is used by the oil industry in Oman and Europe to indicate subsurface zones of overpressured salt, where natural hydrofracturing has occurred, and hydrocarbons have penetrated up to 100 m into the sealing salt mass. Hence its dark color (naturally hydrofractured salt and its textures are the focus of the second article in this series on salt leakage). Fluid entry in this type of "black' salt is ascribed to temperature-related changes in the dihedral angle of the halite crystals in "black" salt zones. In a similar fashion, the term "black" salt was used in a recent paper in Science by Ghanbarzadeh et al. (2015) and the dihedral angle changes are ascribed to temperature increases in halokinetic salt intervals in the offshore Gulf of Mexico. There the authors argue temperature increases have changed the intercrystalline dihedral angle in a salt mass, and so facilitated the entry of fluids from adjacent strata into the salt body.

1 Pungent-smelling condiment Kala Namak (black salt) is widely used in South Asia, it consists primarily of sodium chloride with trace impurities of sodium sulphate, sodium bisulphate, sodium bisulphite, sodium sulphide. Kala Namak is also known as Himalayan Black Salt, Sulemani Namak, Bit Lobon , Kala Noon or as Bire Noon in Nepal. Its characteristic smell and taste is mainly due to its elevated sulfur content, which to a western nose is reminiscent of rotten eggs, largely due to the presence of greigite. The various iron impurities impart a brownish pink to dark violet colour to the coarse translucent crystals and, when ground into a powder, transform into a light purple to pink color.
Traditionally, mined sal

t was transformed from the raw natural form of salt into commercially-sold kala namak through a reductive chemical process. This heating transforms some of the naturally occurring iron oxidew and sodium sulfates in the raw salt into pungent hydrogen sulfide and sodium sulfide daughter products (along with greigite.[The various sulphate salt impurities in the halite typify the partially recrystallised meteoric overprints that typify textures and structures in nearsurface salt residues in the Himalayan thrust belt (see Richards et al., 2015 for documentation of the geological and structural characteristics of this salt – this article can be downloaded from the publications page on this website).

Historically, the transformation of Himalayan thrust belt salt into kala namak involved firing the raw salt in a furnace for 24 hours, while sealed in a ceramic jar containing charcoal along with small quantities of harad seeds, amla, bahera, babul bark, or natron. The fired salt was then cooled, stored, and aged prior to sale. Kala namak is still prepared in this manner in northern India with production concentrated in Hisar district, Haryana. Although the kala namak can still be produced from natural salts with the required compounds, it is now common to now manufacture it synthetically using halite from non-Himalayan sources. This is done through combining sodium chloride with smaller quantities of sodium sulfate, sodium bisulfate and ferric sulfate, which are then chemically reduced with charcoal in a furnace. Reportedly, it is also possible to create similar products through reductive heat treatment of sodium chloride, 5–10% of sodium carbonate, sodium sulfate, and some sugar.

So, the term "black" salt is used in the geological community without reference to geological criteria that can separate what I consider are at least two distinct styles of "black" or "dark" salt formation and leakage. One type of salt leakage occurs when the salt is relatively shallow and subject to dissolution driven by the entry of meteoric and other near-surface undersaturated waters into folded and refolded shear (anomalous) salt zones in and about salt stems and décollements. This typically occurs when the flowing salt crest is relatively shallow and tends to occur in regions where the leaking "black" salt zone is in contact with the nonsalt boundary edges of the halokinetic salt mass. This process set ultimately leads to an accumulation of insoluble residues (clays, anhydrite, gypsum, calcite, etc.) that define a unit called a caprock. The term "cap" is somewhat of a misnomer as "caprock" units also form on the sides and undersides of a salt mass, wherever the salt unit is in contact with undersaturated cross-flowing formational waters (Warren, 2016). The other type of "black salt, exemplified by the Ara salt in Oman is related to deeper salt burial, salt flow and an association with intrasalt pressurized fluids (a focus of next article in this series on salt leakage). Accordingly, if we are not to confuse styles of "black" salt genesis (meteoric or undersaturated fluid entry versus intrasalt overpressures) then a better non genetic term should be used to describe zones of "black" or "dark" salt. Although less euphonious, the better term is "anomalous" salt. This describes all zones within halite-dominant intervals with features that are not typical of the bulk of the main diapiric salt mass (Kupfer, 1990).

In this first article we look at various types of anomalous salt in salt mines, largely related to the entry of, or interaction with, undersaturated relatively shallow formation waters. The next article focuses on salt leakage and "black" salt related to overpressure. Then, as we shall see in the third article on salt leakage, there are significant implications of occurrences of anomalous salt with respect to practicalities of safe intrasalt storage and fluid contamination with respect to separating the two types of black salt. This is especially so when working in the subsurface without the luxury of core or mine wall exposures. Ignoring the origins of "black" or "dark" salt, and the associated implications for wireline interpretation, means any conclusions in terms of waste storage outcomes and/or hydrocarbon seal potential, by generalizing lab-based experimental results on leaking salt to all "black" salt occurrences in halokinetic settings, will be somewhat confused (e.g. Ghanbarzadeh et al., 2015).

Black salt (dark salt) in anomalous salt in response to undersaturated fluid entry

Intervals of "black" or dark salt are described in US Gulf Coast salt mines in publications by Balk (1953), Kupfer (1976, 1990) and Looff et al., (2010), the following observations are largely based on their work. Nearsurface (<1-2 km) portions of mined or cored diapirs with "black" salt zones in the Gulf Coast USA and Germany are segmented into a number of intradiapir zones showing differential movement between adjacent salt spines or flowing masses. The more homogenous intervals of consistently mineable salt ore are separated by anomalous zones, formerly called "shear" zones. This association of homogenous spines separated by narrower shear or anomalous zones was first mapped in mine walls in the Jefferson Island salt dome by Balk (1953). His work was one of a series of classic papers mapping the internal structural complexities and shears in various mined salt diapirs in the US Gulf Coast and the Zechstein of Germany. Subsequent work by Kupfer (1976) on the same US Gulf Coast Five-Island salt mines (Jefferson Island, Avery Island, Weeks Island, Cote Blanche and Belle Isle) further refined notions of internal shear and occurrences of "black" or "dark" salt in diapirs. Today, only the Cote Blanche and Avery Island salt mines are still in operation along the Five Island Salt Dome Trend (Figure 1).

A shear zone in a diapiric structure forms where adjacent parts of a salt structure are moving (rising or falling) at different rates. Such zones tend to dominate the perimeter of a salt structure across which salt mass is rising or falling with respect to the adjacent sediment and so grade outward from the salt spine into a boundary "shale sheath". Older shear zones and shale sheaths also are commonplace in re-folded intervals within a salt stem. Mapping of these zones by Balk (1953), Muehlberger and Claubaugh (1968) and Kupfer (1976) across many salt mines showed salt in

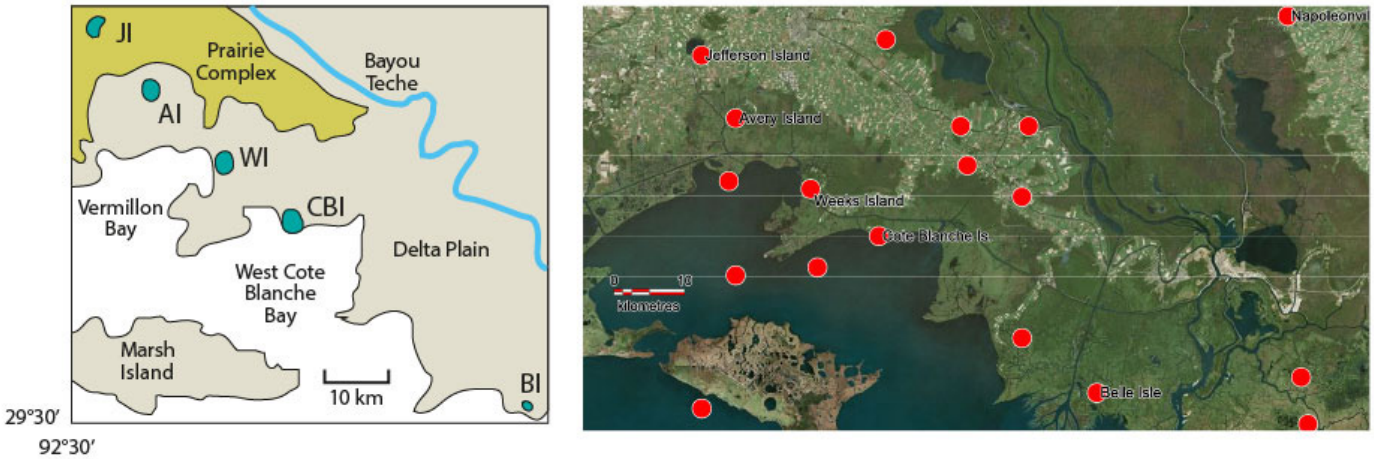

Figure 1. Five Island Salt Dome Trend, Louisiana (red circles are regions underlain by salt diapirs - extracted and plotted from SaltWork database Version 1.6)

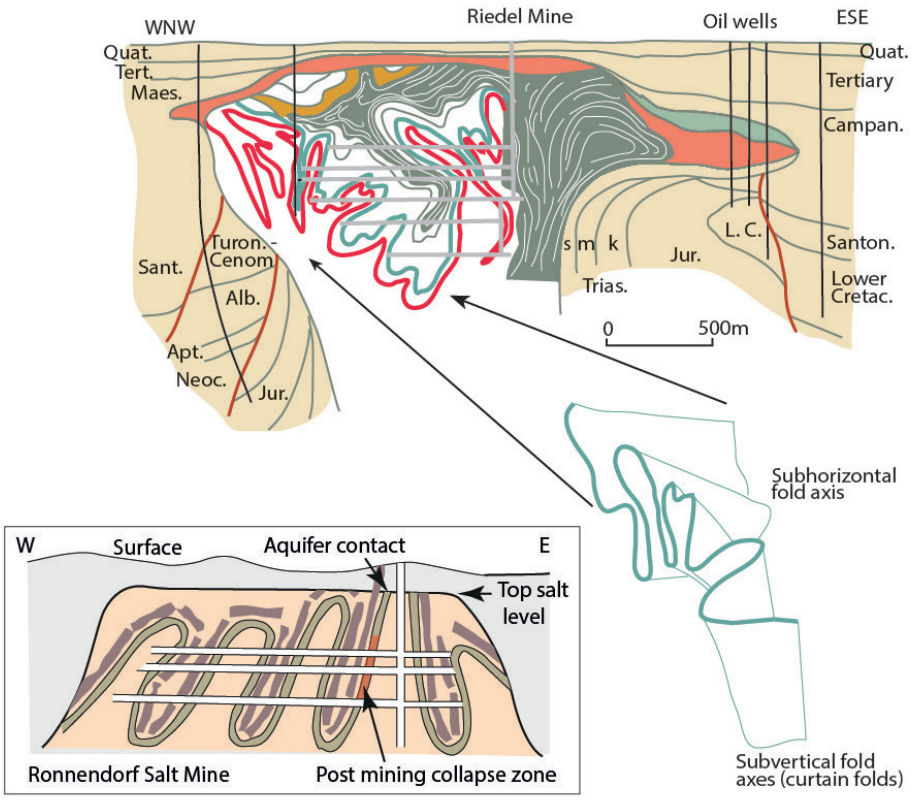

Figure 2. Internal fold complexities documented in two mined Zechstein salt diapirs. Note the tendency toward subvertical orientations in the salt stem and sub-horizontal orientations in the overhangs.

a diapir must flow at different rates at different times. Otherwise, the complex and highly variable internal refolded drape and napkin folds seen in diapirs in all the world's salt mines could not form. Figure 2 illustrates some internal complexities the diapir scale typifying various diapiric salt structures across the world and the dominantlyvertical flow fabrics in diapir stems and subhorizonatal flow textures in overhangs and salt tongues. Figure 3 shows that same vertical dominance (biaxial elongation) of salt crystals from cores collected in diapir stems cored various salt mines, while Figure 4 shows the typical vertical banding fold style that typifies diapir stems.

Walden and Jacoby (1963) were the first to call attention to a Gulf Coast anomalous salt zone. They documented a fault zone in the Avery Island salt mine that separated the region of salt being mined, across an anomalous zone, from the domal core. To call attention to the zonal ductile, not brittle, nature of intradiapir salt flow, Kupfer, 1974 changed the description of such anomalous zones from "fault" zones to "shear" zones and concluded most intradiapir shear zones were not faulted zones (defined by brittle fracture offset). In a later paper, he suggested abandoning of the genetic and misleading term "shear zone" and proposed replacement with the broader nongenetic term "anomalous salt zone" (Kupfer, 1990).

The term "anomalous salt," as defined by Kupfer (1990), is based on his then more than twenty years experience in various salt mines in the US Gulf Coast. An anomalous salt zone is defined broadly as a zone of anomalous features in salt of whatever origin. He noted that typical anomalous salt zone features are different to the majority of features in the adjacent salt and involve varying combinations of anomalous features that include:

Textures--Coarse-grained, piokiloblastic, friable

Inclusions--Sediments, hydrocarbons, brine, gases

Structures--Sheared salt, gas outbursts, brine leaks, undue roof and wall slabbing, jointing, voids, and slight porosity development

Compositions--Potash/magnesium, high anhydrite content, very black salt (made up of disseminated fluid and solid impurities.

The terms "anomalous salt" and "anomalous zones" as defined by Kupfer (1990), are based on observations across the various Five Island salt mines of South Louisiana (Figure 1). As later refined in Kupfer et al. (1998), anomalous salt is a rocksalt zone that deviates from what are considered typical domal salt. Typical Gulf Coast rocksalt according to Kupfer is reasonably pure halite (97%+/- 2%), with minor amounts of disseminated anhydrite ($CaSO_4$) being the primary non-halite impurity. Grainsize is considered to be uniform with grain diameters of 3 – 10 mm (0.12 – 0.39 inches). With continued mapping of Five Island mines, Kupfer et al. (1998) and Looff et al. (2010) documented an even wider variety of anomalous salt zone characteristics and concluded that the creation of anomalous zones need not be related to faulting or shearing, but also can be related to fluid entry and salt dissolution (Figure 5). Anomalous salt

Figure 3. Flow oriented halite textures seen in cores from various US Gulf Coast salt domes (after Looff et al., 2010)

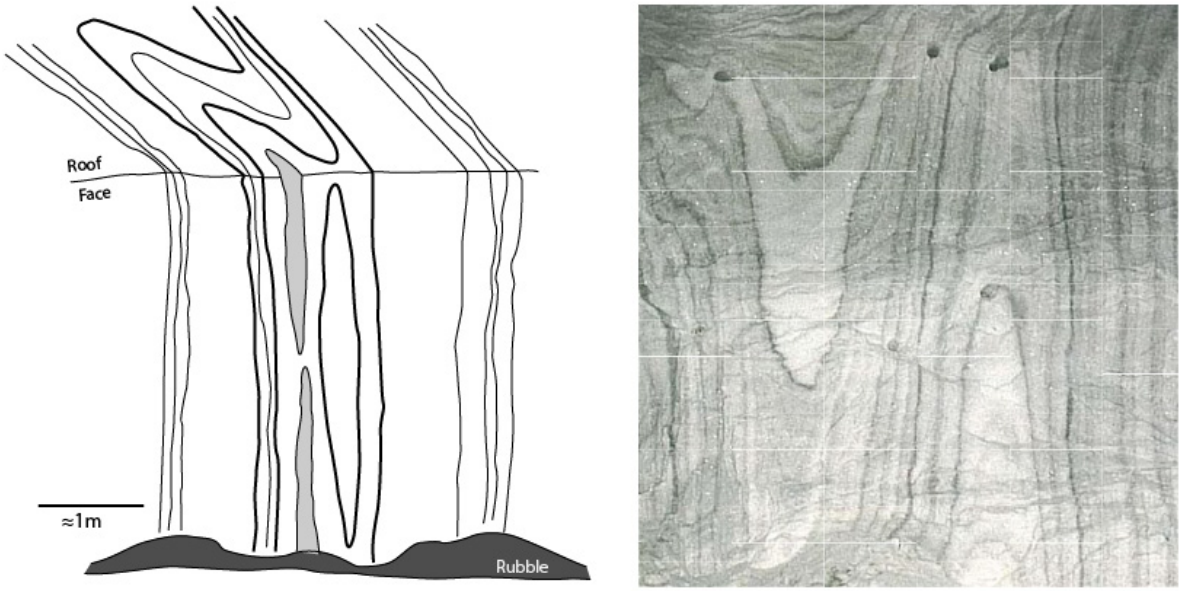

Figure 4. The detail of dominantly vertically-plunging folds as seen in a room and face of a room in the Avery Island Salt Mine (after Lock, 2000)

can be defined by impurity content, structure, colour, or other features. Anomalous features may not have sharp contacts or uniform thickness, and most are not continuous over long distances. Individual anomalous features commonly disappear for tens of metres (hundreds of feet) only to appear over some horizontal distance. The internal salt fabric of a salt dome is always composed of both typical (volumetrically dominant) and anomalous salt. Kupfer (op. cit.) noted that other salt deposits, including horizontally bedded nonhalokinetic salt deposits in the Permian of West Texas and the Devonian of Western Canada, all have anomalous zones of various origins.

Further work in both the salt mines and salt cavern storage industry has increasingly invoked the concept of anomalous features, anomalous zones and boundary shear zones although there is still a significant confusion over the appropriate use of the terminology (Looff et al., 2010). Because of the flow experienced by diapiric salt, most anomalous salt features parallel the near vertical internal banding of the salt. Many anomalous salt features may create zones of differing creep, strength, or dissolution characteristics that can impact the solution mining and operation of a salt storage cavern and some are tied to zones of problematic fluid entry in a mine. An anomalous zone is any zone in a salt diapir that contains 3 or more dissimilar anomalous features (Kupfer, 1990). The term "anomalous" implies nothing regarding the genesis of the zone. While many anomalous zones may extend laterally over hundreds of metres in length, they are variable in nature, near vertical, and parallel to layering (Figure 5). Typical widths are poorly known but are commonly in the order of 30-50m; however individual structures or anomalous features within the anomalous zone may be as thin as millimetres.

Boundary Shear Zones (BSZ) and Edge Zones (EZ) are the two types of anomalous zones that have a genetic interpretation (Looff et al., 2010). Boundary shear zones are those zones that bound an active salt spine where the salt experiences increased shear stress due to differential salt movement. An edge zone is similar to a boundary shear zone except, instead of being internal within the dome, it is confined to the periphery of the salt stock. Anomalous salt is not restricted to shear zones, however within and about as diaper edge one can expect most anomalous salt to be associated with shear zones (Kupfer, 1990; Looff, 2000).

Anomalous zones within a salt spine are in many cases the remnants of relict BSZ's from older spines incorporated into younger active salt spines and this especially obvious with those

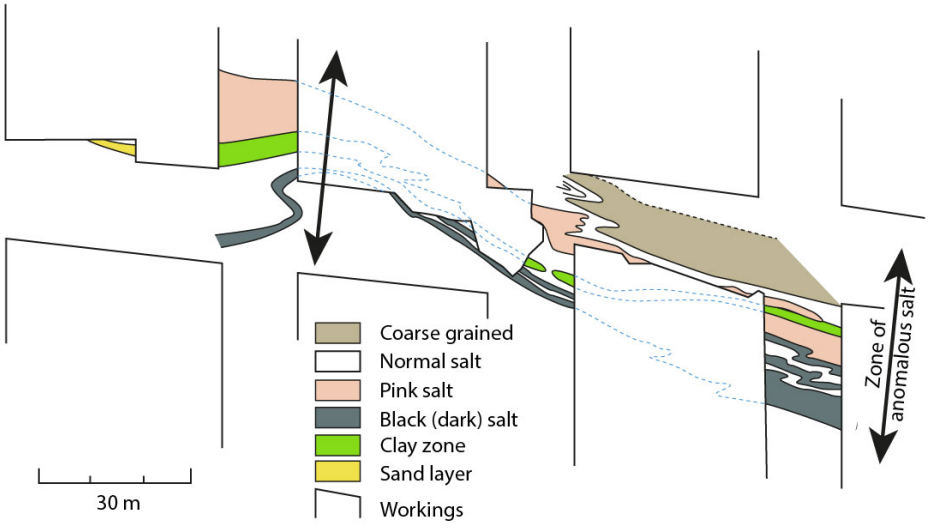

Figure 5. Anomalous salt subzone, 160 m long and about 45 m wide; average width of sand is 10 cm but actual width is as much as 90 cm. Sand is observed along 40% of the length, and over 6.5% of the area (after Kupfer, 1990).

boundary zones associated with clastic impurities (Figure 6). Boundary shear zones and edge zones around the dome tend to be more problematic for storage caverns as they are likely to contain greater occurrences of anomalous salt, higher impurity content (including gas and brine) and structural features that may degrade salt quality and enable leakage. Thus salt caverns can be constructed within boundary salt zones, but if possible, they should be avoided as they can result in non-optimal operating conditions, long-term operational difficulties and in the most severe cases contribute to the loss of cavern integrity (Looff et al., 2010). In the case of edge zones, additional distance to the edge of the salt dome needs to be maintained not only to cover any uncertainty regarding the placement of the edge of salt with respect of mine workings but also to account for the potential for degraded salt quality and to provide a sufficient pillar of good quality salt between the mine or cavern wall and the edge of dome.

A top-of-salt boundary between aggradational and dissolutional components atop diapirs in the Five Islands salt landscape typically coincides with underlying anomalous zones of differential shear within the underlying diaper typically indicated by "black" or "dark" salt zones in the various diapirs (Kupfer, 1976; Lock, 2000). Where such interior anomalous "black" salt zones have intersected the edge of the salt mass, they tend to create intervals with a greater propensity for water entry or gas outbursts and unstable roof zone bible to slabbing and and collapse (Figure 6). Such anomalous zones can leak water into a mine, and over the longer term create stability problems, as illustrated by problems in; the now abandoned Weeks Island oil storage facility, the Avery Island Salt Mine, and the likely association of a subvertical zone with anomalous salt, and the enhanced fluid entry that occurred during the Lake Peigneur collapse, which was tied to 1980 flooding of the former Jefferson Island Salt Mine. Today, only two of the former mines in the Five Island Salt Dome trend remain unflooded. For a more detailed discussion of these and other salt leakage scenarios tied to undersaturated fluid entry into salt mines and caverns, see case histories in Chapter 13, Warren 2016.

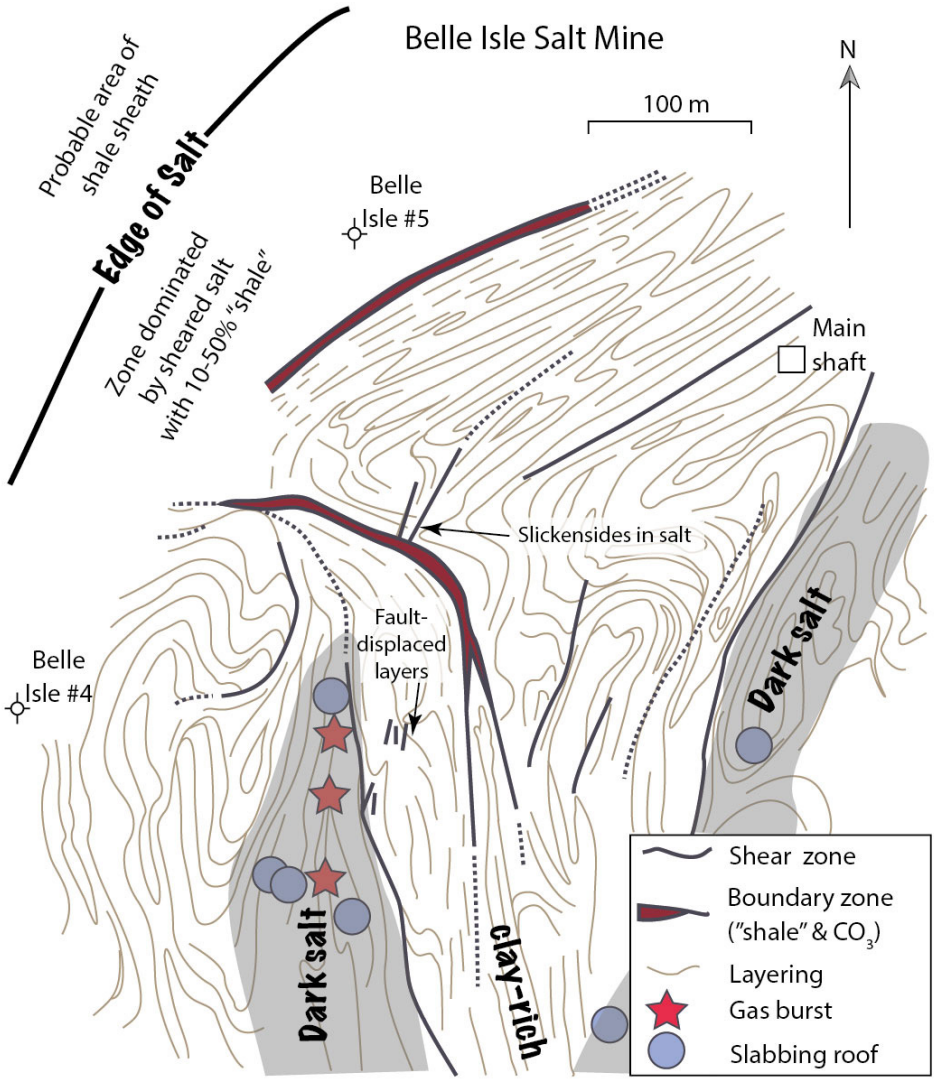

Figure 6. Geological map of Belle Island Salt Mine showing two salt spines separated by boundary shear zone,s now located in the salt. Also shows show how anomalous regions of "dark" or "black" salt are zones of relative instability and leakage within the main diapir salt stem (in part after Kupfer, 1974).

"Black" or "Dark" Salt zones and leakage into the former Weeks Island storage facility

In the walls of the now-flooded Weeks Island salt mine, Kupfer (1976) noted that wide black beds of the internal "shear" zone are unusual and not found over most of the rest of the mine where salt was extracted. In places, the anomalous zone beds contain black clay (Room J-21), orange sandstone (S-20), and other fragments of clastic material (Paine et al., 1965). These clastic remnants typically occur as balls or roundish blebs ranging in size up to tens of cm in diameter. Petroleum leaked out of seams in this black salt zone and seams in the surrounding salt; the escaping fluid ranged from yellow grease and heavy, blue oil to very light, straw-yellow distillate. Methane and carbon dioxide were also common. The width (surmised) and structural complexity of the anomalous zone suggest that internal salt movement continued after a clastic boundary sheath-zone was incorporated into the salt stock (Figure 7).

The cause of the drainage and abandonment of the Weeks Island oil storage facility was an active subsidence sinkhole some 10 metres across and

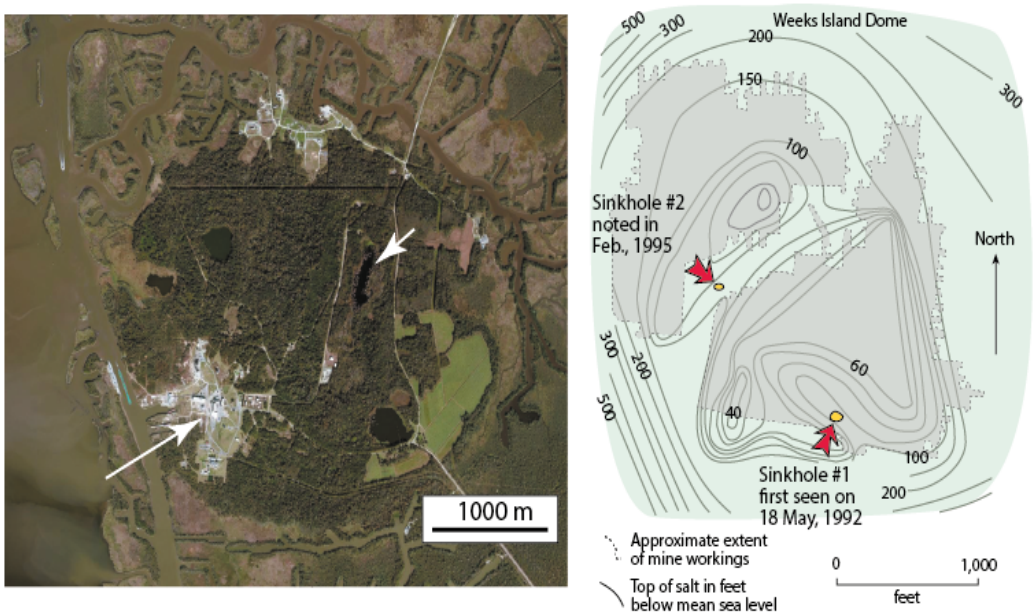

Figure 7. Strategic Petroleum Reserve facility, Weeks Island, Louisiana. A) Location of SPR facility showing the presence of at-surface natural water-filled mostly circular collapse dolines. B) Top of salt contours showing how sinkholes developed in depressions atop the upper part of the salt. The sinkholes occur in regions near the edge of the cavern, with the potential for foundering of the cavern roof into the chambers of the former Morton Salt mine.

10 metres deep, first noted near the edge of the SPR facility in May 1992, and perhaps reaching the surface about a year earlier. The growing doline depression was located on the south-central portion of the island, directly over a subsurface trough, which was obvious in the top-of-salt contours based on former mine records before conversion to a hydrocarbon storage facility (Figure7; Neal and Myers, 1995). Earlier shallow exploratory drilling around the Department of Energy service and production shafts in 1986 had identified the presence of irregularities and brine-filled voids along the top of salt mass across this region. A second, much smaller sinkhole was noticed in early February 1995, but it did not constitute a serious threat as it lay outside the area of cavern storage.

The first sinkhole occurs in a position of sharp change in landform slope (transition from high island to gully fill) and lies atop the projected alignment of what is known as Shear Zone E (a dark salt zone) in the underlying salt (Autin and McCulloh, 1995). Neal (1994) pointed out that Kupfer's 1976 map of that part of the Weeks Island salt mine, located beneath the first sinkhole, was defined by black salt (also shown as Figure 8 which is based on the more recent Kupfer et al. (1998) map). Miners always avoided such "black" salt or "dark" salt zones in the various subsurface workings and the lateral extent of workings in many of the Five Island mines extended only as far as intersections with significant "black" or "dark" salt regions (Figure 6 & 7).

The volume of the first Weeks Island sinkhole (estimated as 650 m^3 when first noted), its occurrence over a trough in the top of salt, and its position directly above the oil-filled mine caverns, meant it was of urgent concern to the SPR authorities, especially in terms of the stability of the roof of the storage cavern. This feature did not form overnight; it lies atop a shear zone that formed during the diapiric rise of the salt and capped by a rockhead valley containing Pleistocene sediment fill. Salt extraction during mine operations probably created tension across the shear zone, thereby favouring fracture enlargement in the anomalous salt zone, as early perhaps as 1970

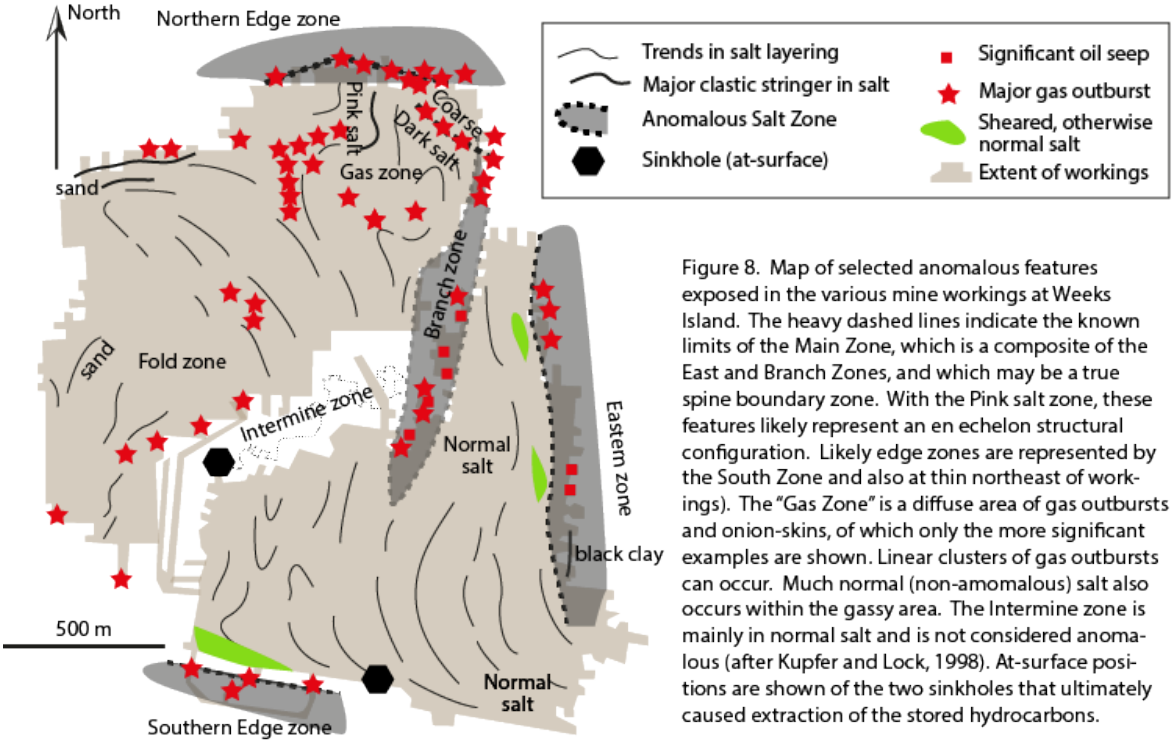

Figure 8. Map of selected anomalous features exposed in the various mine workings at Weeks Island. The heavy dashed lines indicate the known limits of the Main Zone, which is a composite of the East and Branch Zones, and which may be a true spine boundary zone. With the Pink salt zone, these features likely represent an en echelon structural configuration. Likely edge zones are represented by the South Zone and also at thin northeast of workings). The "Gas Zone" is a diffuse area of gas outbursts and onion-skins, of which only the more significant examples are shown. Linear clusters of gas outbursts can occur. Much normal (non-amomalous) salt also occurs within the gassy area. The Intermine zone is mainly in normal salt and is not considered anomalous (after Kupfer and Lock, 1998). At-surface positions are shown of the two sinkholes that ultimately caused extraction of the stored hydrocarbons.

(Figure 6; Waltham et al., 2005). Eventually, an incursion of undersaturated groundwater traversed the fracture zone across some 107 m, from a level equivalent to the rockhead down to the mine where it emerged. Over time, ongoing dissolution enlarged a void at the top of the anomalous salt zone, creating the collapse environment for the sinkhole first noted at the land surface in 1991. Investigations were undertaken in 1994 and 1995 into the cause of active at-surface sinkholes verified that water from the aquifer above the Weeks Island salt dome was seeping into the underground oil storage chamber at the first sinkhole site (Figures 7& 8; Neal and Myers, 1995; Neal et al., 1995, 1997). Drainage and decommissioning of the Weeks Island facility followed.

Beginning in 1994, and continuing until the abandonment of the facility, saturated brine was injected directly into the throat of the first sinkhole, which lay some 75 metres beneath the surface. This essentially arrested further dissolution and bought time for DOE (Department of Energy) to prepare for the safe and orderly transfer of crude oil to another storage facility. To provide added insurance during the oil transfer stage, a "freeze curtain" was constructed in 1995. It consisted of a 54 well installation around the principal sinkhole, which froze the overburden and uppermost salt to a depth of 67 metres (Figure 9; Martinez et al., 1998). Until the mine was filled with brine and its hydrocarbons removed, this freeze wall prevented groundwater flow into the mine via the region of black salt around the sinkhole. Dealing with this sinkhole was costly. Mitigation and the removal and transfer of oil, including the dismantling of infrastructure (pipelines, pumps, etc.), cost a total of nearly US$100 million; the freeze curtain itself cost nearly $10 million.

Following oil fill in 1980-1982, the Weeks Island facility had stored some 72.5 million BBL of crude oil in abandoned mine chambers. Then in November 1995, the Department of Energy (DOE) initiated oil drawdown procedures, along with brine refill and oil skimming, plus numerous plugging and sealing activities. In 1999, at the end of this recovery operation, about 98% of the crude oil had been recovered and transferred to other SPR facilities in Louisiana and Texas; approximately 1.47 MMBL remains in the now plugged and abandoned mine workings. In hindsight, based on an earlier leak into the mine, while it was an operational mine, and the noted presence of black salt in a shear zone in the mined salt, one might fault the initial DOE decision to select this mine for oil storage. In 1978 groundwater had already leaked into a part of the mine adjacent to the sinkhole and this was forewarning of events to come (Martinez et al., 1998). Injection of cement grout into the flow path controlled the leak into the operation mine at that time, but it could just as easily have become uncontrollable and formed a sinkhole then.

Black salt zones in the now-flooded Jefferson Island Salt Mine and the 1980 Lake Peigneur collapse

The most recently risen part of the Jefferson Island stock crest is now 250 m (800 ft) higher than the adjacent flat-topped salt mass, which is also overlain by a cap rock (Figure 10). The

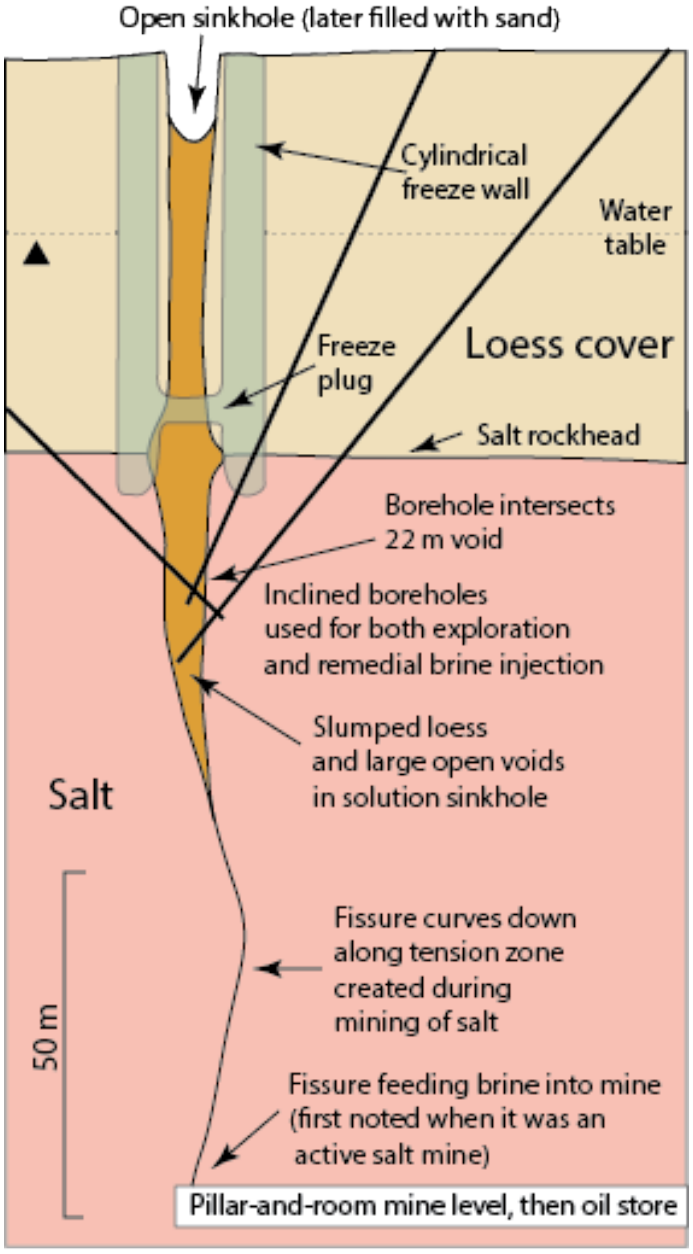

Figure 9. Schematic section through the main Weeks Island sinkhole and its remedial freeze curtain (after Waltham et al., 2005).

boundary separating the spine from the less active portion of the crest is a finer-grained and a "shale-rich" anomalous zone, penetrated by the former Jefferson Island mine workings. It defined a limit to the extent of salt mining in the diapir, which was focused on extracting the purer salt within the Jefferson Island spine. The spine and its boundary "shear" are reflected in the topography of the Jefferson Island landscape, with a solution lake, called Lake Peigneur, defining the zone of shallower salt created by the active spine. There on November 20, 1980, one of the most spectacular sinkhole events associated with oilwell drilling occurred atop the Jefferson Island dome just west of New Iberia. Lake Peigneur disappeared as it drained into an underlying salt mine cavern and a collapse sinkhole, some 0.91 km2 in area, developed in the SE portion of the lake (Figure 11; Autin, 2002; Warren 2016). In the 12 hours following the first intersection the underlying mine had flooded and the lake was completely drained. The lake is about

2.4 km in diameter, has a bean-shaped configuration, with a topographic promontory along the southeast shore of the lake rising to more than 23 m above sea level and the surrounding delta plain (Figure 10).

Drainage and collapse of the lake began when a Texaco oilrig, drilling from a pontoon in the lake, breached an unused section of the salt mine some 1000 feet (350 metres) below the lake floor (Figure 11). Witnesses working below ground described how a wave of water instantly filled an old sump in the mine measuring some 200 ft across and 24 feet deep. This old sump was in contact with a zone of anomalous "black" (shear zone) salt. The volume of floodwater engulfing the mine corridors couldn't be drained by the available pumps. At the time of flooding the mine had four working levels and one projected future level. The shallowest was at 800 feet, it was the first mined level and had been exploited since 1922. The deepest part of the mine at the time of flooding was the approach rampways for a planned 1800 foot level. Some 23-28 million m3 of salt had been extracted in the preceding 58 years of mine life. The rapid flush of lake water into the mine, probably augmented by the drainage of natural solution cavities in the anomalous salt zone and associated collapse grabens below the lake floor, meant landslides and mudflows developed along the perimeter of the Peigneur sinkhole, so that post flooding the lake was enlarged by 28 ha.

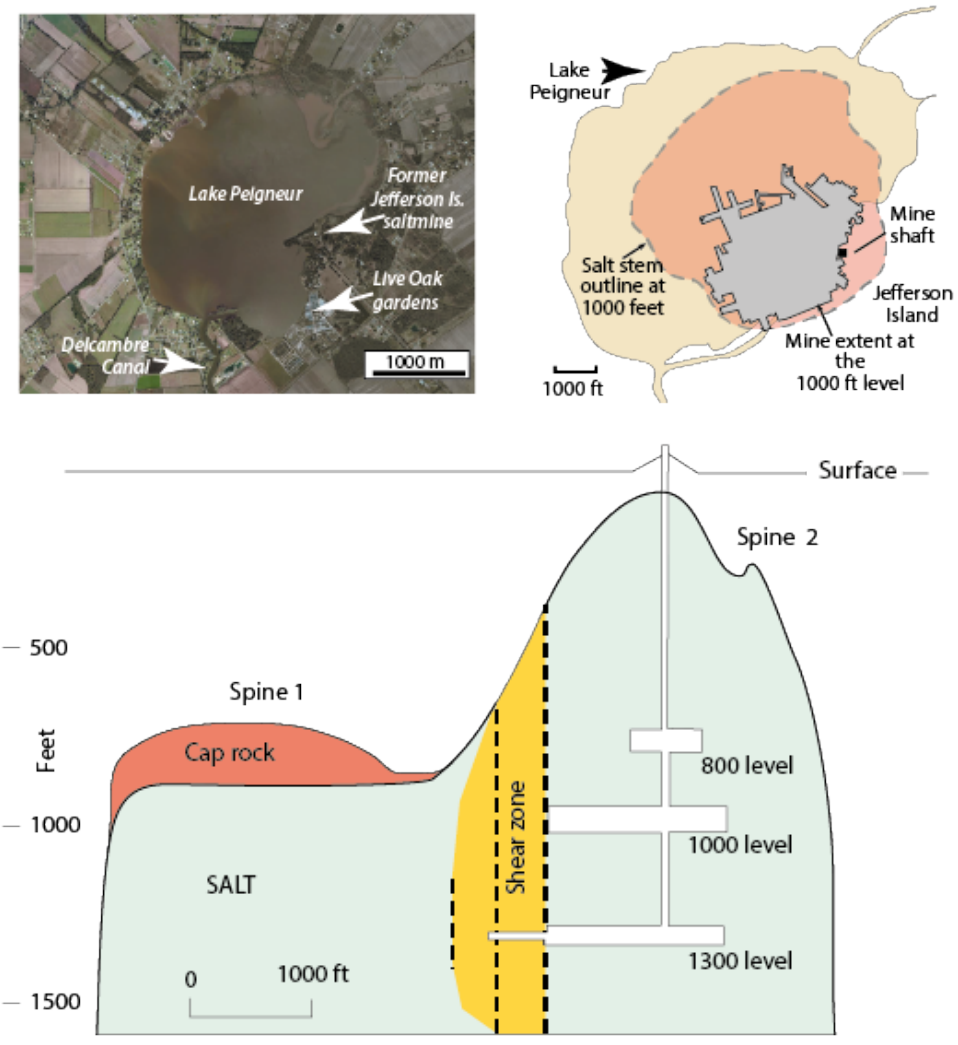

Figure 10. Lake Peigneur, located above the former Jefferson Island Salt mine, which was flooded in 1980 by an influx of lake waters. Note the anomalous salt (shear) zone that separatesthe elvaated caprock free active spine from the capped less active salt spine (after Warren 2016 and sources therein).

With water filling the mine workings, the surface entry hole in the floor of Lake Peigneur quickly grew into a half-mile-wide crater. Eyewitnesses all agreed that the lake drained like a giant unplugged bathtub—taking with it trees, two oil rigs (worth more than $5 million), eleven barges, a tugboat and a sizeable part of the Live Oak Botanical Garden. It almost took local fisherman Leonce Viator Jr. as well. He was out fishing with his nephew Timmy on his fourteen-foot aluminium boat when the disaster struck. The water drained from the lake so quickly that the boat got stuck in the mud, and they were able to walk away! The drained lake didn't stay dry for long, within two days it was refilled to its normal level by Gulf of Mexico waters flowing backwards into the lake depression through a connecting bayou (Delcambre Canal, aka Carline Bayou) former what was a waterfall with the highest drop in the Stat of Louisiana. Since parts of the lake bottom had slumped into the sinkhole during the collapse, the final water level in some sections of the lake was higher than before relative to previous land features. This ground movement and subsidence left one former lakefront house aslant under 12 feet of water.

Implications for other salt mines with anomalous salt zone intersections.

The Peigneur disaster had wider resource implications as it detrimentally affected the profitability of other salt mines in the Five Islands region (Autin, 2002). Even as the legal and political battles at Lake Peigneur subsided, safe mining operations at the nearby Belle Isle salt mine came into contention with public perceptions questioning the structural integrity of the salt dome roof. During ongoing operations, horizontal stress on the mineshaft near the level where the Louann Salt contacts the overlying Pleistocene Prairie Complex across a zone of anomalous salt had caused some mine shaft deterioration. Broad ground subsidence over the mine area was well documented and monitored, as was

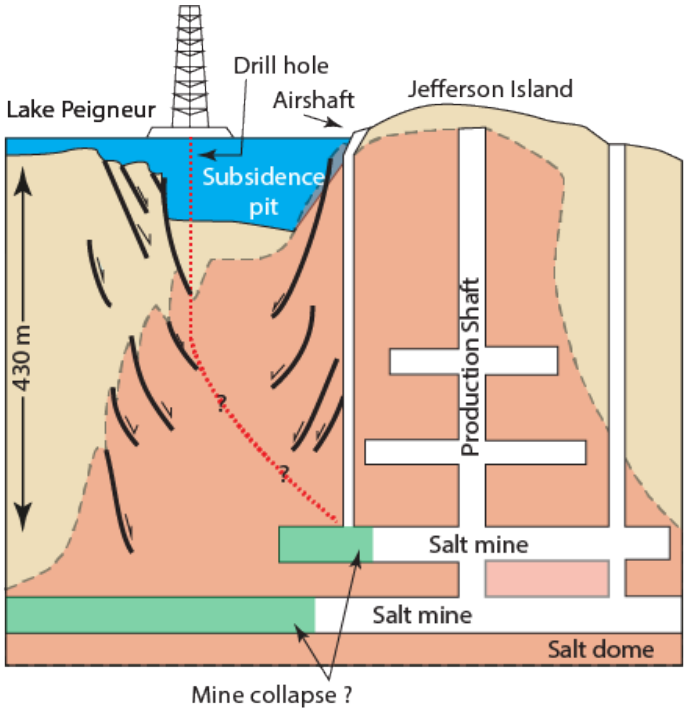

Figure 11. Lake Peigneur and schmatic mine cross section

near continuous ground water leakage into the mine workings. The Peigneur disaster meant an increased perception of continued difficulty with mine operations and an increased risk of catastrophic collapse was considered a distinct possibility. In 1985, a controlled flooding of the Belle Isle Salt m\Mine was completed as part of a safe closure plan.

Subsidence over the nearby Avery Island salt mine (operated by Cargill Salt) has been monitored since 1986 when small bead-shaped sinkholes were initially noticed in the above mine region. Subsidence monitoring post-1986 defined a broad area of bowl-shaped subsidence, within associated areas of gully erosion (Autin, 2002). Avery mine is today the oldest operating salt mine in the United States and has been in continual operation since the American Civil War. The mine underwent a major reconstruction and a improved safety workover after the Lake Peigneur disaster. Subsidence is still occurring today along the active mine edge, which coincides with a topographic saddle above an anomalous salt zone, which is located inside the mined salt area. At times, ground water has seeped into the mine, and there are a number of known soil gas anomalies and solution dolines on the island. These are natural features that predate mining. Much of the subsidence on Avery Island is a natural process as differential subsidence occurs atop any shallow salt structure with the associated creation of zones of anomalous salt (Warren, 2016). Dating of middens and human artifacts around salt-solution induced, water-filled depressions atop the dome, shows dissolution-induced subsidence is a natural process, as are short episodes of lake floor collapse, slumping and the creation of water-filled suprasalt dolines (circular lakes). Such landscape events and their sedimentary signatures have histories that extend back well beyond the 3,000 years of human occupation documented on Avery Island (Autin, 2002).

Compared to the other salt domes of the Five Islands region of Louisiana, the Cote Blanche Island salt mine has benefited from a safe, stable salt mine operation throughout the mine life (Autin, 2002). Reasons for this success to date are possibly; (i) mining operations have not been conducted as long at Cote Blanche Island as other nearby domes, (ii) the Cote Blanche salt dome may have better natural structural integrity than other islands, thus allowing for greater mine stability (although it too has anomalous salt zones, a salt overhang, and other structural complexities), and (iii) the Cote Blanche Salt Mine is surrounded by more clayey (impervious) sediments than the other Five Islands diapirs, all with sandier surrounds, perhaps allowing for lower rates of undersaturated fluid crossflow and greater hydrologic stability.

Significance

And so, today, we know that anomalous salt zones near diapirs crests are often tied to subvertical fault or shear zones, and that many are also associated with the presence of past crossflows of undersaturated waters. Across the various US Gulf Coast mines (present and past) the anomalous ("shear") salt zones within diapirs are known to be potential problematic leakage zones and so are avoided, if possible, during mining operations. This style of black salt distribution and the potential for intrasalt leakage must be taken into account when near-crestal and shallower portions of domes are to be utilised for any fluid or waste storage. Without an understanding of the significance of such "black" salt or anomalous salt layers, there are potential undefined leakage problems within some salt structures (Looff et al., 2010; Warren 2016).

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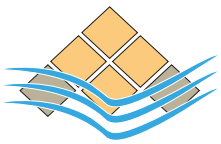

John Warren, Chief Technical Director
SaltWork Consultants Pte Ltd (ACN 068 889 127)
Kingston Park, Adelaide, South Australia 5049

www.saltworkconsultants.com