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Salt usually seals, but sometimes leaks: Implications for mine and cavern stabilities in the short and long term

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ABSTRACT

Thick evaporite masses (bedded and halokinetic) dominated by the mineral halite, are currently mined using conventional solution mining techniques. After excavation, the resulting salt cavities are sometimes used as subsurface storage vessels for hydrocarbons or various types of waste, including low-level nuclear waste. There are plans being discussed to use purposed-designed solution cavities in thick salt masses for the long term storage of high-level nuclear waste. If high-level nuclear waste is ever to be safely stored in salt, it will involve a need for the encasing salt not to leak over time frames measured in tens of thousands of years. Understanding how, where and why accessible salt masses leak is the rationale for this review. It is the first step in assessing it a particular site's salt geology is suitable for storage.

We know salt can act as an excellent longterm seal over hundreds of thousands of years, as evidenced by its ability to hold back significant columns of highly overpressured fluids, even in structurally complex settings. But we also know that locally salt bodies do occasionally leak large volumes of fluid, as evidenced by the loss of a number of salt mines to uncontrolled floods, the rapid creation of solution dolines atop subcropping salt masses and to black salt haloes around highly pressurized hydrocarbon reservoirs. These types of leakage are usually tied to the edges of a salt body being exposed to longterm crossflows of undersaturated pore waters or to the build-up of internal pressure to levels that exceed lithostatic.

In fact, most zones where a salt body is liable to leak, or has leaked, are indicated by anomalous textural or mineralogical features when compared to the regional character of the salt. The time of leakage can be early (eogenetic), related to burial (mesogenetic) or related to uplift (telogenetic). If the salt mass is not entirely dissolved in the fluid crossflow, then the remaining salt tends to re-seal, especially in zones of ongoing salt flow. However, if non-salt sediment remains in the re-annealed salt mass, it will tend to retain permeability, and when intersected in a salt mine or by a well bore it will flow fluid. More problematic in terms of significant leakage are zones in contact with an aquifer external to the salt mass. These anomalous areas can transfer large volumes of fluid. For this reason, active telogenetic anomalies in a salt mass are the most problematic in terms of both mine safety and waste storage.

Identifying the type of salt anomaly, the time in diagenesis when leakage occurred and proximity and volume of intersected fluids in the zone of leaking salt is fundamental to mine safety and reliable waste storage.

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1. Introduction

In this review, I discuss salt's ability to act as a fluid seal in a variety of bedded and halokinetic settings and how variation in this ability impacts on salt mining and the possibility of using man-made cavities in massive salt bodies for longterm waste storage. We shall consider the macro and microscopic nature of the sealing salt, its evolution during burial, halokinesis, and finally salt's ability to uphold and maintain long term seal capacity.

We shall use the diagenetic classification of Choquette and Pray (1970) in our discussion of poroperm evolution in salt in the subsurface. Their classification, first designed for use in carbonate sediments, divides the diagenetic realm into three zones; eogenetic, mesogenetic and telogenetic. The eogenetic zone extends from the surface of newly deposited sediment to depths where hydrological processes genetically related to surface become ineffective. The mesogenetic zone lies below major influences of processes operating at the surface and is often considered equivalent to the zone of burial diagenesis. The telogenetic zone encompasses uplifted and eroded sediments. It extends from an uplifted and typically eroded surface down to depths where major surface-related geohydrological processes become ineffective. Below a subaerial erosion surface, the practical lower limit of telogenesis is controlled by the position of the watertable and the base of the related surface-driven zone of phreatic meteoric water circulation, it includes both unconfined and confined aquifers. The three terms —eogenetic, mesogenetic and telogenetic— also apply to time, processes, or features developed in their respective hydrological zones.

Texture is important in documenting present and past salt leakage in both the bedded and halokinetic seals. Immediately after it is deposited (as a primary precipitate), a salt bed is both porous and permeable, but primary porosity and permeability are quickly lost during the early stages of burial. Cores collected from a variety of Quaternary-age salt units in continental sumps have lost all effective porosity and permeability by depths of 60 to 100 m (Fig. 1). Salt beds tend to lose primary porosity via ongoing cementation as the basin subsides and the saline sediments accumulate in a longterm brine curtain constructed by reflux brines, typically saturated with respect to $CaSO_4$ and halite. Oscillation in salinity in a holomictic brine body is the main eogenetic process driving both reflux and the associated subsurface halite cements, so inducing loss of primary porosity (Warren, 2016; Chapter 2 for details). Throughout this paper, we shall assume that all the salt deposits under consideration have lost primary porosity during early burial and are essentially impermeable on entering the mesogenetic realm.

2. When salt is a seal

The ability of evaporites to form highly efficient seals is clearly demonstrated by an inventory of instances where significant hydrocarbon reserves are sealed by evaporites (Warren, 2016, Chapter 10). Even though evaporites constitute <2% of the worlds sedimentary rocks (compared to mudstones and shales which comprise 65%), 14 of the world's 25 largest oil fields and 9 of the world's 25 largest gas fields are sealed by evaporites. Unlike thick shales, once a salt bed is buried below depths of a few hundred meters of overburden, subsurface salt better fits Hunt's (1990) definition of a pressure seal. A pressure seal

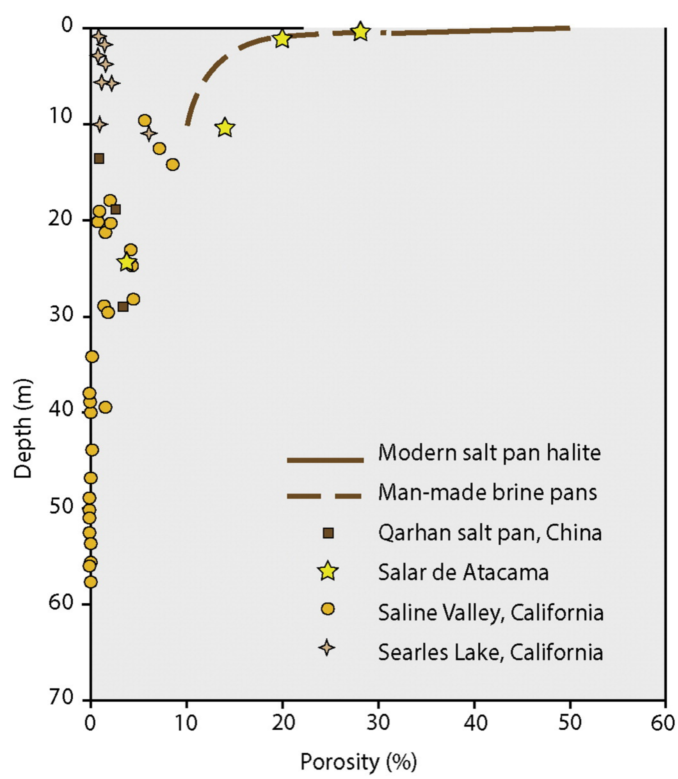

Fig. 1. Primary halite beds have lost effective primary porosity by 70–100 m burial (after Casas and Lowenstein, 1989).

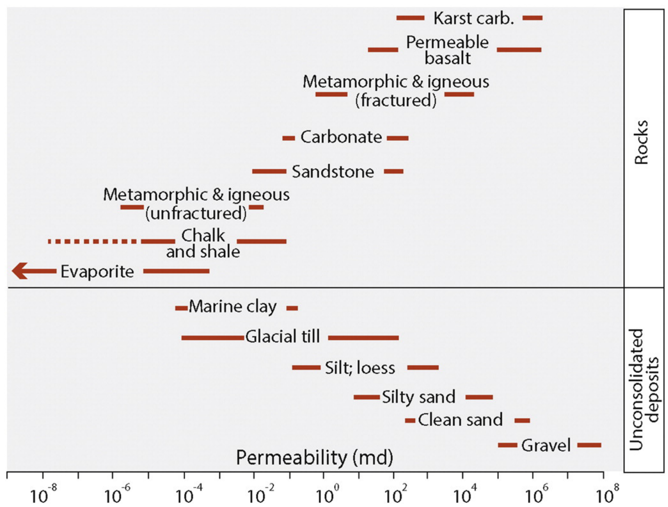

Fig. 2. Relative ranking of permeability of various lithologies (in part after Beauheim and Roberts, 2002).

is an impermeable rock, with zero transmissivity maintained over long periods (tens of millions of years) of geologic time. Very little subsalt fluid can escape vertically through a thick subsurface salt mass that, until breached, tends to hold back all compactional and thermohaline waters, gases or liquid hydrocarbons rising from below. In contrast, subsurface shale-seals consistently leak all these fluids to varying degrees.

Like clathrate seals, evaporite layers can generate overpressures at very shallow burial depths. Unlike clathrates, they do not dissolve and dissipate in response to the rising temperatures intrinsic to the diagenetic burial realm. Evaporites create most of the sharpest and most extreme depth-related pressure differentials known in sedimentary basins in both overpressured and underpressured settings (Fertl, 1976). Like clathrates, salt-sealed overpressured intervals can be as shallow as a few hundred meters below the surface, unlike clathrates they maintain seal integrity to levels deeper than 6000 m.

Quantitative measurement of evaporite permeability is beyond the capacity of standard instruments used in the oil and salt mining industries and is mostly a specialised topic of study for engineers working with waste-storage caverns (Peach and Spiers, 1996; Popp et al., 2001; Schulze et al., 2001). Their work shows permeability of undisturbed halite is a nanodarcy or less, that is, undamaged subsurface salt has measured permeabilities that are $<10^{-21}$ m^2 (10^{-6} md) with some of the tighter halites possessing permeabilities $\approx 10^{-7}$ to 10^{-9} md (Fig. 2). In contrast, typical permeabilities of massive anhydrite seals are $\approx 10^{-5}$ md (Beauheim and Roberts, 2002). This helps explain a general "rule of thumb" used in the oil industry that a halite bed should be at least 2 m thick to be considered a possible seal, while an anhydrite bed should be at least 10 m thick. Equally important is the reliability of the geological model of the evaporite, and its host/country rock, used to extrapolate lateral continuity in the seal (Warren, 2016). Massive thick bedded pure halite units in the diagenetic realm usually contain few, if any, interconnected pore throats. The distance between NaCl lattice units is 2.8×10^{-10} m, while the smallest molecular diameter of a hydrocarbon molecule (methane) is 3.8×10^{-10} m.

Evaporite seals, with their high entry pressure, superior ductility, very low permeability and large lateral extent, tend to maintain excellent seal integrity over vast areas, even when tectonised and exposed to a wide range of subsurface temperature and pressure conditions (Macgregor, 1996). The most frequent zone where hydrocarbons migrate through a non-fractured, undissolved, halite bed is where the bed contains enough shale or carbonate impurities to render it locally porous or make it brittle in deformation. Pore pressures in thick sealing halite units atop active fluid columns can approach lithostatic (Ehgartner et al., 1998). When lithostatic pressure is exceeded, salt can locally fracture and leak as evidenced in naturally-fractured hydrocarbon haloes that define the "black" salts of Oman (Schoenherr et al., 2007a, 2007b).

2.1. Seal capacity in flowing pure salt

When subject to external stresses, halite's very high ductility and its ability to stream, re-anneal, and re-establish widespread lattice bonding via pressure-solution creep, give it a low susceptibility to fracturing even when deforming (Fig. 3). This is why cross-salt subsurface fault and fracture patterns, as seen in most salt-entraining basins, make the oil industry consider salt layers a "crack-stopper." Worldwide, seismic

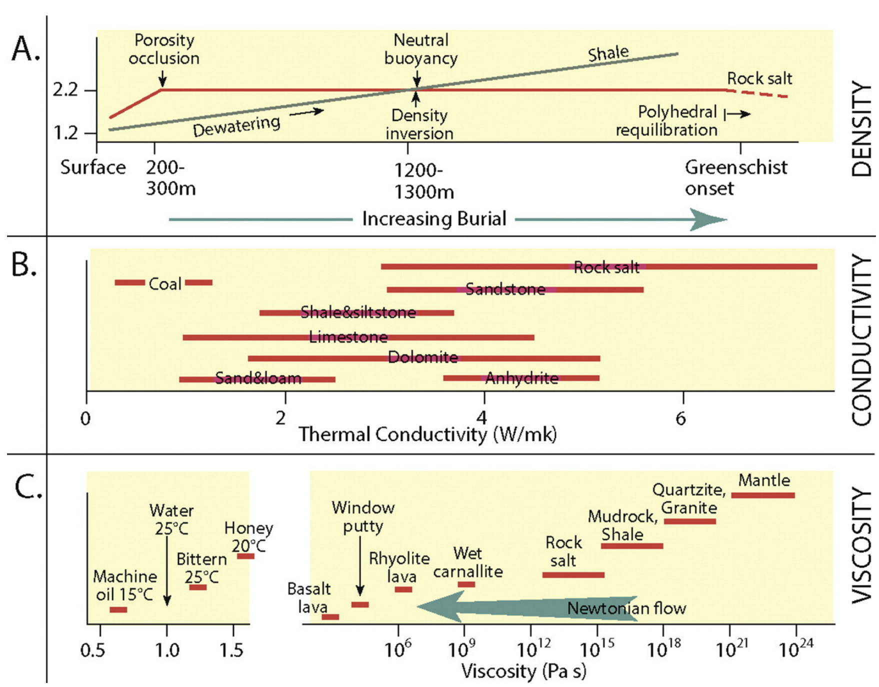

Fig. 3. Physical properties of rock salt compared to other lithologies. A) Density changes with burial. B) Thermal conductivity. C) Viscosity (after Warren, 2016).

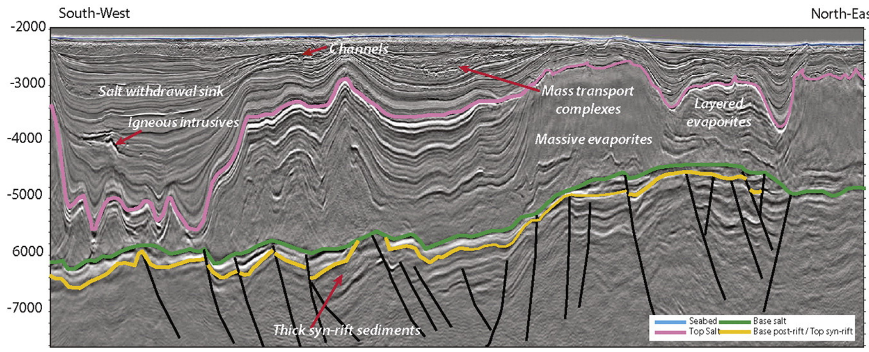

Fig. 4. Typical subsalt-suprasalt relationships in the vicinity of Libra Field (Santos Basin) showing salt acting as a "crack-stopper." Internally the Aptian salt shows layered versus massive character of salt in this region, which is related to distinct mineralogical contrast in the intrasalt beds but not necessarily tied to the presence or absence of potash salts (seismic image courtesy of CCG).

imaging of halokinetic realms shows salt flows, while adjacent carbonate and siliciclastics sequences fracture (Fig. 4). Halite's ability to maintain seal integrity under stress, and so prevent the escape of hydrocarbons, reveals a combination of its ability to flow and re-anneal via varying blends of pressure-solution creep and dislocation creep across temperatures of the diagenetic realm. (Fig. 5). In contrast, in non-evaporite sediments, dislocation creep and other flow mechanism can only dominate at much higher temperatures and pressures (Hobbs and Ord, 2015).

In a comprehensive study of salt flow character tied to lithological variations at the microscale, Závada et al. (2015) and Desbois et al. (2012) show there are significant differences in flow and fluid responses between "dirty salt and "clean" salt in the Miocene Salt diapirs of Iran. The solid-inclusion-rich ("dirty") rock salt in these diapirs contain abundant disaggregated siltstone and dolomite interlayers, while "clean" salts contain microscopic hematite and remnants of abundant fluid inclusions in non-recrystallized cores of salt porphyroclasts. Flow occurs in both the recrystallized "dirty" and "clean" salt types and is accommodated by combined mechanisms of pressure-solution creep, grain boundary sliding, transgranular microcracking and dislocation creep accommodated via grain boundary migration (Fig. 5). Viscosity contrasts observed in the salt outcrops in both types of namakier salt are explained by: 1) enhanced ductility of "dirty" salt due to increased diffusion rates along the solid inclusion-halite contacts, rather than along halite–halite contacts, and 2) slower rates of intergranular diffusion due to dissolved iron and inhibited dislocation creep due to hematite inclusions in "clean" salt types. These rheological contrasts, as inferred by microstructural analysis between both salt rock classes apply in general for the "dirty" salt forming Lower Hormuz and the "clean" salt forming the Upper Hormuz of the Hormuz Formation and so explain differing strain rate gradients and decoupling along horizons of mobilized salt types of different composition and microstructure. Later in this review, we shall come back to these differences in the context of mine-scale leakage within "dark" (dirty) salt zones.

The propensity for rock salt to flow easily under stress in subsurface diagenetic conditions and geological time frames, where it exhibits a tendency toward Newtonian flow, is why many laboratory tests and measurements regularly underrepresent salt's actual seal integrity. Inherently, any lab experiment is tied to static measurements across short time frames of weeks up to a few years. However, laboratory tests on rock salt are likely more relevant to real-world subsurface situations of anthropogenic hydrocarbon or waste storage where salt in the vicinity of any wellbore is damaged by the nearby passage of the drill bit and its associated fluids. The applicability of laboratory measurements to real-world undisturbed subsurface situations where salt is acting as a very efficient fluid seal points to a philosophical quandary inherent to many natural science experiments with a time-related possible-error component. By putting equipment into a natural subsurface salt region, or by removing salt samples from their natural deep subsurface environment to take measures in the lab, or by growing salt crystals in the lab to work on, we always alter things and so get outcomes that can never be 100% accurate with respect to the original unaltered subsurface rock salt setting. That is, within observational errors, how do we quantify random versus systematic errors when we are always

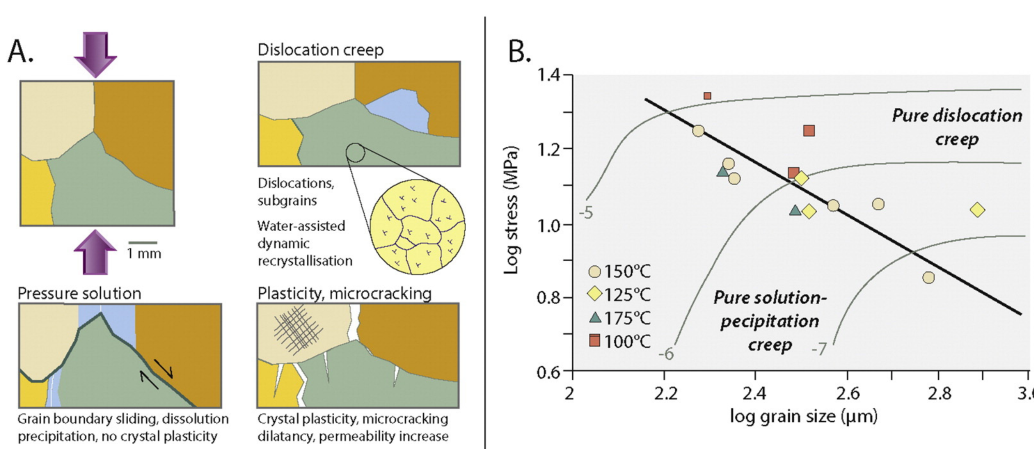

Fig. 5. Crystal-scale deformation. A) Schematic showing the microstructural processes that can operate during the deformation of rock salt at temperatures in the range 20–200 °C. Different shades represent crystals with different orientation. The circular expanded inset illustrates subgrains (with same orientation). See text for further explanation. B) Dynamically recrystallised grain-size versus stress data for synthetic rock salt samples, superimposed on a deformation mechanism map, showing that halite deforms across a transition region between dislocation creep and solution-precipitation creep, both playing a role in the deformation (after Ter Heege et al., 2005; Urai et al., 2008).

altering the samples and the surrounds via the process of gaining access for measurement?

Hence, whether buried anthropogenically-undisturbed rock salt beds that enclose organic intrabeds can release (leak) volatiles to sediments outside the salt mass during catagenesis is still a matter of ongoing discussion among geochemists (Dewing and Obermajer, 2009; Hite and Anders, 1991; Hite et al., 1984). The long-term lack of fractures or pore throats in buried salt beds is why organic-rich intrasalt carbonate or shale laminites tend to be inefficient source rocks in style 1a salt-encased source rocks (Warren, 2011). Likewise, possible flushing and maturation effects are poorly understood in subsurface situations where encased organic-rich beds are in contact with hydrated evaporite salts converting to their anhydrous equivalents (such as gypsum to anhydrite, carnallite to sylvite or mirabilite to thenardite). Loss of water of crystallization in shallow burial (<0.5 km) has the potential to allow immature organic-rich fluids to escape early as the hydrated salts transform to their anhydrous forms (Schofield et al., 2014). Burial transformations tied to gypsum dehydration are near complete in the first kilometer of burial and so may only allow immature hydrocarbons to escape from proto-kerogens into adjacent more porous sediments (Hite and Anders, 1991). These immature hydrocarbons must be stored, mature and then remigrate during later burial, if they are to act as hydrocarbon source rocks (Warren, 1986, 2011). Meta-evaporite associations show many intrasalt-sealed organic-rich beds remained encased well into the metamorphic realm and evolved into graphitic pelites and marbles, usually sheathed in meta-evaporitic albitites and scapolites (Warren, 2016, Chapter 14 for case histories). However, when a buried hydrated salt unit, such as a carnallite bed still in the diagenetic realm, is cross-cut by later igneous dikes and seals the hydrated salt releases its water of crystallization and becomes thixotropic as it converts to sylvite, while forming highly disturbed peperite-like flow intervals sandwiched between unaltered halite layers (Schofield et al., 2014).

As a general rule, even if a subsurface halite bed fractures, its inherent lack of strength and resultant ability to flow means any microscale intercrystalline fractures quickly re-anneal via a combination of flow and pressure-solution induced recrystallization (Fig. 5). The current consensus in the oil and gas industry is that some thin impurity-rich salt beds, interlayered with carrier beds, do leak small amounts of volatiles, possibly via intercrystal microfractures, but they leak hydrocarbons much less efficiently than thicker organic-rich mudstones and shales. Organics encased in thick pure salt beds probably cannot leak from the unit until the enclosing salt dissolves or natural hydrofracturing occurs, as in the Ara Salt of Oman (Schoenherr et al., 2007a). Evaporite beds and salt allochthons in the diagenetic realm constitute some of the sturdiest long-term subsurface barriers to the vertical migration of hydrocarbons in a sedimentary basin. They are effective seals for natural hydrocarbon accumulations and confinement vehicles in anthropogenic CO_2 sequestration. Salt beds tend to leak when thinned, dissolved, drilled and contain higher levels of non-salt impurities.

3. When salt doesn't seal

The timing of salt leakage in the subsurface ranges from early to late diagenetic and from the eogenetic through mesogenetic to telogenetic. If leakage is early, then later salt cementation and flow generally reseals previous regions of shallow leakage. When the same salt moves into the mesogenetic realm, a re-annealed salt mass usually manages to maintain seal integrity. More problematic, in terms of seal integrity and waste storage are leaks in the telogenetic (uplift) realm, including zones hundreds of meters below the surface flushed by deep meteoric upwelling (See Warren, 2016; Tables 13.5 and 13.6 for relevant case histories). Groundwaters in the upper parts of the telogenetic realm tend to be active phreatic, with salinities in regions of water ingress into the salt mass favouring undersaturation, but become more stagnant and more saline with depth. Because the products of telogenetic leaching in the active phreatic zone are carried away from the site of dissolution, there are lesser opportunities for a salt breach (leak) to heal, compared to leaks that occur in a salt mass on its way down into the mesogenetic realm.

3.1. What are anomalous salt zones?

Fundamental to an understanding of how and where salt leaks is the recognition of “anomalous salt zones,” as first defined in salt mines within the US Gulf Coast (Kupfer, 1990). An anomalous salt zone is broadly defined as a region in a salt body with atypical features, of whatever origin. Although initially defined in diapiric salt (see later for details), the concept of anomalous salt features is also used to explain discontinuities in bedded salt. Kupfer (1976, 1990) itemized anomalous salt zones via changing combinations of inconsistent features, including variations in:

Textures-Coarse-grained, piokiloblastic, friable

Inclusions-Sediments, hydrocarbons, brine, gases

Structures-Sheared salt, gas outbursts, brine leaks, excessive mine roof and wall slabbing, rapid closure, jointing, voids, and slight porosity development

Compositions-Potash/magnesium, high anhydrite content, very black salt (due to disseminated fluid and solid impurities).

All these anomalous features in a regionally-uniform salt mass signify alteration occurs postdeposition, and is possibly related to crossflows of undersaturated fluids tied to zones of leakage, either present or past.

4. Leakage across and within bedded salt units

The supreme rule for safe, conventional salt mining in bedded and halokinetic ore hosts is “stay in the salt.” Problem areas encountered in most halite and potash mines are related to thinning or disappearing salt-ore seams, usually in zones showing evidence of water-related dissolution and solution collapse. In other words, problems tend to occur when there is an unexpected intersection with a precinct of anomalous salt features (Woods, 1979; Boys, 1990, 1993; Warren, 2016).

Uncontrollable water inflow is the greatest threat to any operating salt/potash mine in both bedded and halokinetic ore hosts, as can be seen in the following listing of losses of operational potash and salt mines over the past five decades. In 1970, the decision was made to allow the Cane Creek (Moab) potash mine to flood, after five difficult years trying to deal with unexpected water inflows, gas explosions[1] and ore-grade problems. In 1975 the Ronneberg potash mine in Germany, which had operated from 1905 to 1973, was abandoned after water inflow rates had increased by three orders of magnitude to >15 m^3/min (250 l/s). In 1977, the Holle Mine in West Africa was lost to flooding after expanding operations breached a salt anomaly.[2] In 1986, Uralkali's Mine 3 was abandoned due to flooding. There are ongoing water ingress problems in this potash-producing region of the Urals, such as the appearance of a massive sinkhole in November 2014 atop former workings of the Solikamsk-2 mine. In October 2006, Uralkali's (URKA–RT) Mine 1 was closed due to flooding, with associated ground

[1] A gas explosion occurred in the Cane Creek mine about 4:40 p.m., Tuesday, August 27, 1963. Twenty-five men were underground at the time; 18 died from the flame, forces, or asphyxiation. Examination of the entire mine after the disaster showed that the explosion originated in the maintenance shop area. All evidence indicated that the combustible gas ignited in the shop area was released initially at the face of 2-south drift when a round of shots was fired therein at 4:20 p.m. Methane gas, liberated by blasting in the face of 2 south drift, was carried by return air toward the shop. The return fan, operated openly in the shop area, drew some of the gas-laden return air from 2-south into the shop and then recirculated it. Ignition of the combustible gas in the shop area might have, and easily could have, been from an electric arc or spark, an open flame, or a heated exhaust manifold on a shuttle car (Gwynn, 1984).

[2] A salt anomaly is a region of subsurface salt that shows differences from typical nearby salt; these can be differences in colour, texture, mineralogy, inclusions, clasts, etc.

collapse, resulting in the loss of some 3% or 1.2 million tonnes/year of global production. In 1994, the Retsof Salt Mine in New York State was lost due to flooding associated with catastrophic failure of a roof beam. Uncontrolled water inflows caused the closure of active salt mining the Wieliczka Mine in Poland in 1996, but due to ongoing pumping, the shallow section of the mine workings with World Heritage salt carvings remains open the public. Cassidy Lake (Potacan) potash mine in New Brunswick closed in October 1997 because of irreparable damage from severe flooding, at the time its capacity was 1.3 million tonnes (see Warren, 2016; Chapters 7, 11 and 13 for detail on the various case histories).

As in all salt mines, the history of potash mining in the Saskatchewan, the largest supplier of potash to the world, is underlined by a continual chronicle of dealing with water inflows, tied to intersections with salt anomalies. The first attempt to mine sylvinite in Canada, failed in 1951 due to flooding. In early 1987, the Patience Lake potash mine was closed due to uncontrollable flooding after breaching a salt anomaly. Water inflows were first encountered there during routine mining in 1975 and after a number of years of trying to cope with the inflows the former conventional underground mine was closed, allowed to flood, and a new solution mine started in 1988. Prugger and Prugger (1991) reported that, of the seventeen potash shafts started in Saskatchewan, five had major water inflows or were completely flooded during shaft sinking. Of the existing nine potash shaft mines in Saskatchewan, all but one experienced water inflows during the mine life (Coode and Strathdee, 1993). Brine inflow history of Canadian potash mines indicates that between 1970 and 1997, there were at least eleven occurrences of significant brine inflows into active mines (De Souza, 1998). Today, Mosaic's Esterhazy K1 and K2 facilities are dealing with ongoing water inflow problems. A flood at the Esterhazy complex (current capacity of 5.3 million tonnes/year) would affect some 9% of current global capacity, and it probably represents the most credible known current risk for a potash mine to flood.

4.1. Salt anomalies in bedded salt units that are variably "leaky"

Increased water inflows in Saskatchewan potash mines are consistently linked to salt anomalies, that is, to natural areas of little or no potash within the potash ore bed (Gendzwill and Martin, 1996). Geology of potash ore quality in three salt anomalies was studied by Boys (1990) in the PCS Cory mine, Canada, which extracts potash from the Patience Lake Member of the Prairie Evaporite Formation. Boys defined five postburial facies in the vicinity of the salt anomalies, all related to current or previous crossflows of water undersaturated with respect to potash and halite (Fig. 6a). Where undersaturated groundwater continually interacts with a sylvinite bed, it ultimately dissolves all the salt to leave behind only insoluble residues in a solution-collapse breccia (facies 1). A potash and halite-free insolube interval is at the one end of the facies

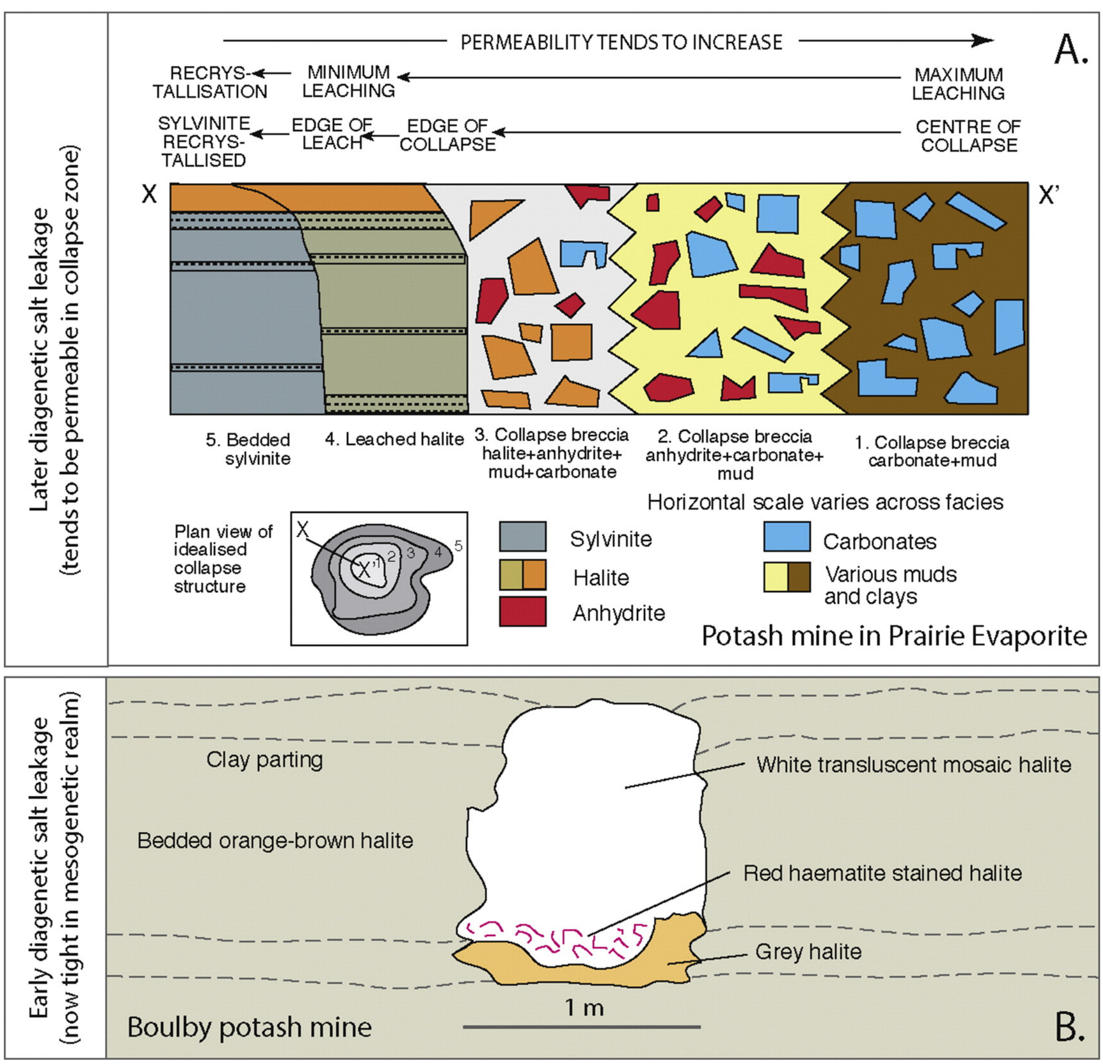

Fig. 6. Salt anomalies related to dissolution in potash mines A) cross section A-A′ through half of an idealised collapse structure in the Prairie Evaporite Formation, Variable scale from 100 to >500 m across (after Boys, 1990, 1993). B) Recemented solution cavity in the Boulby Halite, Boulby Mine, UK. This interval is located below the main potash zone (after Woods, 1979).

continuum defining salt anomalies in the PCS mine (Fig. 6a; facies 1). At the other end of the groundwater-potash interaction spectrum are beds composed of completely recrystallized and often potash-enriched sylvinite ores (facies 5). These sweetspots lie adjacent to leached beds where recrystallized halite (facies 4) passes laterally into collapse breccias with blocks of residual anhydrite and halite (facies 3 and 2; solution residues made up of the less soluble salts), which in turn pass laterally into the most mature dissolution breccias of facies 1, where no evaporite salts remain. When a drive or a test hole passes out of the ore into facies 1, the potential for water problems is high.

In the Boys model, salt anomalies indicate proximity to collapse structures acting as conduits for overlying (or possibly pressurized underlying?) formation waters. Such collapse structures are commonly found; 1) over the edges or tops of Winnipegosis Formation mudmounds, 2) are common in topographical lows in the top salt, and 3) can be associated with faults (Boys, 1990; Gendzwill and Wilson, 1987). The leaching-fluid crossflow may have come from above or below. As the crossflow transects the salt it drives a halo of pervasive leaching and recrystallization within the Prairie Evaporite Formation. The same fluids that cause widespread recrystallization, and possibly enrichment of the potash salts at the outer edge of the salt anomaly, also dissolve water-filled cavities in the more central parts of the same anomaly zone. The intensity of the leaching and the geometry of the leached halo is variable, while the timing of the main leaching events in the Prairie Evaporite is still poorly constrained. Boys (1990) postulates at least two major water crossflow events in the PCS mine, possibly driven by uplift and tectonism: one occurred in the Late Devonian, the other in the Cretaceous. Boys (1990) argues both leakage episodes are tied to the gravity-driven ascent or descent of undersaturated waters ("per ascendum" versus "per descendum" hydrologies).

Effects of the leaching events that produce the salt anomalies and loss of potash ore in mines in Canada and elsewhere, range from weak to strong, from selectively preserving delicate laminae and chevron textures, to deforming and destroying salt beds (Boys, 1990). Excellent preservation of iron oxides in halite may indicate that the leaching was weak or of short duration. In many leach anomalies fed from above, the proportion of salinity indicator minerals tends to increase downward within a leached region, possibly because early reflux fluids exit downward and NaCl-saturated fluids tend to follow the chemical gradient provided by potash beds.

4.2. Salt anomalies within bedded hydrologies that are no longer "leaky"

Early-leached solution cavity-fill salt anomalies occur in the Boulby Potash Mine in the UK (Woods, 1979). Most of the documented halite-karst features hosted in the Boulby Halite formed in the early-burial mesogenetic realm and are now halite-cemented. The cementing fill consists mostly of lenses of coarse pure inclusion-free translucent secondary halite (Fig. 6b). These early-leakage salt anomalies are less of a potential fluid-influx problem, compared to still-active salt anomaly collapse zones in Saskatchewan mines defined by Boys (1990, 1993). Intersected zones in the Boulby ore zone are up to 2 m across and typically overlie a band of halite encrusted with red hematite (Woods, 1979). The amount of anhydrite at the base of many cavities is greater than would accumulate as a simple insoluble residue implying they formed from water crossflows close to $CaSO_4$ saturation. According to Woods (1979), the cavities formed in the shallow subsurface from $CaSO_4$-saturated brines that were involved in dissolving the carnallite and sylvite as the Boulby halite unit was subsiding into the mesogenetic realm. Ensuing brines were supersaturated with respect to NaCl, causing halite to precipitate and accumulate on the cavity floor and so plug porosity as the unit sank into the mesogenetic realm.

At a smaller scale, I have observed similar early-leached $CaSO_4$-floored dm-scale cavities in the core from the Maha Sarakham potash intervals in Thailand. Cavities formed early beneath exposed highs, with bedded sylvinite accumulating in adjacent salt withdrawal depressions (Fig. 7; Warren, 2016). It seems that vadose and shallow phreatic dissolution in salt beds on the passage into the mesogenetic realm is routine in many potash intervals worldwide. Cavity fill, however, is not always halite and in some densely recrystallized halite intervals in Thailand, some of the anhydrite-floored cavities are filled by clear coarse-grained sylvite, not halite, and are made up interpenetrating crystal mosaics with single glass-clear sylvite crystals >30 cm across.

Salt anomalies form barren crosscutting intervals in the Permian potash ores in New Mexico (Linn and Adams, 1966). Locally called "salt horses," these crosscutting irregular salt anomaly zones range from 0.3 to 100 m in width and 3 to 200 m in length (Fig. 8a). Beds in salt horses are thinner than the equivalent beds in ore. Contacts between salt horses and ore are sharp, and colour of the defining clay layers in salt horses change from grey in ore to brown, perhaps indicating more oxygenated crossflushing waters. Pods and lenses of near-pure langbeinite, leonite, kainite, recrystallized halite, and recrystallized sylvite occur in McNutt ore near the salt horses, while disseminated polyhalite of the typical marker bed is locally concentrated into intergranular seams and pods in or near horses. Based on three decades of detailed geological study in the same area, both at the WIPP site and the surrounding potash mines, Hovorka et al. (2007; p. 351) note that most of the large salt horses in Salado potash ore zones contain relatively pure halite and form relatively early in burial as halite-filled synsedimentary dissolution pits (Fig. 8a). Holt and Powers (2011) go on to document numerous occurrences of preserved salt karst (salt horse) features in the WIPP that record an early burial mode of formation. These pre-mesogenetic features, although highly porous zones when they formed, are no longer associated with any relict permeability. Based on the three-dimensional exposures at the WIPP site, Hovorka et al. (2007) argue that a least a proportion of geometrically similar large early pits, as mapped in various potash mines in the Devonian Prairie Evaporite, are also synsedimentary. Nonetheless, a distinction must be drawn between salt anomalies formed in early diagenesis in the Saskatchewan mines, and other salt anomalies in the same mines that are diagenetically-later collapse zones, tied to crossflows of telogenetic waters (Figs. 9 and 12 and later discussion).

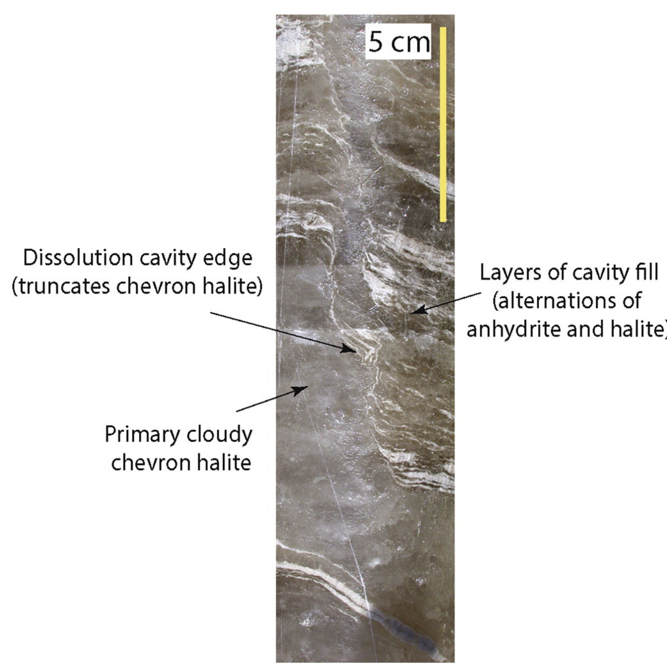

Fig. 7. Typical multistage dissolution collapse and fill, in Maha Sarakham Fm. (Cretaceous, NE Thailand). Infill shows base of cavity anhydrite geopetals that outline successive stages of cavity fill. Cavities are sometimes filled by clear sylvite, not halite.

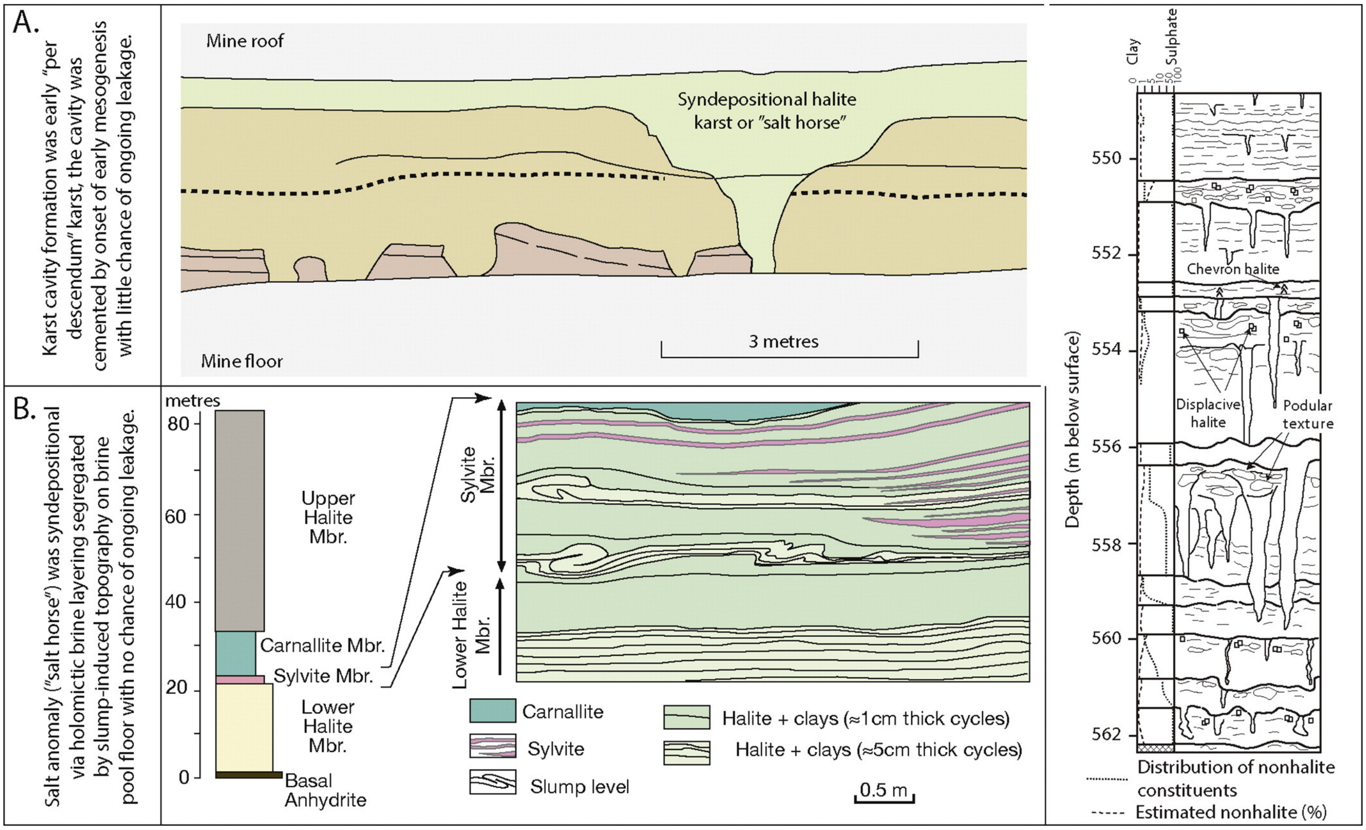

Fig. 8. Early salt anomalies. A) Sedimentary structures in mine wall show an abundance of vadose textures including a downcutting "salt horse" with a halite cavern infill in the Salado Formation of the Delaware Basin, as exposed in the WIPP shaft, west Texas, USA (after Hovorka et al., 2007) with details of syndepositional karst textures after Holt and Powers, 2011. B) Stratigraphy of Upper Eocene potash section based on sequence cored in Biurrun borehole and tied to a mine wall sketch from Subiza Mine, showing barren body made up of two superimposed slump structures with corresponding upper sections, where the overlapping sylvite beds evolve from absent to continuous (after Cendon et al., 1998).

In a study of "barren bodies" or salt anomalies in the Subiza Mine, Navarra, Spain, Cendon et al. (1998) recognize a syndepositional mechanism of "salt horse" formation. Salt anomalies in Spanish potash ore zone start diagenetically earlier than salt karst in West Texas and Boulby, and are depositional responses to topographic irregularities on the floor of the active brine pool (Fig. 8b). The hosting Subiza potash deposit is a 100 m-thick Upper Eocene succession of alternating claystone and evaporite (sulphate, halite, and sylvite). The evaporites accumulated in an elongated endorheic basin that is one of the depocentres within the 250 km-long South Pyrenean foreland basin. Slope instability along the margin of the basin, perhaps promoted by tectonism, created mass wasting of pre-ore evaporite beds. This formed subaqueous halite mounds 0.5–2 m high and tens of meters across. As evaporation progressed, a stratified brine system developed and encroached over the mounds. Halite precipitated at the air-brine interface and sank to the bottom of the basin, along with eolian terrigenous clays. Sylvite, however, precipitated via cooling of lower denser bottom-hugging brine. This brine was warm where it formed about the basin edge and cooled as it seeped and sank into the deeper parts of the density-stratified brine-covered basin floor. As many mound crests extended into the upper less saline brine layer, the sylvite could not precipitate over these subaqueous highs. With progressive accumulation, the lower brine ultimately covered the mounds as sylvite beds overlapped the mound tops.

The Subiza model, however, is in my opinion problematic in terms of its depositional and hydrological restraints: it requires a gently-sloping hydrological system that encapsulates sylvite saturation and precipitation in a cooling lower brine with simultaneous halite precipitation in the upper brine layer. Such a system is hard to maintain over time frames that allow meter-thick beds of subaqueous halite to accumulate in a perennial meters-deep brine body. The more likely modern analogy for this type of salt horse is evidenced in what were un-expectedly compartmentalised carnallitite brine ponds in saltworks across the southern Dead Sea, on both the Jordanian and Israeli sides of the border (Talbot et al., 1996; Warren, 2016). That is, for this type of syndepositional salt horse, the modern carnallite-precipitating ponds in the southern Dead Sea saltworks offer a more likely hydrology. The depositional system is made up a polygonal network of desiccating and concentrating holomictic potash-saturated brine bodies, separated by networks of earlier-deposited halite "reefs" or salt "mushrooms." As each halite-reef encased pool reaches holomictic saturation with potash, the adjacent "reef" halite is a few cm above the brine surface. Whichever model is accepted, what is most important in terms of potash geology is that breached syndepositional salt anomalies (horses), or barren zones of this type, are less likely to possess subsequent subsurface hydrologies that will flood mines, as compared with anomalies induced by later subsurface leaching, as defined by Boys (1993).

Hence, neither the "Navarra" nor the "WIPP" types of salt anomaly are likely to create potential undersaturated fluid inflow portals in an active salt mine. Salt anomalies formed either syndepositionally or as early burial karst features tend to be completely cemented and annealed by the time the unit resides in the mesogenetic realm and by the time it is mined. These early salt anomaly features are problems in terms of ore continuity in an active potash or salt mine but, unless reactivated by a later superimposed hydrology, do not create problems as possible fluid influx zones in an active salt mine. In contrast, most of the more problematic sites of salt leakage in an active mine are tied to the effects of later uplift (telogenesis) and ingress of pressurized undersaturated

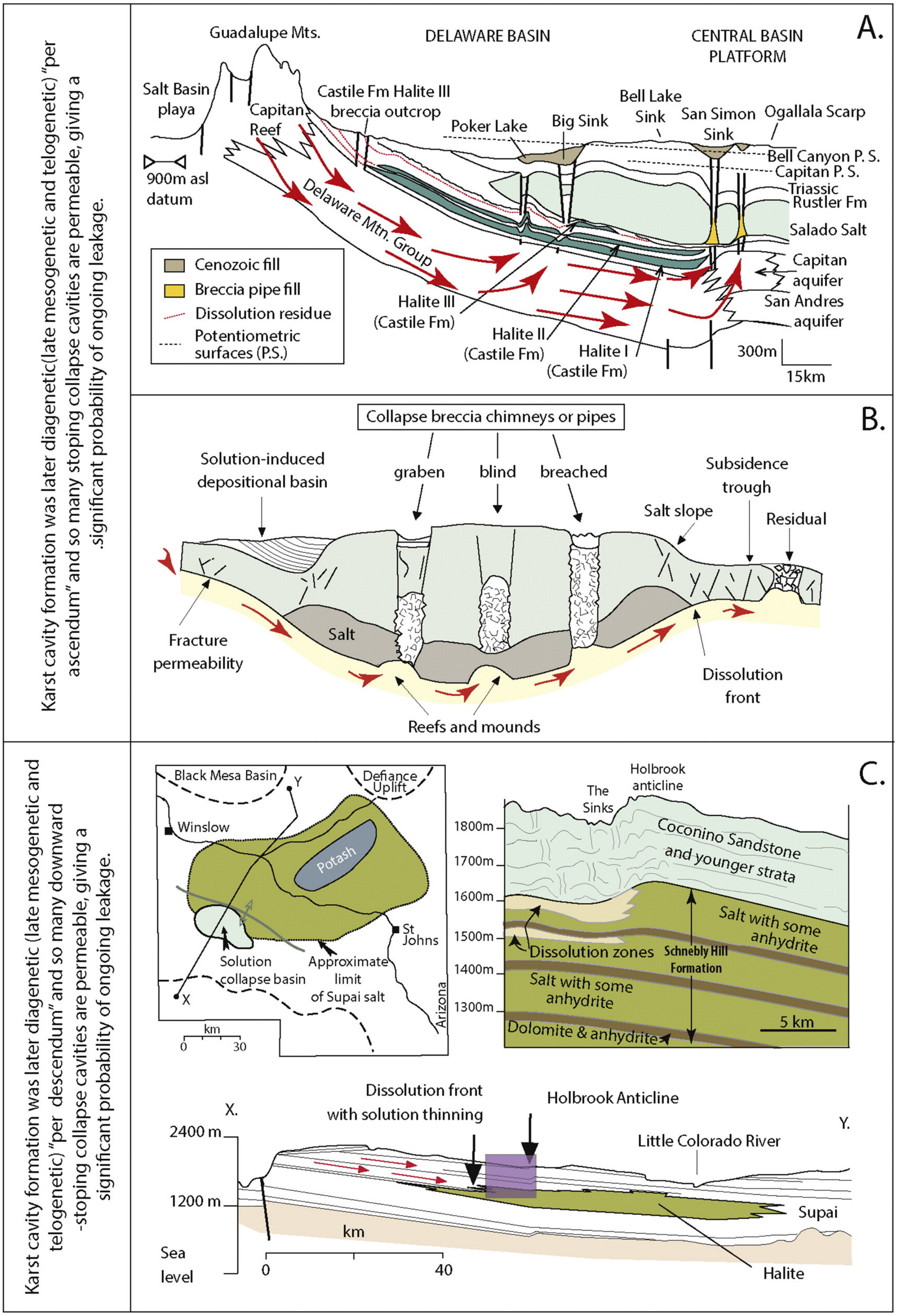

Fig. 9. Typical hydrologies that create salt anomalies during the uplift or telogenetic stage. A) Salt dissolution features, New Mexico, as illustrated in a cross section from Salt Flat playa to Ogallala Escarpment showing the extent of salt and focusing of dissolution pipes (salt anomalies) in the Castile and Salado halites and the expressions of that dissolution on the landscape. (after Anderson, 1981). B) Schematic showing interrelationships between larger scale dissolution features, artesian flow and various types of upward stoping breccia pipes. Based on relationships in the Western Canada Sedimentary Basin (not to scale; in part after Ford and Williams, 2007; Warren, 2016). C) Holbrook Anticline, Arizona shows salt collapse and dissolution driven by lateral and per descendum hydrologies and their relationship to the underlying Permian Schnebly Hill (Supai) salt. Cross sections show the Holbrook Anticline is a monocline flexure created by dissolution of the underlying Schnebly Hill Formation (in part after Neal, 1995; Johnson, 2008).

basinal and meteoric waters, fed either from above or below the salt level ("per ascendum" versus "per descendum" hydrologies).

4.3. Problems with leaky bedded salt anomalies

There are other intrasalt and landscape features in the same basins in addition to early relatively-benign diagenetically-early salt horses or salt anomalies in the Delaware Basin, the Western Canadian Basin and elsewhere. These later diagenetic features do leak, showing that significant portions of the same salt units that host early-diagenetic now-tight "salt horse" anomalies can also experience later, and in some cases still ongoing, crossflows of deeply-circulated meteoric-phreatic (telogenetic) or undersaturated basinal (mesogenetic) waters. Regions with active uplift-related telogenetic hydrologies are usually marked by significant subsidence troughs and collapse dolines where undersaturated trans-salt waters attain the modern land surface and often feed saline springs (Fig. 9; Warren, 2016; case histories in Chapter 7).

According to Linn and Adams (1966), the NaCl-saturated brines creating this type of telogenetic salt anomaly in the Delaware Basin of West Texas entered the salt unit from below ("per ascendum" hydrologies). Fluid entry from below is likely in the Delaware Basin, as the evaporites occur across the buried-deeper eastern part of the basin and sit atop a regional subsalt aquifer that entrains deeply circulating meteoric waters fed from the Guadalupe Mountains to the west (Fig. 9a). A similar artesian hydrology ("per ascendum'), in this case fed by inflows in the Rocky Mountains, explains a significant portion of the active and lately-active salt anomalies in the potash province of the Western Canada Sedimentary Basin (Fig. 10b; Ford and Williams, 2007). Active crossflowing hydrologies fed from above and laterally ("per descendum" hydrologies) define the style and subsurface expression of collapse features in the Permian salts of the Schnebly Hill Formation and its purity in the vicinity of the Holbrook Anticline in Arizona (Fig. 9c).

In both West Texas and Saskatchewan, upward-stoping artesian collapse chimneys (zones underlain by leaking salt) are often located atop the carbonate platform edge or local mud mound highs that were carbonate paleohighs, created via platform deposition in the open-marine stage preceding the main episode of evaporite drawdown and deposition. Given that a dense hypersaline brine mass or curtain encases all subsurface evaporite units worldwide, it is much more likely that the initial stages of collapse chimneys in any salt bed in an uplifted evaporite basin are driven by artesian processes. Artesian hydrologies driving the formation of telogenetic salt anomalies from below, are fed by the upward escape of less saline subsalt-focused waters. This sets up a buoyant hydrology with potential zones of stoping focused into elevated zones in the pre-salt basin architecture (Fig. 9a, b). It is much more difficult for a fresher less saline water body to penetrate the brine curtain from above and so transect an underlying saline and denser brine layer (as defined by a "per descendum" hydrology). Once an upward-stoping artesian-fed collapse cone has breached the salt unit and its brine curtain, the escaping artesian waters will mix with those less saline waters carried in aquifers located above the salt unit. Over time, as ongoing dissolution occurs along the upper edge of the salt mass in contact with the overlying aquifer and a body of dense brine forms along the upper side of the dissolving salt unit. This newly formed dense brine refluxes into the earlier-formed artesian breach in the salt, so the earlier "per ascendum" hydrology can reverse into a "per descendum" mode. See Chapters 2 and 8 in Warren (2016), for details

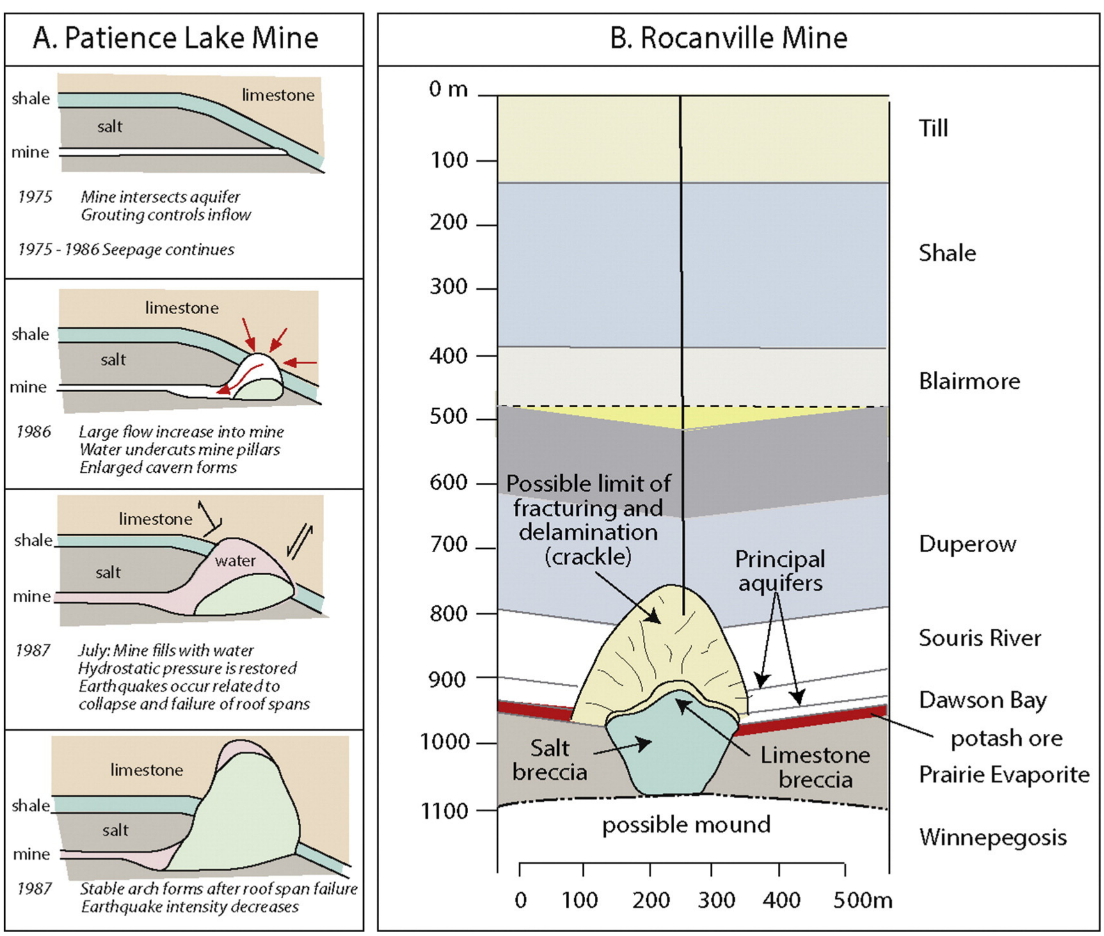

Fig. 10. Flooding related to intersection of salt anomalies and aquifer entry in Canadian Potash Mines. A) Sequence of events controlling the flooding of the Patience Lake Mine (after Gendzwill and Martin, 1996). B) Dimensions of the salt collapse chimney that was breached in the Rocanville Mine in 1984 (after Prugger and Prugger, 1991).

on this and other varieties of hydrological evolution in evaporite basins where salt units are dissolving.

Identifying proximity to a salt anomaly in a mine and whether the hydrology that created that anomaly is still active is of fundamental import in terms mine safety and ore quality (Boys, 1990). Geological indicators of proximity to a salt anomaly, and hence to a salt interval with the potential to leak, include: a change in insoluble seam colour from greenish-grey to mottled brown and greenish-grey (probably corresponds to increasingly oxidized fluids in the crossflow structure), unusual local increases in ore grade, large patches of sylvite-poor potash crosscutting units near the top of the ore zone, and drops in topography of up to 10 m in marker seams across an anomaly (Fig. 6). For example, within 5 m of a large salt anomaly, Boys (1990) found large blebs (>200 cm^2 on the mine wall) of sylvite-poor evaporite that crosscut the units of an incomplete potash cycle near the top of the main ore zone. Anhydrite, a less soluble salt, is also more common in a salt anomaly than in adjacent ore. Once into the salt anomaly facies, possible indicators of a nearby major collapse feature include: stretched clay seams; folded beds; small collapse features (1–20 m scale); and split clay seams with salt appearing to be injected into the seam.

Intersecting unexpected salt anomalies, especially those associated with active inflows of undersaturated brine should always be noted and dealt with as early as possible in a mine plan. Otherwise, these zones can impair and eventually destroy a mine as inflow volumes increase via ongoing salt dissolution in the vicinity of the fluid entry portal. In the 1970s, the Patience Lake potash mine operation, located on the eastern outskirts of Saskatoon, encountered a salt anomaly that was a natural collapse structure. Initial grouting managed to control the inflow and mining continued. Then, in January of 1986, the rate of water inflow began to increase dramatically from the same fractured interval (Fig. 10a; Gendzwill and Martin, 1996). At its worst, the fractures associated with the structure were leaking 75 m^3/min (680,000 bbl/day) of halite-undersaturated water into the mine. Inflow water chemistry equated with that in the overlying Cretaceous Mannville and possibly in the Duperow Formation aquifers. Finally, in January 1987, the mine was abandoned. It took another six months for the mine[3] to fill with water. Subsequent seismic shot over the offending structure suggests that main collapse wasn't even penetrated; the mine had merely intersected a fracture within a marginal zone of a partial collapse cone (Gendzwill and Martin, 1996). Part of the problem was that the inflow water was undersaturated and so quickly weakened pillars and supports, so compromising the structural integrity of the workings. The unexpected intersection of one simple fracture system resulted in the loss of a billion-dollar mine.

Prugger and Prugger (1991) documented the successful treatment of another underground inflow into the nearby Rocanville potash mine, Saskatchewan, that occurred in 1984 (Fig. 10b). In this case, the mine was saved. Inflow began when a mine entry accidentally penetrated a salt anomaly (collapse structure) that then began to leak brine into the mine at rates exceeding 10 m^3/min (90,576 bbl/day). Seismic showed that the offending structure was roughly circular, relatively small in size (300 m in diameter), and was isolated from other nearby collapse structures. A grout well was drilled from the surface and encountered the collapse zone upon penetrating carbonates of the overlying Duperow Formation, suggesting that fracturing associated with the collapse structure had extended as a blind chimney a considerable distance up from the Prairie level. Unlike the Patience Lake Mine flood, a combination of grouting and bulkhead emplacement in Rocanville succeeded in sealing off the inflow, thus saving the mine. Also unlike Patience Lake, the brine from the breached structure was halite-saturated so limiting the amount of dissolution damage to the mine workings. Different outcomes between the loss of the Patience Lake Mine and recovery from flooding in the Rocanville Mine may reflect the difference in leakage volumes between intersecting a collapse chimney that made its way to the Cretaceous land surface, and is now overlain by a wide-draining set of porous water-bearing sediments, versus crossing a blind chimney that never broke out at the landsurface (Fig. 9b). Blind (Rocanville) versus breached (Patience Lake) collapse zones (salt anomalies), assuming an artesian source for the undersaturated waters, are illustrated schematically in Fig. 9b.

4.4. Types of salt anomaly in bedded salt (some leak and some do not)

The notion of ore continuity in the sylvinite units of the Prairie Evaporite in the potash area of the Western Canada Sedimentary Basin is a commonly stated precept. But when the actual distribution and scale of salt horses are mapped as a mining operation proceeds it is evident that numerous small 10 m-scale discontinuities are present in any salt bed. Sometimes they thin and degrade potash ore quality (Section A-A1-A2), other times locally they enrich ore grade (B-B1 in Fig. 11). Anomalies are much more widespread than often traditionally considered present in what is the richest potash ore deposit in the world. The Prairie Evaporite is widely cited for the lateral continuity of its ore zones (Fig. 11; Baar, 1974). In geological models used to extrapolate ore trend in salt and potash mining a dictum of habitual continuity in salt bed geology should be replaced by a view that bedded salt has and can leak more than once in its history. The corollary is that unexpectedly intersecting a salt anomaly in an ore zone can have a range of outcomes ranging from the inconsequential to the catastrophic, in part because there is more than one type of salt anomaly or "salt horse." It is essential that a mine's geology team reliably interprets the type of anomaly present in front of the expanding mine.

Fig. 12 summarizes what are considered the three most common salt anomalies in bedded salt and their occurrence styles are in part time-related (Boys, 1990; Warren, 2016). Washouts are defined as "salt-filled V- or U-shaped structures, which transect the normal bedded sequence and obliterate the stratigraphy" (Fig. 12a; Mackintosh and McVittie, 1983, p. 60). They are typically enriched or filled by insoluble materials in their lower one-third and medium-coarse-grained halite in the upper two-thirds. Up to several meters across, when traced laterally they pass into halite-cemented paleo-sinks and cavern networks (e.g. Fig. 6b). Most washouts likely formed penecontemporaneous with the potash beds they transect, that is, they are preserved examples of synkarst with infilling of the karst void by a slightly later halite cement. They indicate watertable lowering or freshening in a potash-rich saline sump. This was followed soon after by a period of higher water-tables and brine saturations, when halite cements occluded the washouts and paleocaverns (Fig. 6b). Modern examples of this salt karst process typify the edges of subcropping and contemporary evaporite beds, as about the recently exposed edges of the shallow-buried halite beds beneath the modern Dead Sea depression (Closson et al., 2007; Nof et al., 2013). As such, "wash out" type salt anomalies in ancient salt beds tend to indicate relatively early salt leakage zones due to interactions of the potash or other salt intervals with undersaturated waters related to rising and falling water tables in the evaporite basin. They are likely to be an integral part of the syndepositional salt-remobilization hydrology that focused, and locally enriched, potash ore levels and although driving lowered ore grade are not usually sites of potential catastrophic fluid inflows.

In a leach zone, the stratabound sylvinite ore zone has been partially or wholly replaced by barren halite, without significantly disturbing the normal stratigraphic sequence (Fig. 12b). Some loss of volume or local thinning of the stratigraphy is typical in this type of salt horse in a

[3] Patience Lake Mine now operates as a solution mine by pumping KCl-rich brine from the flooded mine workings to the surface. The operation can produce more than a million tonnes of potash annually. It works by circulating heated brine through the flooded mineshaft into the former workings, which extend up to 18 km from the main shaft. Heated recovered potassium-rich brines are pumped into surface crystallization ponds where the liquor evaporates and cools. Sylvite, potash, and other salt crystals form and settle to the bottom of the pond. This potash sludge is pumped from a floating dredge to the processing plan, while the cooled NaCl-saturated pond brine is reheated and re-injected into the mine to repeat the process.

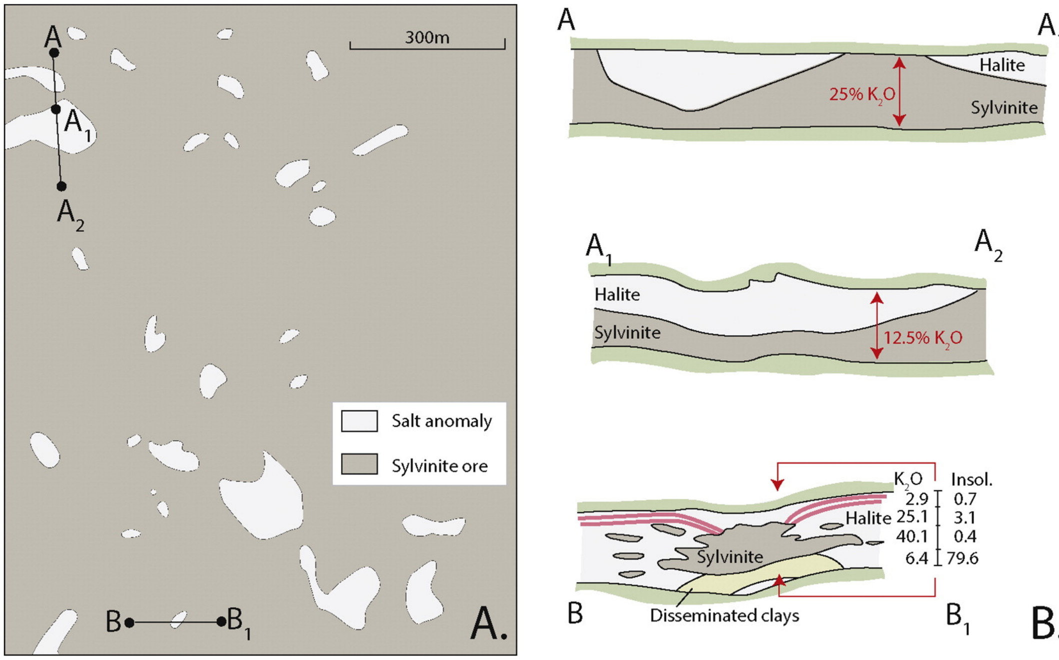

Fig. 11. Salt anomalies (salt horses) mapped in an ore level in a potash mine near Saskatoon, Canada (after Baar, 1974). A) Subsurface distribution of small scale salt anomalies mapped during mining. B) Scaled cross sections of salt anomalies and associated K_2O.

potash ore level. Typically, saucer-shaped, they have diameters ranging from a few meters up to 400 m. Less often, they can be linear features that are up to 20 m wide and 1600 m long. Leach zones can form contemporaneously in ore beds due to brine-filled sumps and back-reactions, or by later low-energy infiltration of Na-saturated, K-undersaturated brines. The latter process can drive local ore enrichment

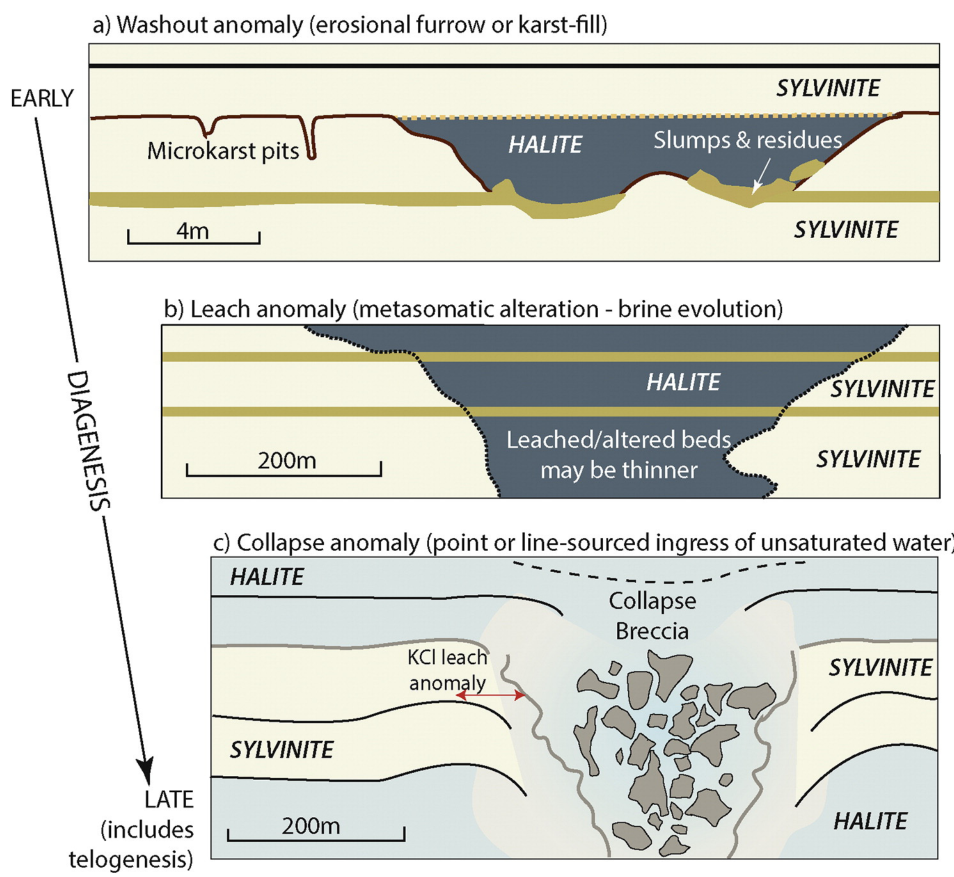

Fig. 12. Three main types of salt anomalies or salt horses likely formed are different stages in the burial history (based on Boys, 1990; Mackintosh and McVittie, 1983; Warren, 2016). A) Syndepositional salt furrows and cavities related to ingress of undersaturated waters and subsequent infill by salt. B) Leach anomaly, typically interpreted as a replacement ("metasomatic") facies formed in the mesogenetic realm. C) Collapse or dissolution anomalies related to cross flows of undersaturated waters. Driven by "per ascendum" or "per descendum" hydrologies and often forms in the early stages of uplift or telogenesis, as illustrated in Fig. 10.

as KCl is leached but then re-precipitates in nearby close proximity to the margins of the collapse zone, creating a situation typically classified as a leach-collapse potash anomaly (McIntosh and Wardlaw, 1968; Mackintosh and McVittie, 1983). Where ore enrichment levels have locally increased in such an anomaly it can constitute an attractive zone for a potash miner, but the enriched zone is located in proximity to a zone that, if breached, may potentially create a zone of uncontrollable water inflow.

Of the three types of salt anomaly illustrated, leach zone processes, where derivative mineral alteration rather than dissolution and collapse are the dominant overprints, are the least understood (Fig. 12b). Historically, when incongruent dissolution of carnallite was a widely accepted mechanism for loss of unit thickness, many leach anomalies were considered metasomatic. That is, a leach anomaly was created in the mesogenetic realm by chemical alteration and *"lit-par-lit"* replacement driven by diffuse crossflows of hydrothermal and other fluids. In fact, prior to the now widely accepted notion of varying seawater chemistry across the Phanerozoic, the abundance of sylvite in most evaporite basins (as opposed to K-Mg sulphates) were thought be the result of the in-congruent dissolution of kainite or carnallite, yielding sylvite and a Mg-rich solution (Dean, 1978).

Many of the notions of metasomatic interpretation were based on decades of detailed work in the various salt mines of the German Zechstein Basin. Intellectually, these halokinetic evaporites were considered by many German researchers to be more akin to metamorphic rocks (Borchert and Muir, 1964; Braitsch, 1971). In the past four decades, widespread observations of the preservation of primary chevron halite in most bedded evaporites, and the documentation of pervasive primary porosity loss in shallow burial, have led to a reduced use of notions of pervasive metamorphic-like metasomatic or solid-state alteration processes in bedded evaporites. There is just too much preserved primary texture in many deeply buried ancient bedded salt deposits to invoke omnipresent burial-metasomatic overprints. So how do leach anomalies, as illustrated in Fig. 12b, occur in nonhalokinetic settings? A possible explanation is given by the depositional salt horse textures documented in the Navarra Potash Province (Fig. 8b). There, the underlying and overlying salt stratigraphy is contiguous, while the intervening sylvite passed laterally into a syndepositional "salt horse."

On the other hand, in some bedded, but mostly in halokinetic situations (which characterize much Zechstein salt), solid-state mineralogical alteration via inclusion-related migration in flowing salt beds is a well-documented set of texture-altering processes (diffusion metasomatism). For example, thermally-driven incongruent alteration of carnallite to mesogenetic sylvite has occurred locally in Zechstein salts where layers of precursor carnallite have come into contact with igneous dykes and sills. The superimposed thermal regime causes carnallite and other hydrated salt layers to dewater and transform into recrystallised halite-dominant potash layers with peperite-like mesogenetic textures (Schofield et al., 2014). This process of incongruent potash alteration is an example of mesogenetic salt leakage and sometimes is used also to explain broader layers of sylvite, tied the production of $MgCl_2$ brines and mesogenetic precipitation of bischofite or langbeinite (Dean, 1978; Harville and Fritz, 1986). According to Braitsch (1971, p. 120), "…The incongruent alteration of carnallite is probably the most important process in the alteration of potash salts." Most workers in such incongruently-altered halokinetic systems would agree that there must have been an original stratiform potassium segregation present during or soon after deposition, and related to initial precipitation, fractional dissolution, and karst-cooling precipitation of primary and syndepositional carnallitite or sylvinite (Warren, 2016; Chapter 11).

Today, we still struggle to explain the mechanisms of alteration and replacement seen in mesogenetic leach anomalies in either bedded or halokinetic salt masses, unlike well documented hydrological analogues for leakage controls in early salt karst or late collapse leakage. The question remains, what documented processes control potassium distribution in what is now in a totally recrystallized and remobilized set of flow textures preserving little or no crystal-scale evidence of primary conditions. The complex layering in such deposits can preserve a broad depositional stratigraphy, but decimeter- to meter-scale mineral distributions are indications of complex interactions of post-eogenetic metasomatic fluids, folds, overfolds, bed disaggregations and local flow thickenings, all tied to a mechanism that must have involved varying degrees of mesogenetic salt leakage.

Collapse zones, the third type of salt anomaly in bedded salt units related to salt leakage are characterized by a loss of recognizable ore strata, which is replaced by brecciated, recemented and recrystallized material, with the breccia blocks typically made of the intrasalt or roof lithologies (Figs. 6a, 12c). Hence, in the Western Canada Sedimentary Basin, angular fragments of the Second Redbeds and dolostones of the Dawson Bay Formation are the most conspicuous components of telogenetic collapse features. Where potash ore dissolution is well developed, all the encasing halite can dissolve, along with the potash salts, as overlying strata collapse into the cavity (these are classic solution-collapse features, as illustrated as chimney features in Fig. 9b). Transitional leached zones typically separate the collapsed core from normally bedded potash (Fig. 6a). Such collapse structures indicate a breach of the ore layers by unsaturated telogenetic waters, fed either from below or above. In the Western Canada Sedimentary Basin, well-developed collapse structures tend to occur over the edges and tops of Devonian mud mounds, while in the Delaware Basin the collapse zones are related to highs in the underlying Capitan reef trend (Fig. 9a,b). Leaching fluids that create this type of salt anomaly may have come from below or above to craft collapse structures. When connected to an active water source, these are the salt anomalies that when intersected by expanding mine workings can quickly move the excavated cavity out of the salt into an adjacent aquifer system, a transition that led to flooding in most of the mine-lost operations listed earlier.

In summary, syndepositional karst fills and early mesogenetic leach anomalies are least likely to be problematic when later penetrated in a mine, as the aquifer system that formed them is likely no longer active. In contrast, penetration or removal of the region around a telogenetic and active salt-depleted collapse breccia may lead to uncontrollable water inflows and ultimately to loss of the mine. Unfortunately, in terms of production planning, the mineralogical features of the periphery of a syndepositional leach anomaly can be comparable with those in the telogenetic halo that typically forms the leached edge of a hydrologically-active collapse zone. Processes of carnallite/sylvite recrystallization that can define the edges of both active and inactive collapse anomalies can lead to local enrichment in sylvite levels, making areas surrounding the collapse core attractive extraction targets (Fig. 6a; Boys, 1990, 1993). Boundaries of any alteration halo about a collapsed centre are not concentric but irregular, making prediction of a feature's geometry difficult, if not impossible. The safest course of action when extracting salt in a conventional mine is to avoid mining salt anomalies. Longwall techniques make this difficult, so anomalies in front of the active extraction zone must be identified and dealt with, making utmost the reliable geological interpretation of conditions in front of the mine face.

5. Leakage across and into halokinetic salt: "black" or "dark" salt and salt anomalies

Within and near the edge of a halokinetic salt mass, impending fluid leakage is regularly indicated by "black" or "dark" salt in anomalous salt zones. Contrasts in style of salt anomalies in assumed sealing boundaries along sub-vertical halokinetic salt stems versus the salt contact transitions along the basal sub-horizontal surfaces of salt allochthons are of particular interest, especially any contrasts or similarities in formative mechanisms that drive texture and permeability in the two settings. So in this section, we focus initially on mine-scale situations where sub-vertical settings and boundary contrasts tend to dominate. Edges of such intersections with anomalous salt zones are traversed by workings in a number of modern salt mines. In contrast to this mine-scale detail, in most oil exploration situations involving halokinetic seals versus leaks, we only have wireline and seismic-scale signatures to interpret in what are deeper and frequently offshore salt locations.

The terms "black" or "dark" salt cover a variety of halokinetic textures and associated mechanisms of formation. Occurrences of "dark" salt are widely used in the US salt mining industry as pointers to problematic zones of current or past natural fluid entry into a halokinetic salt mass. Colouring fluids can be brine, oil or gas, often with solid impurities dominated by shale, anhydrite, organic matter, pyrite or calcite-dolomite. Intrasalt "black" or "dark" salt zones in a mine were formerly referred to as "shear" zones and, like salt anomalies, considered pointers to what are often unstable regions in the mine, liable to fluid entry, gassy outbursts, and roof or wall collapse. Most intradiapir shear zones separate salt spine sectors that have[4]risen at different rates (Kupfer, 1976). However, the likelihood that different subsurface mechanisms can form zones of "black" salt in a diapir means "shear," "black," and "dark," salt zones are better described under the broader term "anomalous salt" zones, many of which were, or are still, in fluid contact with adjacent non-salt sediments and hence capable of acting as possible intervals of salt leakage (Kupfer, 1990).

By comparison, the term "black" salt is used by the oil industry in Oman 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, the dark colour. Fluid entry in this type of "black" salt is ascribed to organic maturation occurring in salt-sealed source rocks at the same time as temperature, and consequently lithostatic fluid pressure, changes alter the dihedral angle of the encasing or adjacent halite making it permeable (Schoenherr et al., 2007a, 2007b).

Unfortunately, the term "black" or "dark" is used by many earth scientists without reference what are two distinct types of salt leakage and fluid entry. One style of fluid entry occurs in the telogenetic realm when the salt is relatively shallow, flowing as tongues and allochthons moving across and at times engulfing a set of adjacent sediments containing undersaturated pore waters that subject parts of the streaming salt mass to dissolution. This type of black salt is created by the entry of extrasalt meteoric, marine and other near-surface undersaturated phreatic waters and sediments, into folded and refolded sheared (anomalous) salt zones in and about salt stems and décollements. These fluid entry zones normally develop in the periphery to the flowing salt mass, typically in a dissolutional hydrology that concurrently makes caprock. A caprock is an accumulation of insoluble residues (clays, anhydrite, gypsum, calcite, etc.). The term "cap" is somewhat of a misnomer as "caprock" units form not just on the top (as a "cap"), but also along the sides and the underbelly of a salt mass, wherever the salt unit is in contact with undersaturated cross-flowing formation waters.

The other type of fluid entry and the other type of "black" or "dark" salt, exemplified by the Ara Salt in Oman, is related to the deeper burial (mesogenetic realm) of flowing salt, tied to highly pressurized intrasalt fluids (Schoenherr et al., 2007a, 2007b). This "black" salt indicates overpressure that requires a preliminary lack of cross-salt leakage (relevant intrasalt and subsalt overpressure settings are discussed later). Accordingly, if we are not to confuse timing and styles of salt leakage tied to occurrences of "black" salt (meteoric or undersaturated extrasalt fluid entry versus intrasalt (overpressured), then a nongenetic term should be used to describe zones of "black" or "dark" salt. Although less euphonious, the better term is "anomalous" salt. Anomalous salt describes all regions within halite-dominant intervals with features that are not typical of the bulk of the main diapiric or bedded salt mass (Kupfer, 1990).

[4] The use of the term "rise" when discussing diapiric salt movement is relative term comparing differential movement of the crest to an adjacent area of salt withdrawal and subsidence (rim syncline). Most salt structures grow via a process of down-building, whereby salt is withdrawn from areas adjacent to the rising diapir as the buoyant crest of the structure maintains its position in earth-space, at or just below the land surface.

5.1. Anomalous salt (dark salt) zones and shallow undersaturated fluid entry (mostly extrasalt fluid)

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 mostly based on their work and a site visit during the 1980s (Fig. 13a). Anomalous salt zones, formerly called "shear" zones in the US Gulf Coast diapirs, are intimately tied to "black" or "dark" salt occurrences. These anomalous zones separate more homogenous and more widespread intervals of consistently mineable salt ore (Kupfer, 1976). Shear zones between adjacent salt spines separate adjacent volumes of salt, each typified by different rates of flow. The association of homogenous mineable spines separated by narrower shear or anomalous zones was first mapped across mine walls in the Jefferson Island salt dome by Balk (1953). His published work was one of a series of classic papers outlining the internal structural complexities and shears in various mined salt diapirs in the US Gulf Coast and the Zechstein of Germany. Walden and Jacoby (1963) were the first to call attention to a Gulf Coast anomalous salt zone (then called a faulted shear). They documented a fault zone in the Avery Island salt mine that separated regions of salt being mined in the domal core, across an anomalous zone to a substantial area of as yet unmined salt.

A shear zone in a diapiric structure forms wherever adjacent parts of a salt structure are moving (rising or falling) at different rates. Shear zones also 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" (Fig. 13b, c). Older shear zones, with higher levels of impurities and relicts of shale sheaths can occur in re-folded intervals within a salt stem (Fig. 13c and later discussion of auto- and allo-sutures). Mapping of salt "shear" zones across many salt mines in the US Gulf Coast by Balk (1953), Muehlberger and Clabaugh (1968) and Kupfer (1976) showed that salt in 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. Subsequent work by Kupfer (1976) on the same US Gulf Coast Five-Island salt mines (Fig. 13a[5];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. To call attention to the zonal-ductile, not brittle-faulted, 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 (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).

Figs. 14 and 15 illustrate some internal complexities typifying various diapiric salt structures across the world. Fig. 14 shows dominantly vertical flow fabrics occur in the salt stem and subhorizontal flow textures in overhangs, tongues and allochthons. These differing orientation are seen in classic mapped cross sections documented in Zechstein Riedel and Ronnendorf salt mines in Germany (Fig. 14a). Fig. 14b is based on the detailed microstructural studies of Urai et al. (2008). Fig. 15 maps the typical meter-scale vertical to sub-vertical banding and fold style that typifies diapir stems.

Fig. 14b summarizes the positions of the various meso- and microstructures and illustrates how the varying stress field controls the salt textures at different levels in the rising salt. There are predictable

[5] Today, only the Cote Blanche and Avery Island salt mines are still in operation along the Five Island Salt Dome Trend.

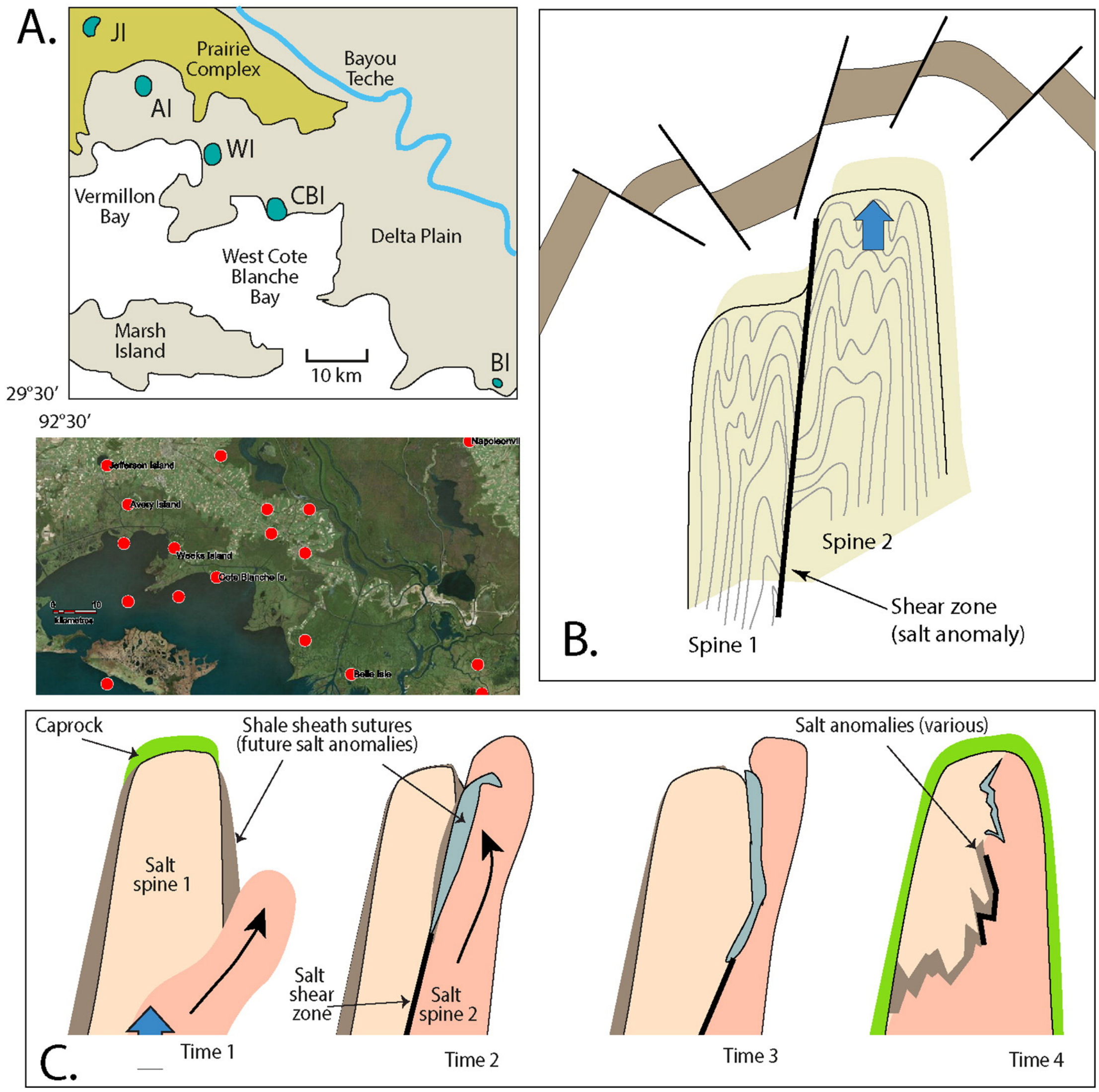

Fig. 13. A) Five Island Salt Dome Trend, Louisiana (red circles are regions underlain by salt diapirs - extracted and plotted from SaltWork database Version 1.6). This is the region where the concepts of salt shear zone and salt anomaly were developed in the 1970s. B) Schematic defining a salt shear zone as being created by differential rise of two adjacent salt spines, C) sequential development of salt anomalies now within the salt from earlier diapir-bounding shale sheaths Shows positions of edge shear zones and boundary shear zones, see also suture development model illustrated in Fig. 37 (in part after Kupfer, 1974, 1976). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

microstructural domains (and greater potential for leakage) within a framework of flowing salt, as it migrates from the mother salt bed, through a diapir stem and into an extrusive structure (based on Urai et al., 2008). In undisturbed rock salt (position 1 in Fig. 14b) the primary microstructures can reflect the depositional conditions, with remnant fluid-inclusion-outlined chevron grains and microkarst textures. In regions of slightly deformed rock salt such as where the salt moves toward and first into the diapir stem (position 2, subgrains develop, together with incipient grain boundary migration zones. As migrating grain boundaries sweep through fluid-inclusion-rich primary crystals, the inclusion fluids collected at the grain boundary. Alternatively, salt solution-precipitation creep (pressure solution creep) is dominant in regions of finer grained flowing salt. Large contrasts in rheology are common in layered salt, even from the onset of tectonic deformation. As the salt rises into the stem and deforms further (position 3), steady-state microstructures are produced after complete recrystallization of the halite, although primary fluid-inclusions fluids are still preserved via migration into intergranular positions. In the cooler portions of the diapir stem, high stress and small subgrains develop (position 4). On attaining the surface, weak mylonitic shear zones form and pressure solution mechanisms dominate (position 5), so allowing a namakier[6] to flow downhill via gravity spreading, at unusually high strain rates compared to the stem and source levels (position 5). In the namakier, mesotextural indicators of Couette flow are more common. Finally, at- and near-surface dissolution and ablation of the salt glacier edges, typically driven by infiltrating rainwater, facilitates halite recycling into ambient landscape sumps, which are often above salt-withdrawal rim synclines. In semi-arid to arid areas, this leads to the formation of saline playas and chotts, where new salt crusts accumulate. These landscape sags are depositional sumps where the recycled salt can accumulate with primary bed (aligned-chevron) textures once more (e.g., the Triassic salt landscape of Germany and the modern desert landscape of north-west Iran; Mohr et al., 2007; Warren, 2008, respectively.

The terms "anomalous salt" and "anomalous zones" as defined by Kupfer (1990), are based on observations across the various Five Island

[6] A namakier is an at-surface and flowing salt glacier or tongue. The word is derived from a combination of the Farsi (Persian) word for salt "namak" and the English term glacier.

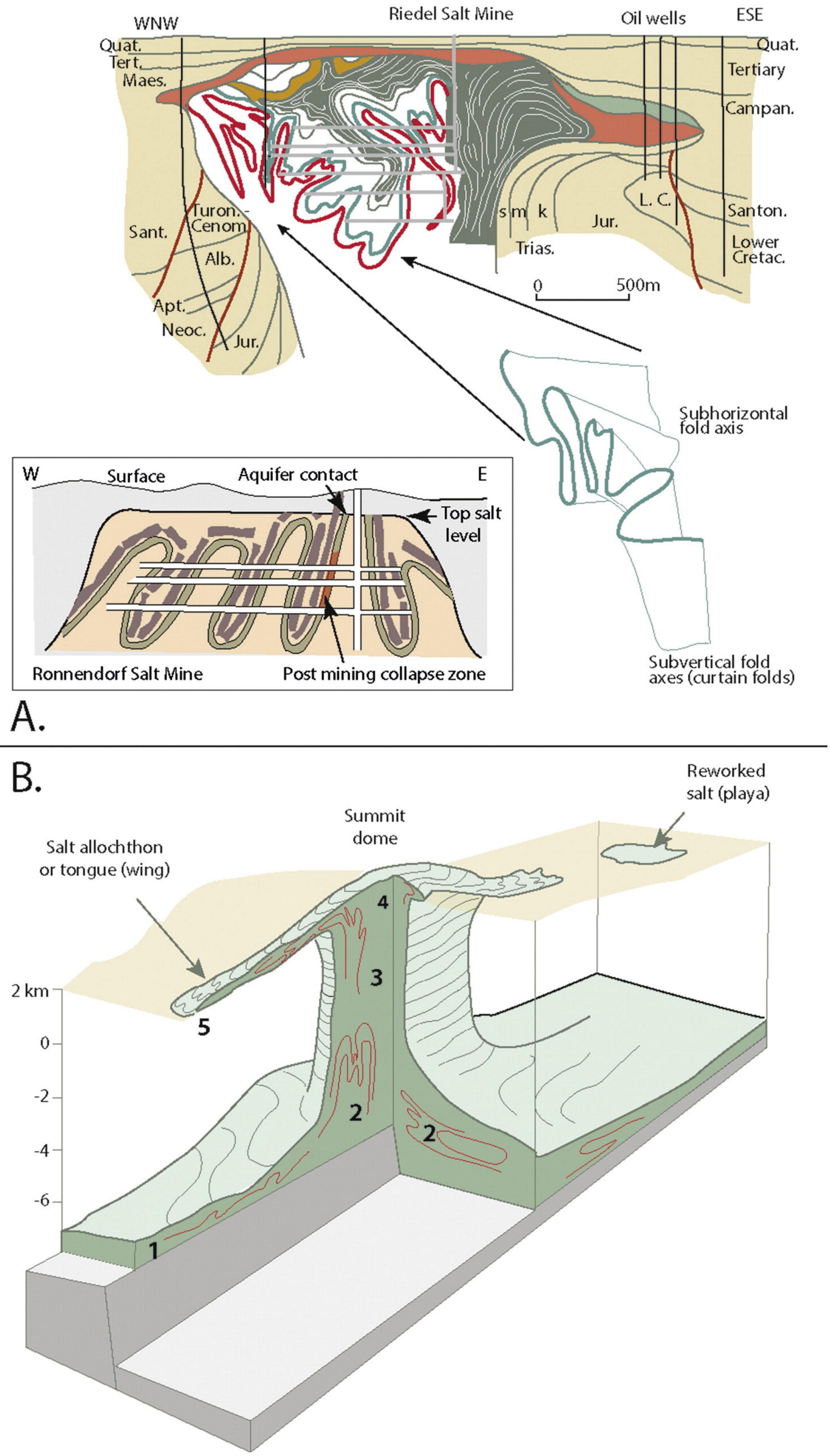

Fig. 14. Internal fold complexities. A) As documented in two mined Zechstein salt diapirs. B) Summary figure of the various micro-and meso-scale structures in a developing salt structure (after Urai et al., 2008). Note the tendency toward subvertical orientations in the salt stem and sub-horizontal orientations in the overhangs.

salt mines of South Louisiana (Fig. 13a). Typical mined Gulf Coast rock-salt, according to Kupfer, is reasonably pure halite (97% ± 2%) with minor amounts of disseminated anhydrite ($CaSO_4$) as the primary non-halite impurity. Crystal-size in zones between shear zones is mostly uniform, with diameters of 3–10 mm (0.12–0.39 in.). Through their ongoing mapping of Five Island mines, Kupfer et al. (1998) and Looff and Rautman (2010) documented a variety of anomalous salt zone characteristics broader than those first defined by Kupfer (1976,

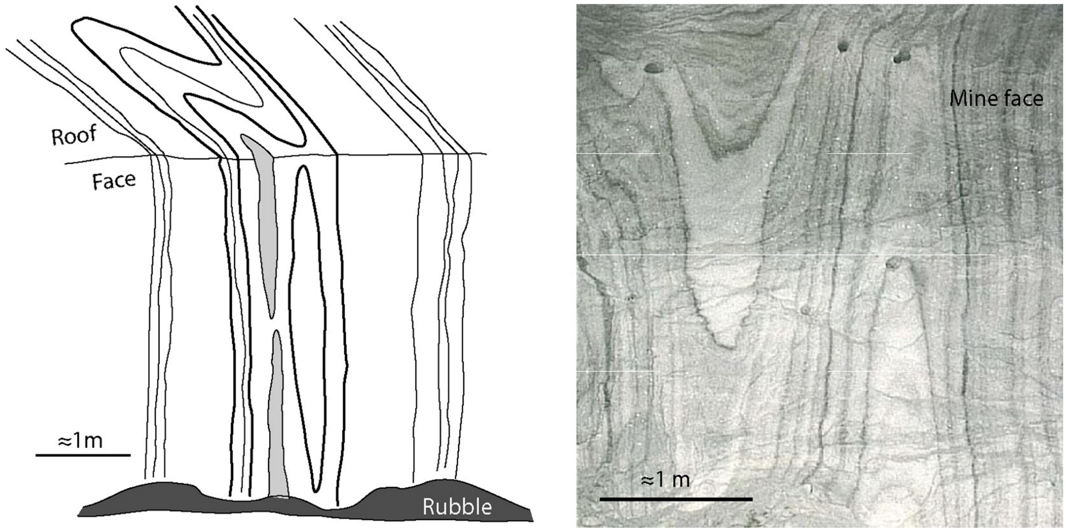

Fig. 15. The detail of dominantly vertically-plunging folds as seen in a room and face of a room in a salt stem in the Avery Island Salt Mine (after Lock, 2000).

1990) and concluded that anomalous salt zones need not be related to faulting or shearing, but also can be related to zones of fluid entry and dissolution within the diapir (Fig. 16). Today, anomalous salt zones in diapirs are defined by atypical impurity contents, structures, colours, or other nonconforming features (Looff and Rautman, 2010). Such features may not have sharp contacts or uniform thickness, and most are not continuous over long distances. Individual anomalous features tend to disappear for tens of meters (hundreds of feet) only to appear again over some horizontal distance. An anomalous zone is any zone in a Gulf Coast salt structure that contains 3 or more dissimilar or atypical features. The term "anomalous" implies nothing regarding the genesis of the zone. While many anomalous zones may extend laterally over hundreds of meters in length, they are variable in nature, typically near-vertical, and parallel to layering in adjacent salt (Fig. 18). Typical widths of anomalous zones are poorly known but are likely of the order of 30–50 m; however individual structures or anomalous features within the anomalous zone may be as thin as millimeters. The internal fabric of any salt structure (and bedded salt) is always composed of both typical (volumetrically dominant) and anomalous salt.

Ongoing work in both the salt mine and salt cavern storage industries has increasingly invoked a concept whereby occurrences of anomalous zones and boundary shear zones explains most problematic zones of fluid entry. But, there is still significant confusion over appropriate terminology for salt leakage and how various anomalous features are related (Looff and Rautman, 2010), As in bedded salt deposits, this compounded by the fact that some anomalous zones leak fluid, while others do not. Because salt must flow in the construction of a diapir, anomalous salt features in a salt stem usually parallel the near vertical internal banding of the salt, while those in a salt allochthon or tongue tend to trend at lower angles within the expanding salt mass (Fig. 14b). Anomalous salt features in halokinetic salt are parallel to, or entrain, zones of differing creep, strength, or local dissolution, all of which can impact the efficient operation of a salt mine or storage cavern. Worldwide, most short- and long-term stability problems in anthropogenic cavities in diapiric salt are tied to poorly-completed drill-holes or zones of problematic fluid entry located in or near a salt anomaly (Warren, 2016; Chapter 13).

For example, a significant portion of salt-encased fluid pockets in salt anomalies in US Gulf Coast diapirs are pressurized, leading Kupfer (1980) to describe such features as "pressure pockets." He lists these pockets as a subtype in what are three types of brine leaks found across the various Five Island salt mines, namely: 1) short-duration leaks that soon dry up, 2) catastrophic leaks, and 3) an intermediate long-duration leak. Leaks occur either within nonsalt anomalous sediment, or in fractures in anomalous zones located as much as 100 m out from intervals of non-salt sediment. Gas leaks, particularly in explosive

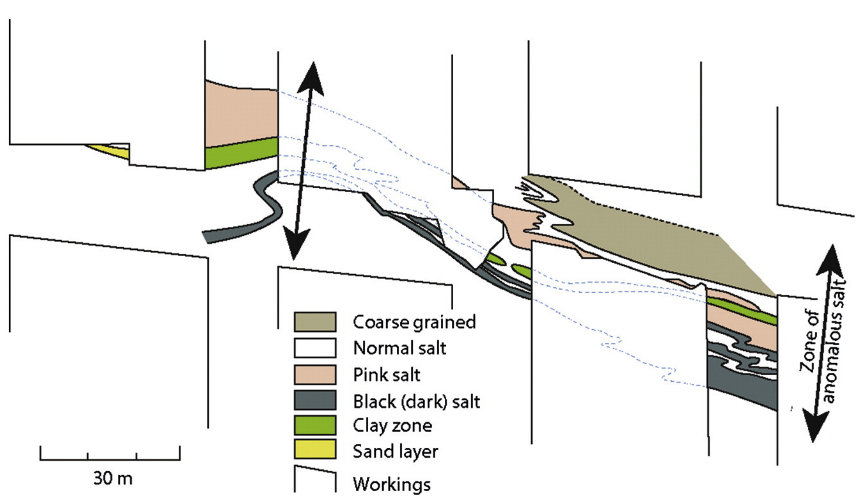

Fig. 16. Anomalous salt subzone, 160 m long and about 45 m wide; average width of sand is 10 cm but actual width is as much as 90 cm. Sand is observed along 40% of the length, and over 6.5% of the area (after Kupfer, 1990).

pressure pockets up to 100 m in height, may extend 200 m out; and these pressure pockets tend to align along a contiguous black-salt horizon in the diapir. Prior to explosion, the gas is in tiny intragranular bubbles in the salt or spread along intergranular fractures; release is caused by the intersection of a pressure pocket during mining.[7] Zones hosting pressurized gas pockets must be dominated by non-leaking salt; otherwise pressures would not be maintained, reinforcing the notion that a salt mass tends to maintain its seal integrity away from local zones of active undersaturated fluid crossflow.

5.2. Boundary and edge anomalies in halokinetic salt

Boundary Shear Zones (BSZ) and Edge Zones (EZ) are the two types of anomalous zones that can leak fluids in diapiric structures and have broadly accepted genetic interpretations (Looff and Rautman, 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 (Fig. 13c). An edge zone is similar to a boundary shear zone except that, 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 in diapirs, but within and about a diapir edge, most anomalous salt is within or proximal to a shear zone (Kupfer, 1990; Looff, 2000).

Anomalous zones between two salt spines that may no longer be moving are usually the remnant or relict of BSZ's from older spines incorporated into younger active salt spines. This especially apparent within those boundary zones associated with clastic impurities and tied to intrasalt sutures (Fig. 17). In terms of seal integrity, boundary shear zones and edge zones around a dome tend to be more problematic areas, especially if proximal to, or intersecting with, anthropogenic storage caverns. As a rule of thumb, BSZ's are likely to contain features that can degrade salt quality and so enable leakage. The origins of many edge and boundary shear zones are closely tied to the concept of sutures in salt allochthon provinces (see later discussion and Fig. 37). Drives and shafts in a salt mine can be excavated within salt anomalies tied to BSZ's, but if possible, a mine or storage cavity plan should avoid such intersections as they can result in non-optimal operating conditions, long-term operational difficulties, and in the most severe cases intersected BSZ's contribute to the loss of cavern integrity, flooding and ultimately loss of the salt mine or cavern (Looff and Rautman, 2010).

In the case of edge shear zones, additional distance to the edge of the anomalous salt mass needs to be maintained not only to cover any uncertainty regarding the placement of the edge of salt with respect of mine workings or cavity placement, but also to account for the potential for degraded salt quality and so leave 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 diapir spines in the Five Islands salt landscape typically coincides with underlying anomalous zones of differential shear within the underlying diapir, typically indicated by “black” or “dark” salt (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, gas outbursts and unstable roof zones[8] liable to slabbing and collapse (Fig. 17). Such anomalous zones can leak water into a mine, and over the longer term create roof and wall stability problems. This is demonstrated by problems in the now-abandoned Weeks Island oil storage facility, by leakage zones in the Avery Island Salt Mine, and by a likely association between a known subvertical zone of anomalous salt and catastrophic fluid entry driving 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 (Warren, 2016).

We shall now look at some of the documented factors contributing to catastrophic fluid entry tied to anomalous salt zones in halokinetic structures.

5.3. Ongoing leakage into the now-abandoned Weeks Island storage facility

The Weeks Island salt mine was converted to a storage facility (Strategic Petroleum Reserve, SPR) in the early 1980s as the former workings were filled with oil by the US Department of Energy (DOE). Following this fill in 1980–1982, the Weeks Island facility enclosed 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 (Molecke, 2000).

The cause of the drainage and abandonment of the Weeks Island oil storage facility was an active subsidence sinkhole some 10 m across and 10 m 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 and BSZ, which was evident in the top-of-salt contours based on former mine records before conversion to a hydrocarbon storage facility (Fig. 18; Neal and Myers, 1995). Earlier shallow exploratory drilling around the Department of Energy service and production shafts in 1986 had identified the presence of anomalies across this region, including brine-filled voids along the top of salt mass. 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.

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 in a shear zone (also shown in Fig. 18, which is based on the more recent Kupfer et al. (1998) map). Kupfer (1976) noted “black” salt intervals were tied to internal “shear” or anomalous zones (BSZ's) not found over most of the rest of the mine. In places, these anomalous zone beds contained black clay (e.g. Room J-21), orange sandstone (S-20), and other fragments of clastic material (Paine et al., 1965). The clastic remnants typically occurred as balls or roundish blebs in a black salt host, ranging in size up to tens of cm in diameter. During mining, petroleum had leaked out of seams in the black salt zone and also from seams cutting the surrounding salt.

[7] Shortly before 11:00 p.m. on June 8, 1979, a scheduled blast was initiated in the Belle Isle Mine, a salt mine. About 10 min later a gas explosion occurred, sending intensely hot hurricane-like winds throughout the mine. The explosion resulted in the death of five of the twenty-two miners underground at the time. The explosion 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 tonnes of broken salt and flammable gases in a salt anomaly. Included in these gases were methane and minute quantities of other hydrocarbons, which were ignited by electric arcs, sparks, or burning electric cable insulation (Plimpton et al., 1980)

[8] About 9:30 a.m., on Thursday, February 19, 1970, a roof fall occurred near the face of the North Main No. 1 entry, a development area on the 1300-foot level of the Jefferson Island Salt Mine. Preparations were being made to move a loading shovel to the face prior to the normal loading cycle. Five men were in the area at the time of the accident; four were killed, and one received minor injuries. Experience had shown that planes of separation above the exposed roof are associated with intrusions of oil and some hydrogen sulphide, which was detected while drilling the face or stains on the salt following blasting. When these conditions were found, the roof was bolted. These indications were not present in the development area where the accident occurred. Therefore, the area was considered self-supporting, and roof supports were not used, based on past experience (Kupfer, 1990).

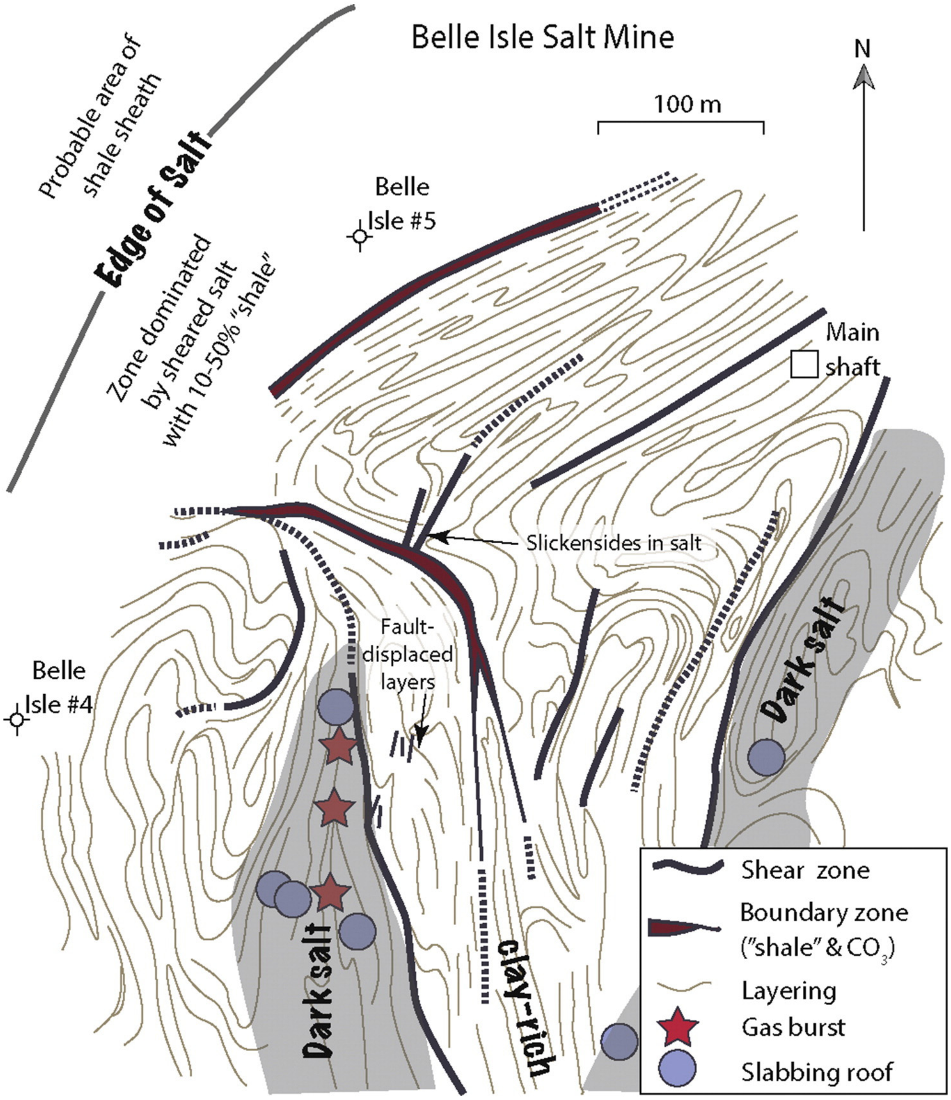

Fig. 17. Geological map of Belle Island Salt Mine showing two salt spines separated by boundary shear zones now located in the salt. Also shows show how anomalous regions of "dark" or "black" salt are zones of relative instability and leakage within the main diapir salt stem (in part after Kupfer, 1974).

The widths (surmised) and structural complexity of the anomalous zone in the Weeks Island salt mine suggested that internal salt movement continued after a clastic boundary sheath-zone was incorporated into the salt stock (Figs. 13c, 18). We would probably now assign some of these anomalous features (edge and boundary shears) to interdiapir suture zones (see Fig. 37). Miners had always avoided extracting salt in such "black" salt or "dark" salt zones across the various Five Island mines, so that active salt extraction zones usually extended only as far as intersections with significant "black" or "dark" salt regions (Figs. 17 & 18; Balk, 1953).

The main Weeks Island sinkhole lay atop a boundary shear zone ("dark" salt anomaly) that formed during the diapiric rise of two salt spines and is capped by a rockhead valley containing Pleistocene sediment fill. Salt extraction during mine operations probably created tension across the boundary shear zone, thereby favouring fracture enlargement in the anomalous salt zone, as early perhaps as 1970 (Fig. 18; Waltham et al., 2005). Eventually, an incursion of undersaturated groundwater (telogenetic water) traversed the fracture zone across some 107 m, from a level equivalent to the rockhead down to where it emerged in the oil-filled mine. Over time, ongoing dissolution enlarged a void at the top of the anomalous salt zone, so creating the collapse environment that underlay 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 at Weeks Island and verified that water from the aquifer above the salt dome was seeping into the underground oil storage chamber at the first sinkhole site (Figs. 18 & 19; Neal and Myers, 1995; Neal et al., 1995, 1997). This set up a likely condition of aquifer connection between a buoyant (less dense) oil mass in the storage cavern and a denser water-filled porosity network in sediments above with little or no intervening salt seal.

To prevent a potential environmental calamity, controlled drainage and decommissioning of the Weeks Island Strategic Storage facility quickly 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 m beneath the surface. This slowed further dissolution and bought time for DOE 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 (Fig. 19; Martinez et al., 1998). Until the mine workings were 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. 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.

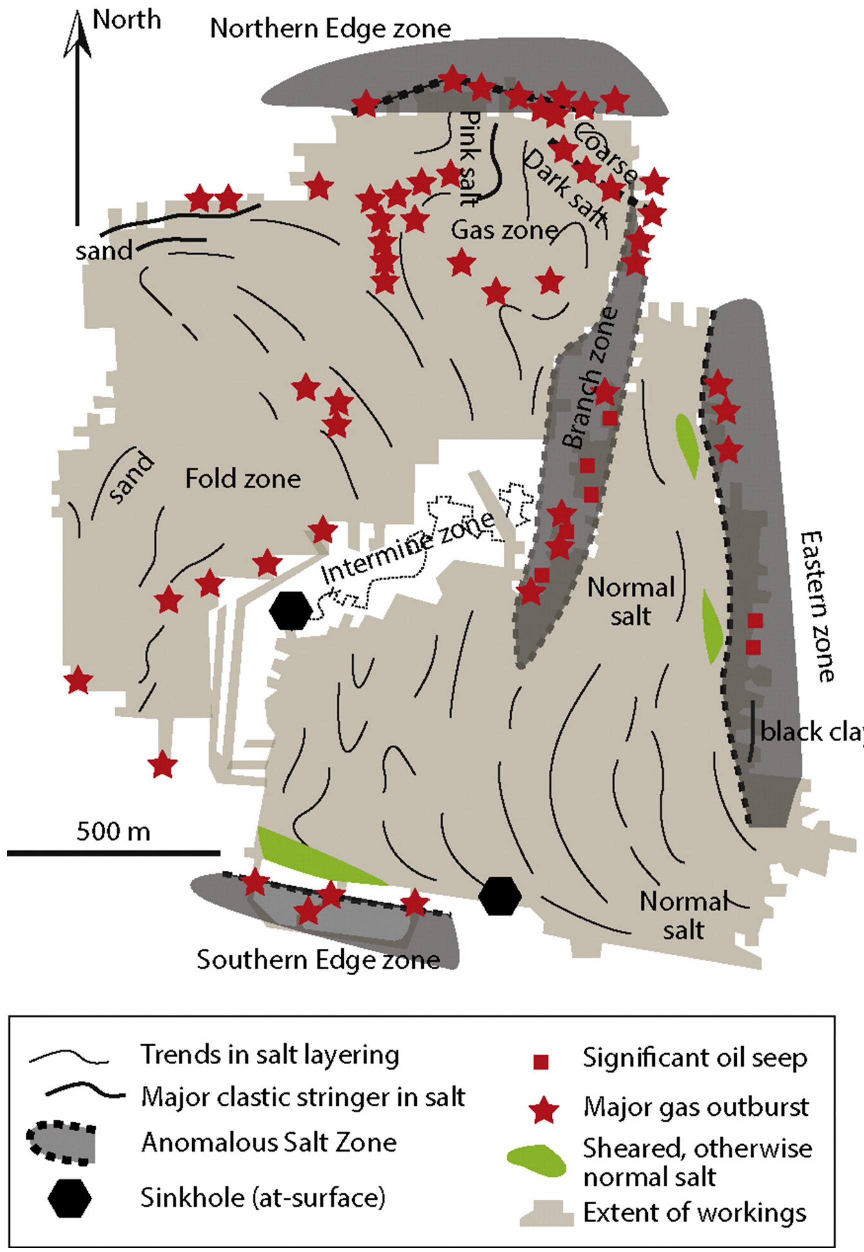

Fig. 18. Map of selected anomalous features exposed in the various mine workings at Weeks Island. The heavy dashed lines indicate the known limits of the Main Zone, which is a composite of the East and Branch Zones, and which may be a true spine boundary zone. With the Pink salt zone, these features 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-anomalous) salt also occurs within the gassy area. The intermine zone is mainly in normal salt and is not considered anomalous (after Kupfer et al. (1998)). At-surface positions are shown of the two sinkholes that ultimately caused extraction of the stored hydrocarbons. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In hindsight, based on an earlier trans-salt leak into the mine, while it was an operational mine, and the noted presence of anomalous ("black") salt in a boundary shear zone intersected by the mine wall, 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). In 1978 an injection of cement grout into the flow path controlled the leak of undersaturated water into a known anomalous salt zone in the mine. If left untreated it could just as easily become uncontrollable and formed a sinkhole a few years later. The grout job delayed, but did not prevent, the ultimate expansion of the leak and today it is likely the offending sinkhole continues to evolve.

5.4. Anomalous salt zones in the now-flooded Jefferson Island salt mine and the 1980 Lake Peigneur collapse, Gulf of Mexico

The most recently risen part (salt spine) of the Jefferson Island stock crest, just west of the town of New Iberia, Louisiana, is now 250 m (800 ft) higher than the adjacent flat-topped salt mass, which is also overlain by a cap rock (Fig. 20). The boundary shear zone separating the spine from the less active portion of the crest contains a finer-grained "shale-rich" anomalous salt zone that had been penetrated in places by the former Jefferson Island mine workings. The known salt anomaly (BSZ) 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, in a mining scenario much like the fault shear anomaly,

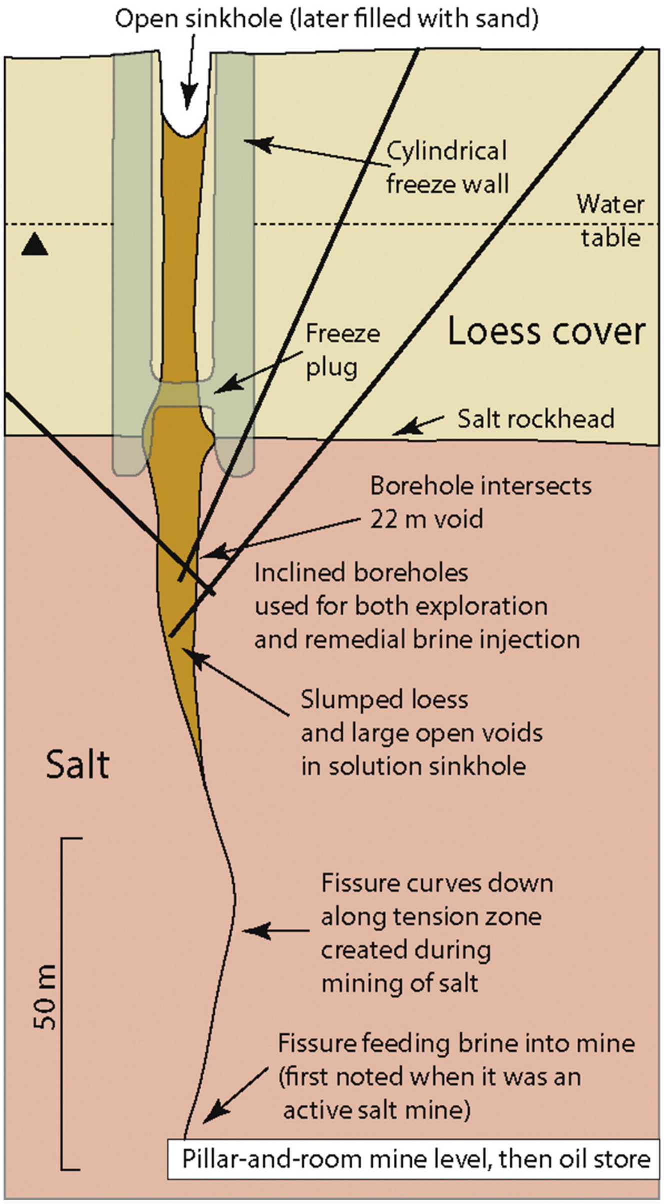

Fig. 19. Schematic section through the main Weeks Island sinkhole and its remedial freeze curtain (after Waltham et al., 2005).

as mapped by Balk (1953), defined the extent of the workings at nearby Avery Island (Fig. 13a). The spine and its boundary "shear" zone are reflected in the topography of the Jefferson Island landscape, with a natural sub-circular solution lake, Lake Peigneur, created by the dissolving shallow crest of the most recently-active salt spine (Fig. 20).

On November 20, 1980, one of the most spectacular sinkhole events associated with oilwell drilling occurred atop the Jefferson Island dome. On that day Lake Peigneur disappeared as it drained into the workings of the underlying Jefferson Island salt mine. In a few hours a collapse sinkhole, some 0.91 km^2 in area, had daylighted in the SE portion of the lake (Fig. 21; Autin, 1984, 2002; Warren, 2016). In the 12 h following the first intersection of the drill hole with the mine workings, the underlying mine was completely flooded and Lake Peigneur was completely drained.

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 ft (350 m) below the lake floor (Fig. 21). 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 ft deep. This old sump was in contact with a zone of anomalous "black" salt (a boundary shear zone). The volume of telogenetic floodwater engulfing the mine corridors couldn't be drained by the available pumps. Some 23–28 million m^3 of salt were extracted during the preceding 58 years of mine life. The rapid flush of lake water into the mine, probably augmented by the drainage of other natural solution cavities in adjacent anomalous salt zones and associated collapse grabens beneath the lake floor, meant landslides and mudflows developed along the perimeter of the overlying Peigneur sinkhole, so that post flooding the lake was enlarged by 28 ha.

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[9] 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. 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) forming what was a short-term waterfall with the highest drop in the State of Louisiana. Associated ground movement and subsidence left one former lake-front house aslant under 12 ft of water (Autin, 1984).

5.5. Implications for other salt mines with anomalous salt zone (BSZ) intersections

The Peigneur disaster had wider resource implications as it detrimentally affected the profitability of other salt mines in the Five Islands region (Fig. 13a; 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 and salt leakage. Broad ground subsidence over the mine area was well documented and monitored, as was near continuous groundwater 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 related to salt anomaly intersections was considered a distinct possibility. In 1985, a controlled flooding of the Belle Isle Salt 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, likely underlain by BSZ's (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. After the Lake Peigneur disaster, the mine underwent a major reconstruction and an improved safety workover. Subsidence is still occurring today along the active mine edge, which coincides with a topographic saddle above an anomalous salt zone (BSZ), 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 above the mine. 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 artefacts around salt-solution induced, water-filled depressions atop the dome, shows dissolution-induced

[9] 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! (<https://en.wikipedia.org/wiki/Lake_Peigneur>)

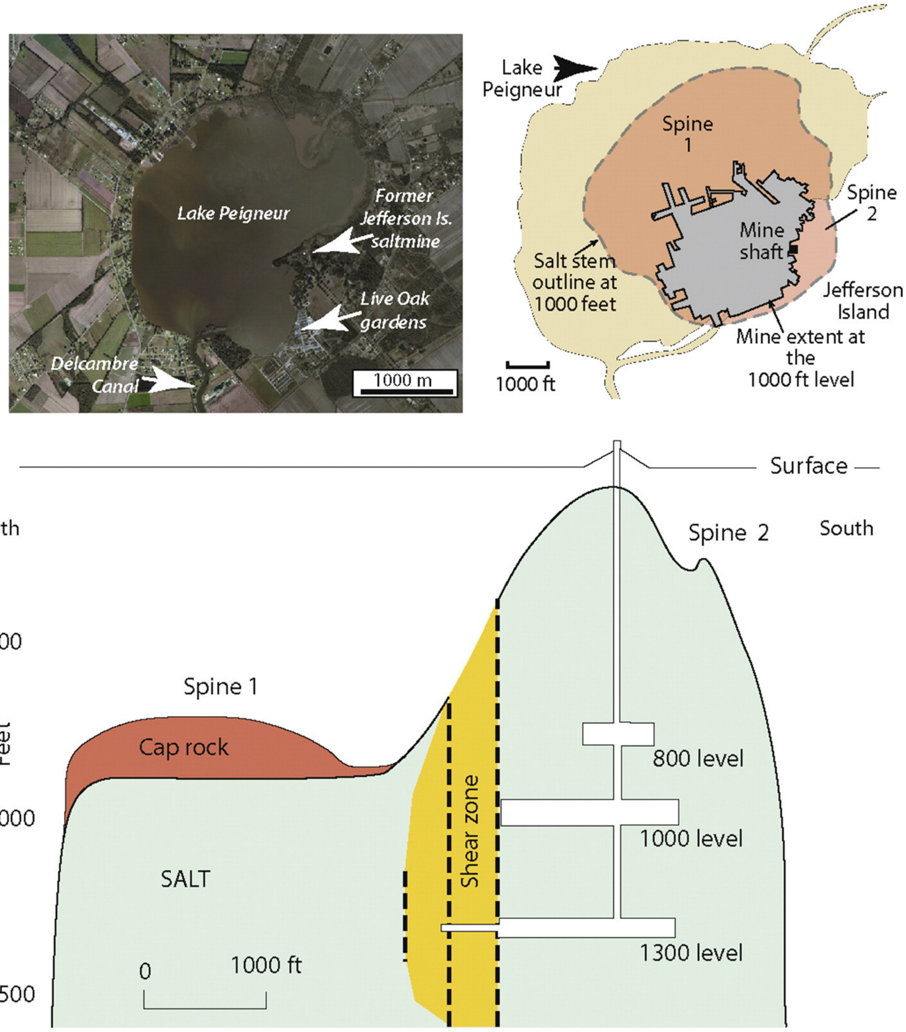

Fig. 20. Lake Peigneur, located above the former Jefferson Island Salt mine, which was flooded in 1980 by an influx of lake waters. Note the anomalous salt (shear) zone that separates the elevated caprock-free active spine from the capped less active salt spine (after Warren, 2016 and sources therein).

subsidence is a natural process, as are short episodes of catastrophic 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 3000 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 of the Five Island region, (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, BSZ's 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.

6. Salt leakage tied to overpressure (intrasalt fluids)

The previous section focused on leakage and black and dark salt zones created by ingress or interaction of undersaturated phreatic-meteoric waters with relatively shallow halokinetic salt masses, with entry zones usually tied to intervals of differential shear (BSZ's and edge zones) in the rising salt. The resulting black or dark salt textures are a style of "anomalous" salt related to relatively low-pressure fluid ingress. Now we shall look at another type of "black' salt where fluid entry or leakage is into a salt mass sited in deeper warmer subsurface (mesogenetic) intervals and typified by high pore fluid pressures. This category of leaking salt is exemplified by "black salt" occurrences in the Ara salt of Oman and intrinsic burial-pressure and temperature-related (generally tied to organic maturation), changes in the dihedral angle of halite (Schoenherr et al., 2007a, 2007b).

6.1. Dihedral angle changes and the permeability of salt

Permeability in intercrystalline pore networks in re-equilibrating and crystallizing subsurface halite is tied to the changes in dihedral angle at solid-solid-liquid triple junctions. Under static laboratory conditions, polyhedral grain boundaries remain sealed when halite's dihedral angle is higher than 60° (Lewis and Holness, 1996; Holness and Lewis, 1997). So, both bedded, and halokinetic recrystallized salt is impermeable at lower mesogenetic temperatures (Fig. 22; Schenk and Urai, 2004; Lewis and Holness, 1996). In this temperature range, a small amount of brine is distributed in micrometer-sized isolated fluid inclusions at termini of salt-crystal polygon apices. In contrast, when the solid-solid-liquid interfaces of increasingly heated and pressurized polyhedral halite attain dihedral angles that are $<60°$ then the fluid-

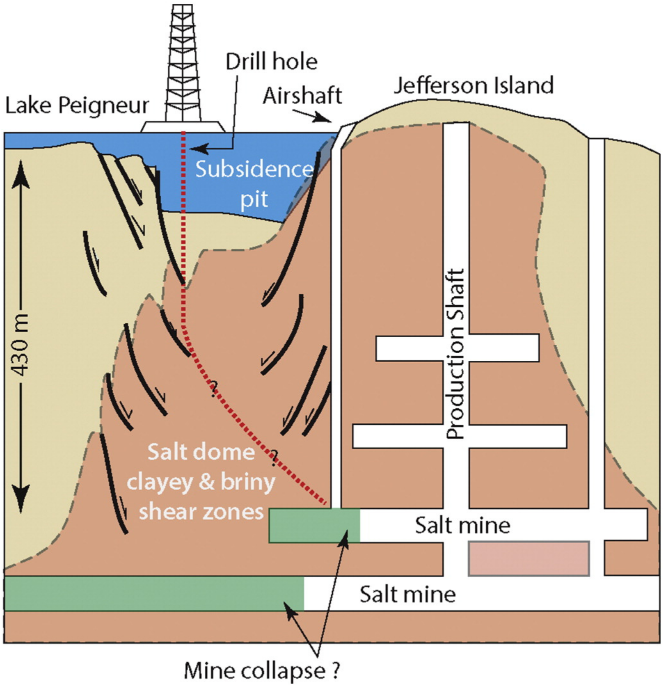

Fig. 21. Lake Peigneur schematic mine cross section (after Warren, 2016 and sources therein).

inclusion filled intercrystal cavities link up, and the salt mass can become permeable.

Accordingly, at burial temperatures >100°–150 °C and pressures of 70 MPa or more, the halite dihedral angle decreases to values <60°, driving a redistribution of intercrystal fluid into a thermodynamically stable network of connected, fluid-filled channels or fused fluid strings at grain

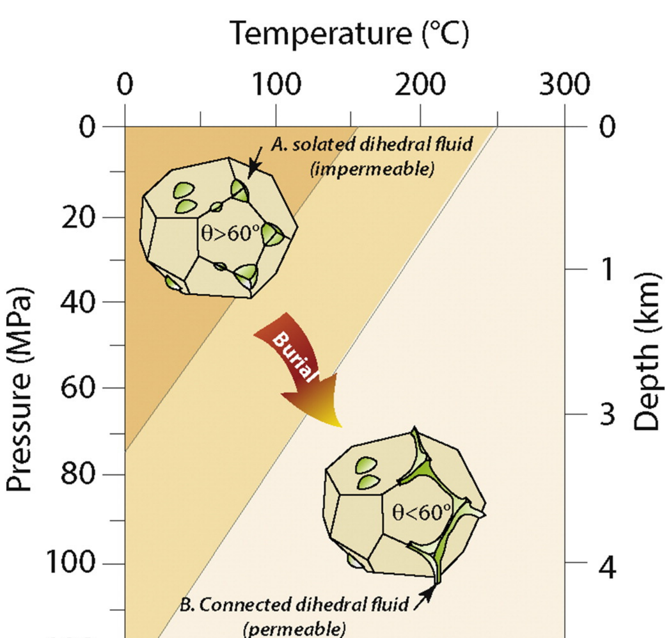

Fig. 22. Effect of dihedral angle on pore connectivity in texturally equilibrated monomineralic and isotopic polycrystalline mosaic halite. Background shading shows two polyhedral porosity fields and transition zone calculated for the Ara Salt (black salt or leaking halite plots in transition zone), Oman. A) Isolated porosity for dihedral angle >60°. B) Connected polyhedral porosity for dihedral angle <60° (after Lewis and Holness, 1996; Kukla et al., 2011b; Warren, 2016).

boundary triple junctions. This transition can be correlated with the observation by Peach and Spiers (1996) that, during natural deformation of rocksalt at great depths, salt undergoes natural hydraulic fracturing or dilatancy. The dihedral angle is, therefore, a thermodynamic property that changes with pressure (P) and temperature (T). Holness and Lewis's static salt laboratory experiments suggest that buried salt masses, subject to higher pressures and elevated temperatures, can acquire intercrystalline or polyhedral permeability comparable to intergranular permeability in a sand. The newly attained intercrystal pore configuration allows penetration and throughflow of hot, dense brines or hydrocarbons (mesogenetic fluids) into and through an altered salt mass made up of linked intercrystal polyhedrons. In Oman, this pressure recrystallization overprint constructs coronas of bituminous black salt centred on carbonate slivers that source the fluids.

Once dihedral recrystallization occurs, mosaic halite loses its ability to act as an aquitard or aquiclude (seal) and instead serves as a permeable conduit for escaping highly-pressurized and hydrocarbon-rich formation waters (Lewis and Holness, 1996). According to Lewis and Holness (1996), the depth at which this occurs may begin as shallow as a few kilometers (Fig. 22). But, their pressure-bomb laboratory-based static-salt experiments likely did not completely encompass the ability of natural subsurface salt to pressure creep and self-seal via longer-term diffusion-controlled pressure solution mechanism (Warren, 2016; Chapter 6). Even if changing dihedral angles alter and open up permeability at shallower depths, there is no guarantee that subsequent flowage associated with pressure solution will not re-anneal these new pores. The documented ability of salt to continue to act as a highly efficient hydrocarbon seal to depths of 6–10 km means, in my opinion, that a thick salt unit does not become a relative aquifer until attaining depths of 6–10 km or more. Pervasive changes in halite's dihedral angle have certainly occurred at temperatures and pressures where halite is entering the[10]greenschist realm. In highly overpressured situations the transition of halite's dihedral angles can be shallower, as in the 40–50 m thick black salt penetrated haloes that typify the salt-encased hydrocarbon-charged carbonate stringers in the Ara Salt of Oman (Kukla et al., 2011a, 2011b). Once a thick salt unit does transform universally into a polyhedral-connected halite mass, the former aquiclude becomes an aquifer flushed by chloride-rich brines, likely carrying other volatiles.

A release of entrained inclusion (±intercrystalline) water at temperatures >300–400 °C (early greenschist) further influences the textures of deeply buried halite. Most of the inclusions in chevron halite and other inclusion-rich cloudy primary salts are due to entrained brine inclusions and not mineral matter. Fig. 23 plots the weight loss of various types of halite during heating. It clearly shows cloudy (inclusion-rich) halite releases up to 5 times more brine (0.2–0.5 wt%) than clear (inclusion-free) coarsely crystalline halite. An analysis of all fluids released during heating shows carbon dioxide and hydrogen contents are much lower than the water volumes: $CO_2/H_2O < 0.01$ and $H_2/H_2O < 0.005$. Organic compounds, with CH_4, are always present (<0.05% H_2O), and are twice as abundant in cloudy halite. There are also traces of nitrogen and, in some samples, hydrogen sulphide and sulphur dioxide released as a salt mass passes into the greenschist realm (Zimmermann and Moretto, 1996). For more detail on metamorphosed evaporites from greenschist to amphibolite grade, the reader is referred to Chapter 14 in Warren (2016).

[10] By the time as a recrystallizing salt mass is passing into the onset realm of the greenschist facies, halite is dissolving and altering into sodic scapolite (Warren, 2016; Chapter 14). Thus, through the later stages of diagenesis and into early to medium grades of metamorphism, halite and its daughter products may act as sources and conduits for flow of chloride-rich metalliferous brines and salt slurries. This occurs as bedded and halokinetic salt units evolve from dense impermeable salt masses into permeable halites with higher dihedral angles, so explaining metamorphosed salt's significant role in the creation of many of massive base metal and IOCG deposits (Warren, 2016; Chapters 15, 16).

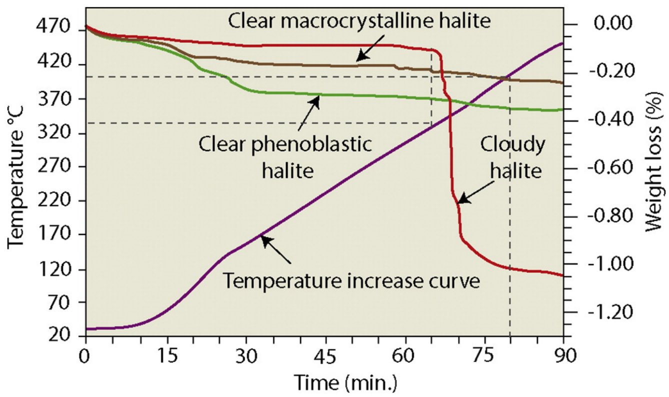

Fig. 23. Weight loss of three pure halite samples upon heating from ambient temperature to 470 °C. Most of the weight loss corresponds to water loss from entrained inclusions, which are more common in cloudy halite (after Zimmermann and Moretto, 1996).

6.2. Black salt, leakage and overpressure in Oman

The influence of overpressure driving changes in the dihedral angle of pressurized salt, salt leakage haloes, and the creation of hydrocarbon inclusion-rimmed sparry salt crystals is evident in regions of "black" salt nimbi encircling some Late Neoproterozoic to early Cambrian intra-salt Ara carbonate sliver reservoirs in the South Oman Salt Basin (Fig. 24; Kukla et al., 2011a, 2011b; Schoenherr et al., 2007a, 2007b). The carbonate reservoir-hosting geobodies are isolated in salt, and generally contain variably salt-plugged low-permeability dolomites, with high initial hydrocarbon production rates due to ongoing overpressure. But not all carbonate slivers with a black salt halo remain overpressured, and a temporal relationship is observed, defined by increasingly overpressured reservoirs within stratigraphically younger units. There are two separate pressure trends in the stringers; one is hydrostatic to slightly-above hydrostatic, and the other is overpressured from 17 to 22 kPa.m^{-1}, almost at lithostatic pressures (Fig. 25).

The black staining of the halite is caused by intragranular microcracks with grain boundaries filled by solid bitumen formed by alteration of an oil-liquid precursor (Fig. 24). The same black salt samples contain plastically-deformed halite crystals retaining evidence of dynamic recrystallization (Fig. 3). Subgrain-size piezometry indicates a maximum differential paleostress of <2 MPa (Schoenherr et al., 2007b). Under such low shear stress, laboratory-calibrated dilatancy criteria suggest that oil can only enter the rock salt at near-zero effective stresses, where fluid pressures are very close to lithostatic, that is, overburden stress is very close to σ_3. In Schoenherr et al.'s model, oil pressure in a carbonate stringer reservoir increases until it is equal to the fluid pressure in the minimal, but interconnected, polyhedral porosity of the adjacent Ara Salt (Fig. 26). When this condition is met the salt dilates (hydrofractures) and its permeability increases by orders of magnitude as oil is expelled from the mature carbonate sliver source into the adjacent rock salt, (i.e., salt leaks as it hydrofractures in a region adjacent to a highly overpressured mature carbonate sliver). Sealing capacity in the encasing mesogenetic salt envelop is lost, and fluid flows into the salt continues until the fluid pressure drops below the minimal principal stress. At this point rocksalt reseals and so maintains the fluid pressure at near-lithostatic values. Inclusion studies in the halite indicate ambient temperatures at the time of fluid entry were >90 °C. The required interlinked intercrystal conduit tubes needed for initial hydrofracture set-up were likely created by changes in the dihedral angle in the halite in response to elevated temperatures and pressures (as inferred by Lewis and Holness, 1996).

IHydrocarbon-stained "black salt" aureoles extend up to 100 m into the encasing salt from the supplying carbonate stringer (Figs. 24, 26). This type of "black" or "dark" salt is the result of a burial-mesogenetic pressurized leak and not the result of much shallower and cooler processes that create telogenetic "black salt" regions, as documented in the salt mines of the onshore Gulf of Mexico. Telogenetic leaks tend to be the result of dissolution, driven by extrasalt undersaturated water entry, and are associated with concurrently formed zones of caprock and entrapped external sediment (sutures). Ara carbonate stringers are enclosed by oil-stained "black" salt, but with pressures now well below lithostatic indicate a deflation event driving complete (C) or partial (E) loss of overpressures. Alternatively, stringers showing overpressure, but below the lithostatic gradient (E), can be explained by regional cooling or some other hitherto unexplained mechanism (Fig. 25a; Kukla et al., 2011a, 2011b).

Structural, petrophysical, and seismic data analysis suggests that overpressure generation in the Ara Salt is driven initially by rapid burial of organic-rich carbonate stringers encased in salt, with subsequent significant contributions to the overpressure from thermally-derived fluids via

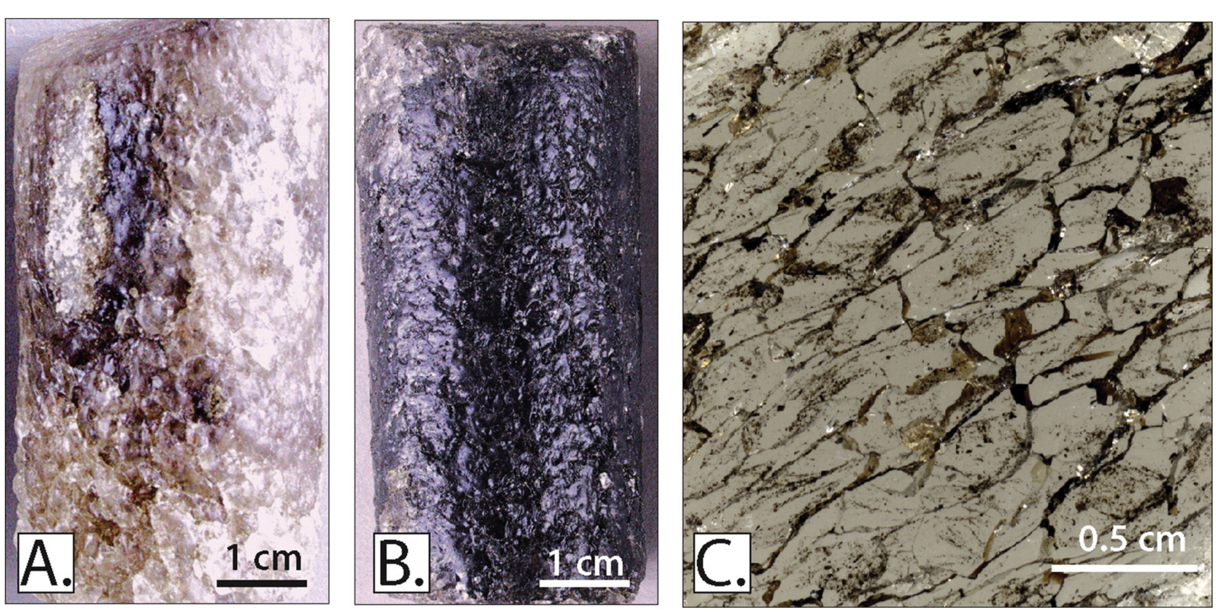

Fig. 24. Hydrocarbon-impregnated halite ("black halite") from the Ara Salt (3000–4000 m depth), South Oman Salt basin. A) Lightly impregnated salt core, B) heavily impregnated zone in salt core, this is classic Omani "black salt". C) Photomicrograph of naturally-impregnated salt showing interconnected polyhedral porosity outlined by the darker hydrocarbons (all images courtesy of Janos Urai).

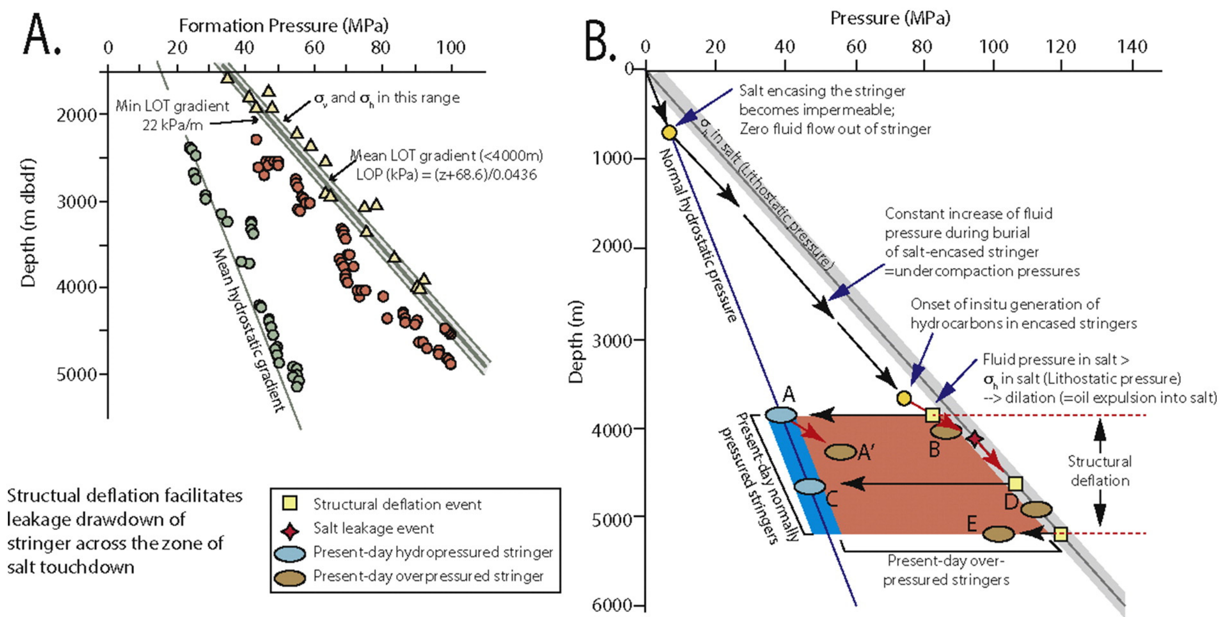

Fig. 25. Overpressure in the carbonate stringers of the South Oman Salt Basin (after Kukla et al., 2011a, 2011b). A) Measured formation pressures in the Ara carbonates (circles) versus depth. The plot shows two different pressure populations: one at near-hydrostatic pressures, with a mean pore-pressure coefficient l = 0.49 (green circles), and one at near-lithostatic pressures, with a mean pore-pressure coefficient l = 0.87 (grey circles). Brown triangles are leakoff test (LOT) data, and z is depth in meters. The thick black band represents the range of differential stress difference (s1–s3 [maximum principal stress - minimum]) in rock salt as derived from integrated density logs and subgrain size piezometry. Tvd_{bdf} = true vertical depth below derrick floor. B) Schematic illustrating mechanisms of overpressure generation and pressure deflation in the Ara Stringers through the burial process (see text for detail). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

kerogen maturation of organic-rich laminites within the same carbonate stringer bodies. If the overpressured stringers come in contact with porous sediments of a siliciclastic minibasin (e.g. touchdown), they will deflate as pressures return to hydrostatic (A in Fig. 25b). When the connection between the minibasin and the carbonate stringers is lost as salt continues to flow and carry the stringer away from the zone of contact, stringers can regain overpressure driven by further oil generation and deeper burial (A'). If hydrocarbon production in an undeflated stringers stops relatively early, the fluid pressures do not reach lithostatic (B). If hydrocarbon generation continues, the fluid pressures exceed the lithostatic pressure (red star), leading to further dilation (hydrofracture) and oil expulsion into the rock salt, so crafting "black salt" (D and E in Fig. 25b).

6.3. Overpressures and leaky salt in the Gulf of Mexico

IAs well as these examples of overpressure associated with older deeply-buried evaporites in the Cambrian salt of Oman, overpressure readily develops in salt-sculpted Tertiary-age basins in the Gulf of Mexico, offshore Angola and Brazil. For example, overpressure occurs in salt-shear edge-zone transitions (aka gumbo[11] zones) beneath some, but not all, shallow salt allochthons in the Green and Mahogany Canyon regions in the Gulf of Mexico (Beckman, 1999; Shaker, 2008). As salt allochthons climb the Mio-Pleistocene stratigraphy of the Gulf of Mexico they can attain the surface and the spread and stream across the seafloor. This creates a potential top seal atop water-saturated seafloor sediment. As ongoing salt squeezing and flow increases the thickness of the laterally-moving salt tongue and its overburden, overpressure can build beneath the expanding salt mass. This can occur much shallower depths than observed in overpressured shale basins.

In terms of extension and compression regimes within a single allochthon tongue, Shaker (2008) noted that in extensional regions in halokinetic basins of the Gulf of Mexico the magnitude and direction of the principal stresses are controlled by sediment load, salt thickness, and salt emplacement-displacement history. Therefore, the maximum principal stress is not necessarily represented by the sheer weight of the overburden, as is usually assumed in quiescent sediment piles. Salt buoyancy often acts upward and has the tendency to accelerate and decelerate the principal stress above and below the salt, respectively (Fig. 27a). A distinctive shift of the pore pressure envelopes and normal compaction trends takes place across the salt body in several wells drilled through salt below Tertiary minibasins in the Mississippi Canyon, Green Canyon, and Garden Banks areas of the Gulf of Mexico. A lower pore pressure gradient has been observed below the salt and a higher gradient above the salt barrier. At the salt-rooted minibasin scale, a high pressure gradient was also observed in areas where the salt was emplaced and a lower gradient where the salt withdrew (Shaker, 2008). On the other hand, in the compressional or toe portion of a salt allochthon system, lateral stress generated by the salt movement piling up salt at the foot of the slope acts as the maximum principal stress, whereas the load of sediment represents the minimum stress (Fig. 27b).

Extreme overpressuring within or below a salt interval indicates fluid inflation and hence no pervasive trans-salt leakage. Overpressure, sometimes approaching lithostatic, is routine at depths of 3000–4000 m in subsalt settings in the Gulf of Mexico. Its variability and unpredictability in front of the drill creates drilling problems, as evidenced by the[12]Macondo spill and explosion on April 20, 2010. Gas generated at

[11] The term gumbo is used mostly by Gulf of Mexico drillers to describe the appearance of the large, pliable sticky and clumped cuttings that come up in the mud returns, whenever these basal salt transition zones are intersected. Gumbo is actually a thick seafood-based soup or stock that originated in the eighteenth century in the Creole region of southern Louisiana and is still a very popular dish in the southeast of the USA.

[12] Deepwater Horizon oil spill is also referred to as the BP oil spill, the BP oil disaster, the Gulf of Mexico oil spill, and the Macondo blowout. At approximately 9:45 pm CDT, on 20 April 2010, high-pressure methane gas from the well expanded into the drilling riser and rose into the drilling rig, where it ignited and exploded, engulfing the platform. At the time, 126 crew members were on board. The disaster claimed the lives of 11 rig personnel whose bodies were never found. The explosion and fire were followed by the sinking of the Deepwater Horizon oil rig and resultant loss of well control. Oil flowed onto the deep seafloor for 87 days, until the well was capped and flow greatly reduced on 15 July 2010. After several failed efforts to contain the flow, the well was declared sealed on 19 September 2010. The total discharge from the Macondo spill is estimated at 4.9 million barrels (210 million US gal; 780,000 m3). The U.S. government's September 2011 report pointed to defective cement in the well as the main cause of the blowout (Graham et al., 2011).

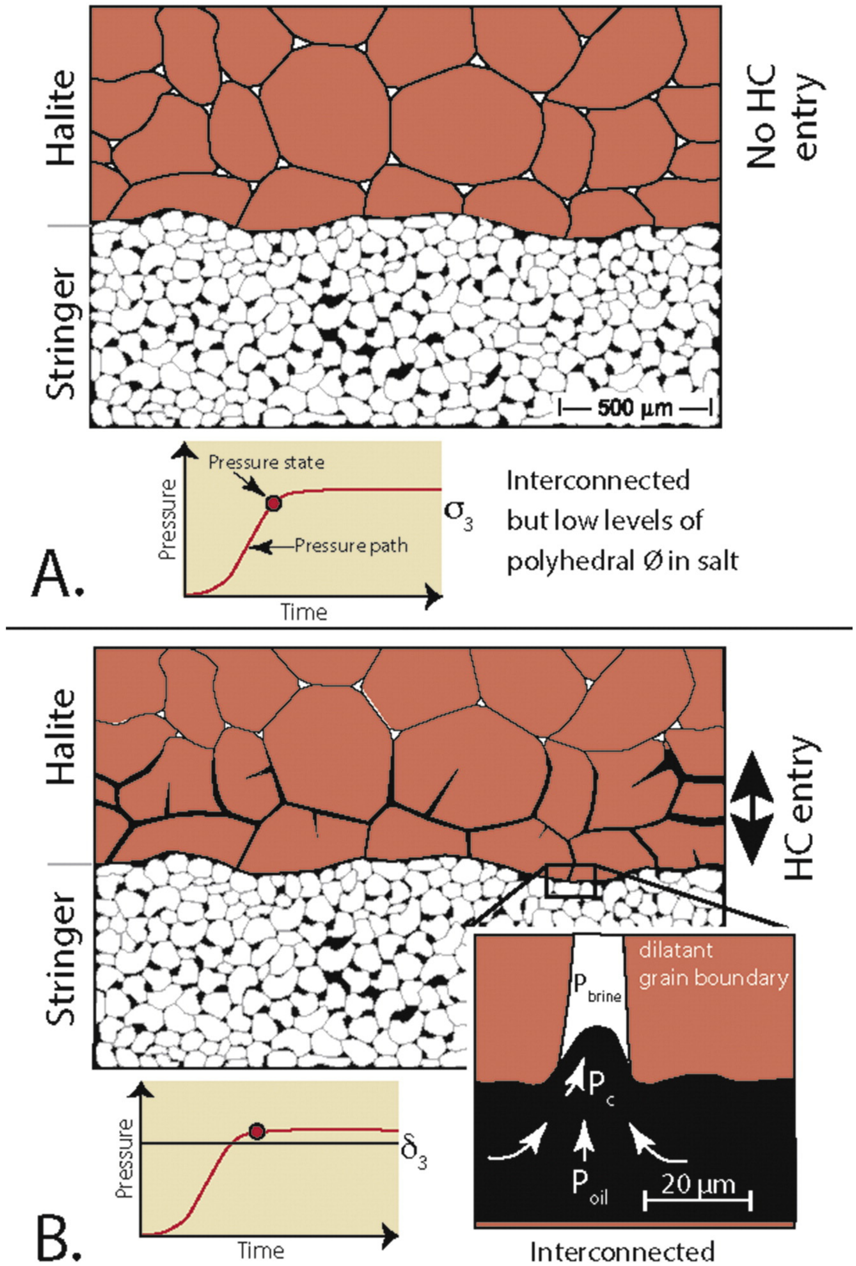

Fig. 26. Entry of pressurized hydrocarbons (HC) into polyhedral salt pores. A) schematic cross section in (a) shows the interface of stringer reservoir and Ara Salt. Halite has an interconnected but low porosity represented by the triangular white spaces between the salt crystals (cut perpendicular to the triple junction tubes - thermal response in salt). The red dot in the schematic pressure-versus-time diagram indicates that the oil pressure (P_{oil}) is equal to σ_3 in the Ara Salt. B) Because of overpressure buildup, P_{oil} in the stringer exceeds the minimum principal stress (σ_3) of the salt by the capillary entry pressure (P_c), allowing the entry of oil into the triple junction tubes of the salt, leading to a diffuse dilation of the Ara Salt by grain boundary opening and intracrystalline microcracking (After Schoenherr et al., 2007b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

greater depths in subsalt regions can be trapped under the allochthon salt seal at pressures approaching lithostatic. It means drilling under the allochthonous salt level on the Gulf Coast slope can intersect undercompacted sediments that are moderately to extremely overpressured and highly friable (Hunt et al., 1998). A lack of consolidation/induration in muddy Neogene sediments about a salt allochthon in the Gulf of Mexico means it can be quite difficult to attain a tight cement seal behind drill casing in weak and friable overpressured lithologies. It is highly possible that a lack of consolidation behind cemented casing was a contributing factor to the blowout and spill that was the BP Deepwater Horizon Macondo disaster (Graham et al., 2011). It was also a contributing factor in the subsequent technical difficulties experienced when trying to re-establish control (kill the well) once the blowout had occurred.

The influence of highly effective (non-leaking) Jurassic salt seals on pressure gradients across the Neogene stratigraphy of the Gulf of Mexico is seen in the increased mud weights typically required for safe drilling, once an evaporite allochthon is breached (Table 1). Many wells intersecting sediments beneath salt allochthons in the deepwater realm of the Gulf of Mexico and the circum-Atlantic Salt basins are overpressured down to some depth below the base of salt, with mud weights controlling pressures ranging from 14 to 17.5 ppg. These pressure-mudweight relationships clearly indicate an overlying salt cap is not pervasively leaking (trans-salt) in most sedimentary

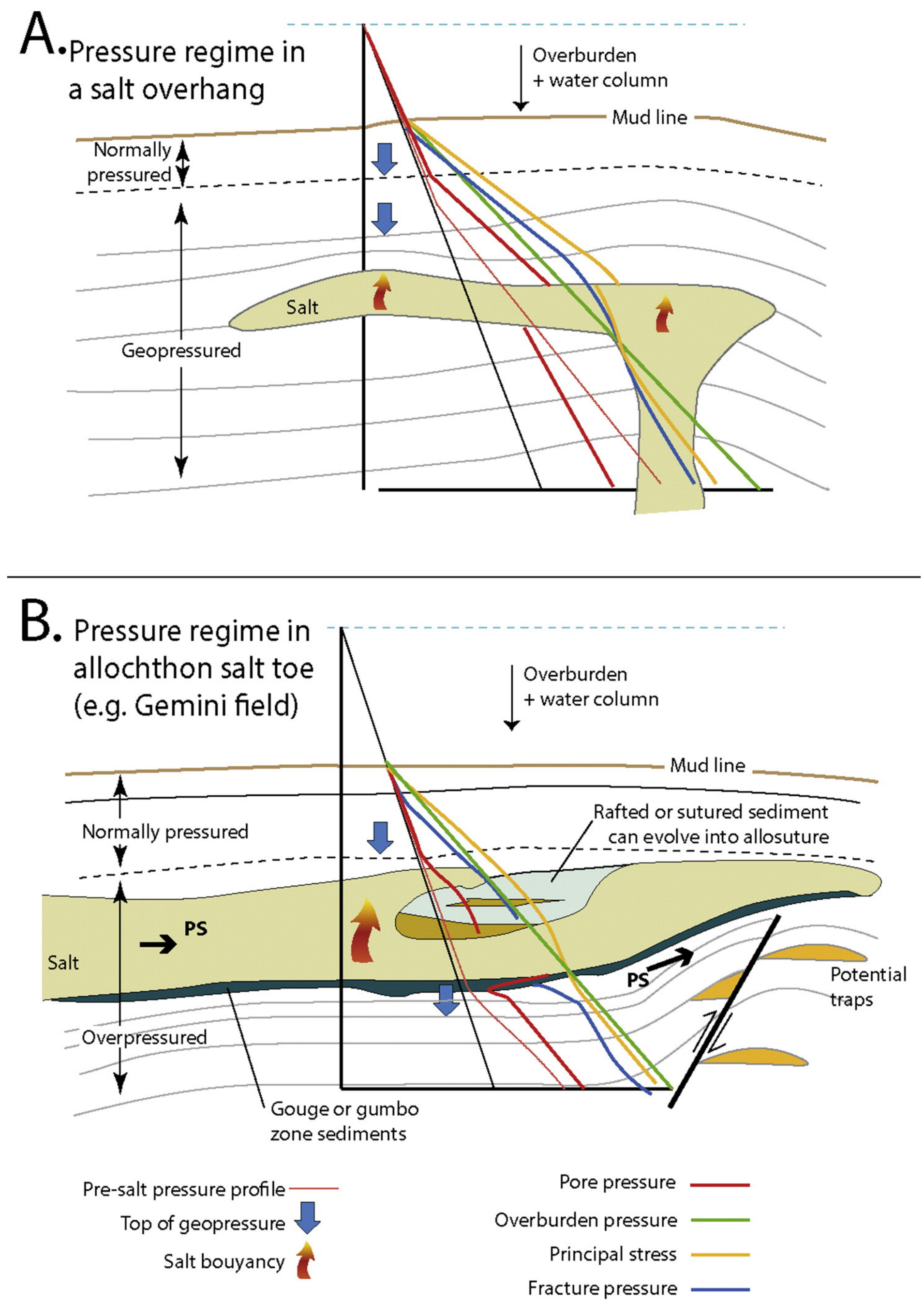

Fig. 27. Geopressure profile models. (after Shaker, 2008) A) For a salt overhang. B) For salt toe and fold-belt exploration plays. PS (principal stress), OB (overburden), FP (fracture pressure), PP (pore pressure), WC (water column pressure), and SB (salt buoyancy).

(diagenetic-mesogenetic) realms. Lost circulation (leakage) zones in actively drilled wells in the Gulf of Mexico and elsewhere are located in the non-salt sediments adjacent to a salt seal. As stated at the start of this article, most salt bodies in the mesogenetic realm do not leak, rather, they tend to focus subsalt fluid flow into salt edges or other breach points in the continuity of the salt. If salt does leak fluid in response to hydrofracturing (pressure exceeds lithostatic) it tends to later reseal as the pressure is released by the creation of “black” salt.

Table 1
Typical mud weights used to drill overpressured sub-allochthon intervals in the Gulf of Mexico (after O'Brien and Lerche, 1994).

Well	Top salt (m)	Base salt (m)	Total salt thickness (m)	Total well depth (m)	Mud weight above salt (ppg)	Mud weight below salt (ppg)	Density profile (gm/cm^3) (above/in salt/below	Sonic log below salt (μsec/ft)
West Cameron, Block 505, No.2	4300	4780	480	5640	12	18	2.45/2.05/2.25	140
Garden Banks, Block 171, No. 1	2590	2925	335	3230	12	14	2.15/2.05/2.25	140
Vermillion, Block 356, No. 1 South	2592	3231	639	5180	13	18	no data	140
South Marsh Island, Block 200, No.1	2685	2987	302	n/a	15.6	17.2	2.15–2.25/2.05/2.15–2.25	130

6.4. Implications of 'black" and other salt anomaly occurrences

Locations of both types of "black" salt and other anomalous salt zones indicate intervals where subsurface salt has locally leaked, either now or in the past. Places and conditions where leakage has occurred are geologically distinct from more typical regional salt character and need to be identified and planned-for. This must be done before broad-scale assumptions of salt seal integrity are made in the design of salt cavities for short and longterm hydrocarbon or waste storage.

The black salt encountered in the salt mines of the US Gulf Coast are indicative of meteoric/active phreatic water entry in relatively shallow conditions (less than a few kilometers) in regions where halokinetic salt is in contact with the overlying or encasing shales and mudstones. In other words, fluid entry is from outside of the salt mass. Fluids move into the salt from its edges and dissolution likely enhances the porosity in the salt, while at the same time creating zones enriched in insoluble residues (upper, lateral and basal caprocks). In contrast, the black salt occurrences in the Ara Salt of Oman indicate overpressured haloes, generated internally via hydrocarbon and fluid expulsion from carbonate slivers, which are fully encased in salt. This creates naturally hydrofractured envelopes in the salt mass in zones where pressure and temperature induced changes in the dihedral angle has generated intercrystalline fluid strings within the recrystallized polyhedral halite. Clearly, the two settings of black or dark salt formation are distinct and there is not a single mechanism that creates black salt.

So far, we have seen that most subsurface salt in the mesogenetic realm is a highly efficient seal that holds back large volumes of hydrocarbons across salt basins worldwide. When salt does leak or transmit fluid, it does so in one of two ways: 1) by the entry of undersaturated waters and; 2) by temperature and pressure-induced changes within salt or in a trap adjacent to the salt. The latter is tied to overpressure and perhaps a change in the dihedral angle of the constituent halite. Another consequence linked to the two dominant modes of salt leakage relates to the source of the fluid entering the leaking salt. In the first case, the undersaturated fluid source is external to the salt ("outside the salt"). In the second case, it can be internal to the main salt mass (sourced "inside the salt") or tied to overpressure build-up ("sourced adjacent to the salt"). However, at greater depths and temperatures (certainly by the onset of greenschist facies) a pervasive change in the dihedral angle of halite in a salt mass occurs and a significant portion of leaking fluid passing through this more deeply-buried altering salt is external to the salt mass ("fluid is trans-salt"). The passage of such trans-salt fluid is likely to facilitate further salt dissolution and the generation of large volumes of chloride brine. These brines are integral to the formation of significant base and precious metal deposits worldwide (Chapters 15 and 16 in Warren, 2016),

7. Styles of diagenetic fluids driving salt leakage

Within the framework of fluids breaching a subsurface salt body in the diagenetic realm, the breached salt can be a primary bed of varying thickness, or it can have flowed into a variety of autochthonous and allochthonous salt masses. Autochthonous salt structures are still firmly rooted in the stratigraphic level of the primary salt bed. Allochthonous salt structurally overlies parts of its (stratigraphically younger) overburden and is often no longer connected to the primary salt bed (mother-salt level).

7.1. Breaches in bedded (non-halokinetic) salt

The principal documented mechanism enabling leakage across bedded salt in the diagenetic realm is dissolution, driven by fluids entering the salt bed from above or below and leading to breaks or terminations in salt bed continuity. Less often, leakage across a salt unit can occur where bedded salt has responded in a brittle fashion and fractured or faulted (Davison, 2009). Timing of the leakage can be early or late diagenetic and there is often more than one time of possible leakage related to the type of hydrology experienced by the salt body

In hydrocarbon-producing basins with widespread bedded evaporite seals, significant fluid leakage tends to occur near the edges of salt beds. For example, in the Middle East, the laterally continuous Hith Anhydrite (Jurassic) acts as a regional seal to underlying Arab Cycle reservoirs and carbonate-mudstone source rock. The high efficiency of the Hith seal controls the stratigraphic position of many of the regions giant and supergiant fields, including Ghawar in Saudi Arabia, which is the largest single oil-filled structure in the world. Intrinsic longterm maintenance of an evaporite's seal capacity prevents vertical migration from mature sub-Hith source rocks into potential reservoirs in the overlying Mesozoic section across much of Saudi Arabia and the western Emirates. However, toward the Hith seal edge are a number of large supra-Hith fields, hosted in Cretaceous carbonates, with a significant portion of the hydrocarbons sourced in Jurassic carbonate muds that lie stratigraphically below the Hith Anhydrite level (see Warren, 2016; Chapter 10 for a summary of this and other relevant case histories).

The modern Hith Anhydrite edge is not the original depositional margin of the laterally extensive evaporite bed. Rather, it is a dissolution edge, where rising basinal brines, focused along the underside of the bedded Hith, are moving up and out of the basin. Their long term escape upwards at the Hith edge have thinned and altered the past continuity of this effective seal as dissolution causes the edge to retreat basinward. The process of ongoing dissolution of the edge of a salt mass, so allowing vertical leakage near the subsurface edge of a buried evaporite interval, typifies not just the edge of bedded salts but also the basinward edges of salt units that are halokinetic. The dissolution edge effect of the Ara Salt and its basinward retreat over time are clearly seen along the eastern edge of the South Oman Salt Basin where the time of filling of the Permian-hosted reservoir structures youngs toward the west (Warren, 2016).

7.2. Leakages associated with the margins of discrete diapiric structures

Once formed, salt diapirs tend to focus upward escape of basinal fluids derived from compaction of both subsalt and suprasalt sediments, as evidenced by: (1) localized development of mud mounds and chemosynthetic seeps at depopod[13] edges above diapirs in the Gulf of Mexico (Fig. 28a); (2) shallow gas anomalies clustered around and above salt diapirs in the North Sea and (Fig. 28b); (3) localized salinity anomalies around salt diapirs, offshore Louisiana and with large pockmarks above diapir margins in West Africa (Cartwright et al., 2007). Likewise, in the eastern Mediterranean region, gas chimneys in the Tertiary overburden are common above regions of thinned Messinian Salt, as in the vicinity of the Latakia Ridge (Fig. 29).

Whenever a salt weld or overburden touchdown occurs, fluids can migrate (leak) vertically across the level of a now flow-thinned or no-longer-present salt level. Such touchdowns or salt welds can be in basin positions located well away from the diapir edge and are a significant feature in the formation of many larger base-metal and sedimentary copper traps, as well as many depopod-hosted siliciclastic oil and gas reservoirs (Fig. 30: Warren, 2016; Chapters 15 and 16).

7.3. Caprocks indicate salt leakage zones

Any caprock confirms salt leakage and fractional dissolution have occurred at an evaporite boundary do not only form a "cap" or top to a salt structure but can also delineate the underbelly or sides of any salt mass or bed (Fig. 31). Historically, in the 1920s and 30s, shallow vuggy and fractured caprocks to salt diapirs were early onshore exploration targets about topographic highs in the Gulf of Mexico (e.g.

[13] A depopod is a sediment-filled basin formed by sediments loading an underlying and flowing salt layer and so is located on or between salt uplifts, with its type area in the Gulf of Mexico, offshore Louisiana.

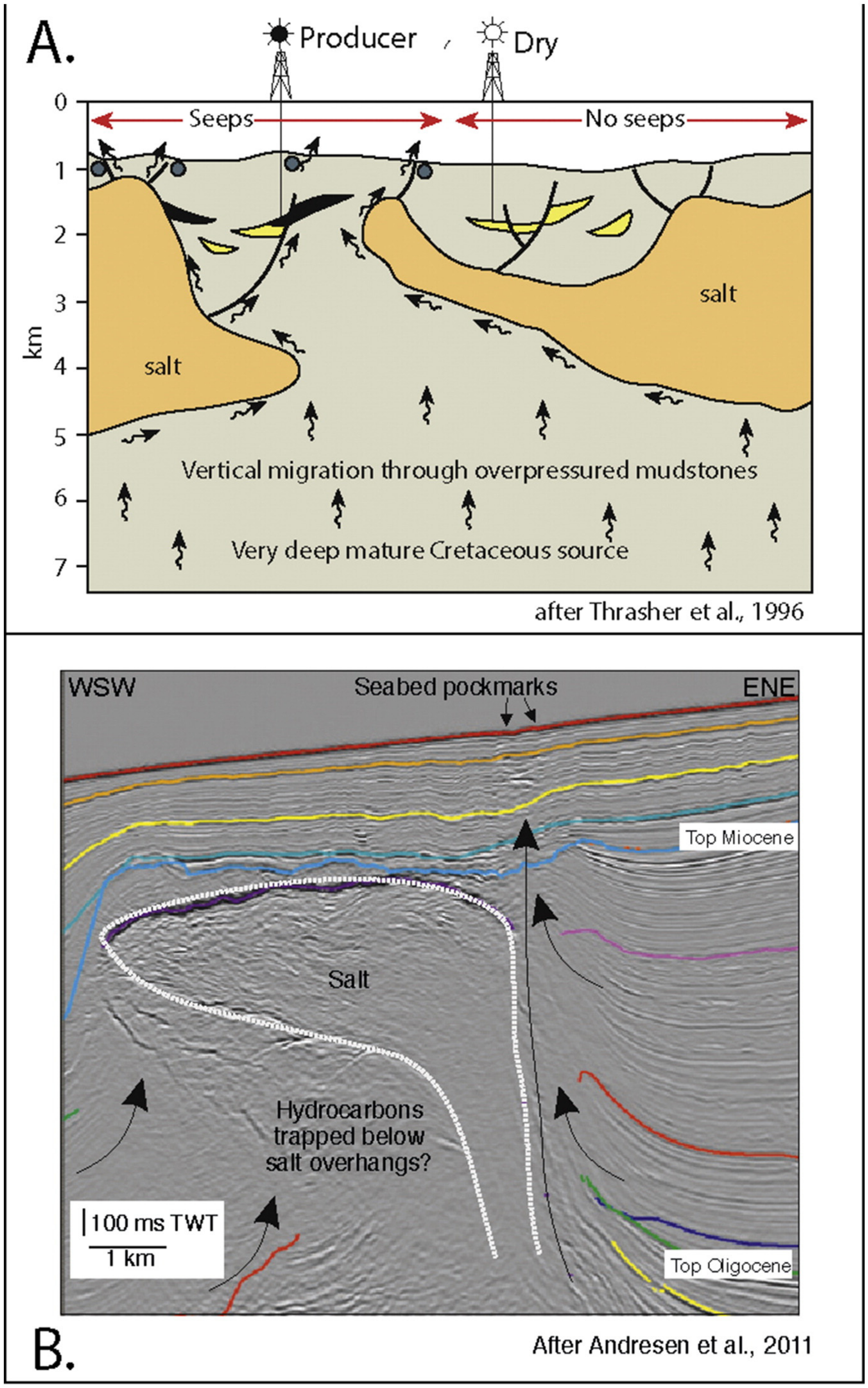

Fig. 28. Salt-focused fluid leakage. A) General association of seeps, chemosynthetic communities and hydrocarbon discoveries in the deepwater Gulf of Mexico (after Thrasher et al., 1996). B) Offshore Angola, shows consistent updip occurrence of seabed pockmarks with respect to downdip overhanging salt structures, whereas pockmarks are absent from the downdip parts, possibly implying that hydrocarbons may be trapped below salt overhangs at the present day (after Andresen et al., 2011). Black arrows indicate likely fluid migration pathways.

Spindletop). Even today, the density of drilling and geological data derived from these onshore diapiric features means many models of caprock formation are based on capstone examples from subcropping diapirs in Texas and Louisiana. Onshore, in the Gulf of Mexico, caprocks form best in dissolution zones at the outer, upper, edges of salt structures, where active cross-flows of meteoric waters are fractionally dissolving the salt (Hanna, 1930; Goldman, 1933). However, rocks composed of fractional dissolution residues, with many of the same textural and mineralogical association as classic onshore Gulf of Mexico caprocks, are now known to mantle the deep sides of subvertical-diapirs beneath the North Sea (e. g., lateral caprock in the Epsilon Diapir; Fig. 31a) and define the basal anhydrite (basal caprock) that defines the underbelly of the Cretaceous Maha Sarakham halite across the Khorat Plateau in NE Thailand (Fig. 31b).

All "caprocks" are fractionally-dissolved accumulations of diapir dissolution products and form in zones of fluid-salt interaction and leakage, wherever a salt mass is in contact with undersaturated pore fluids (Fig. 31). First to dissolve from a typical salt mass is halite, leaving behind anhydrite residues, that undersaturated cross-flushing pore waters can then convert to gypsum and, in the presence of sulphate-reducing bacteria and organic matter, to calcite and H_2S (see Warren, 2016; Chapter 6 for detailed discussion). If the diapir experiences another

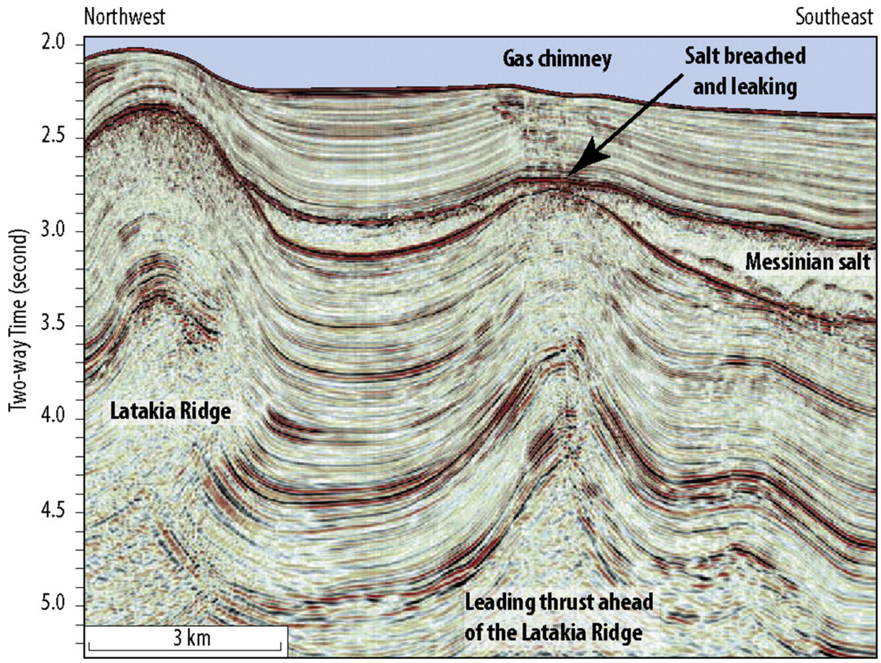

Fig. 29. Gas chimney present above the leading thrust of the Latakia Ridge (After Bowman, 2011).

growth pulse (or downbuilding), the caprock can be broken and penetrated by the rising salt. This helps explain fragments of caprock caught up in shale sheaths or anomalous dark-salt zones, as exemplified by less-pure salt-edge intersection units described as dark and anomalous salt zones in the Gulf of Mexico diapirs (see earlier).

7.4. Salt leakage fluids that are internal to the salt mass

In the real world of the subsurface, there are numerous documented salt seals holding back significant hydrocarbon columns down to mesogenetic depths of >6–7 km. That is, based on a worldwide compilation of salt-sealed hydrocarbon reservoirs, trans-salt leakage across 75–100 m or more of pure salt does not occur at depths <7–8 km, or temperatures of <100–150 °C (see case studies in Chapter 10 in Warren, 2016). In their work on the Haselgebirge Formation in the Alps, Leitner et al. (2011) use a temperature range >100 °C and pressures >70 MPa as defining the onset of the halite dihedral transition.

It seems that across much of the mesogenetic realm, a flowing and compacting salt mass or bed can maintain seal integrity or reseal to much greater depths than postulated by static halite percolation experiments. In the subsurface, there may be local pressured-induced changes in the halite dihedral angle within the salt mass, as seen in the Ara Salt in Oman, but even there, there is no evidence of the total km-scale salt mass transitioning into a leaky aquifer via changes in the halite dihedral angle (Kukla et al., 2011a, 2011b). But indeed, as we move from the diagenetic into the metamorphic realm, even thick pure salt bodies

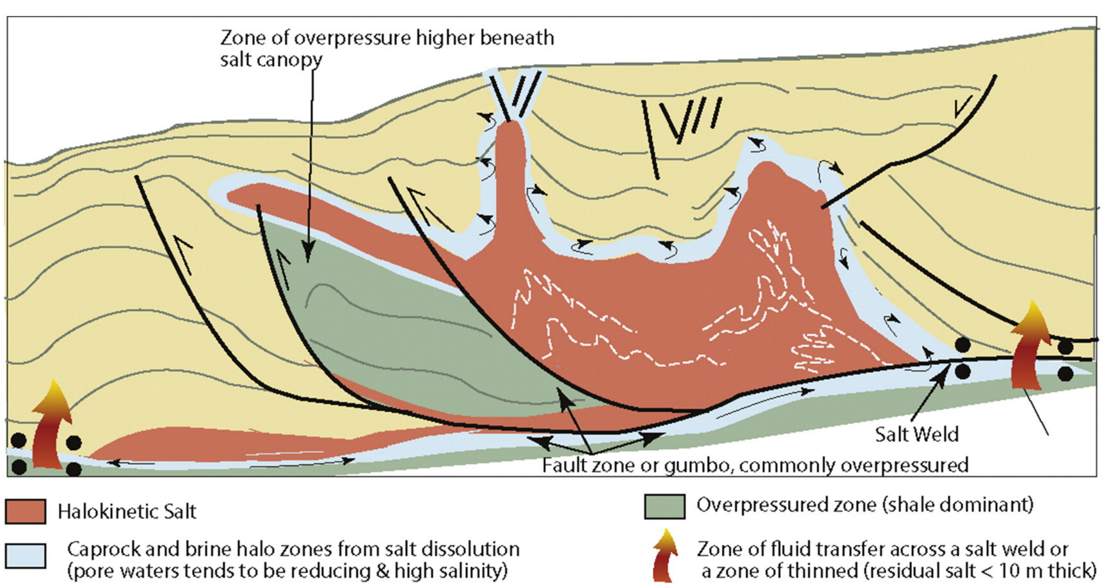

Fig. 30. Zones of leakage and insoluble residue (caprock, lateral caprock and basal caprock) are created at the salt edge in zones of undersaturated circum-salt fluid focus (after Warren, 2016).

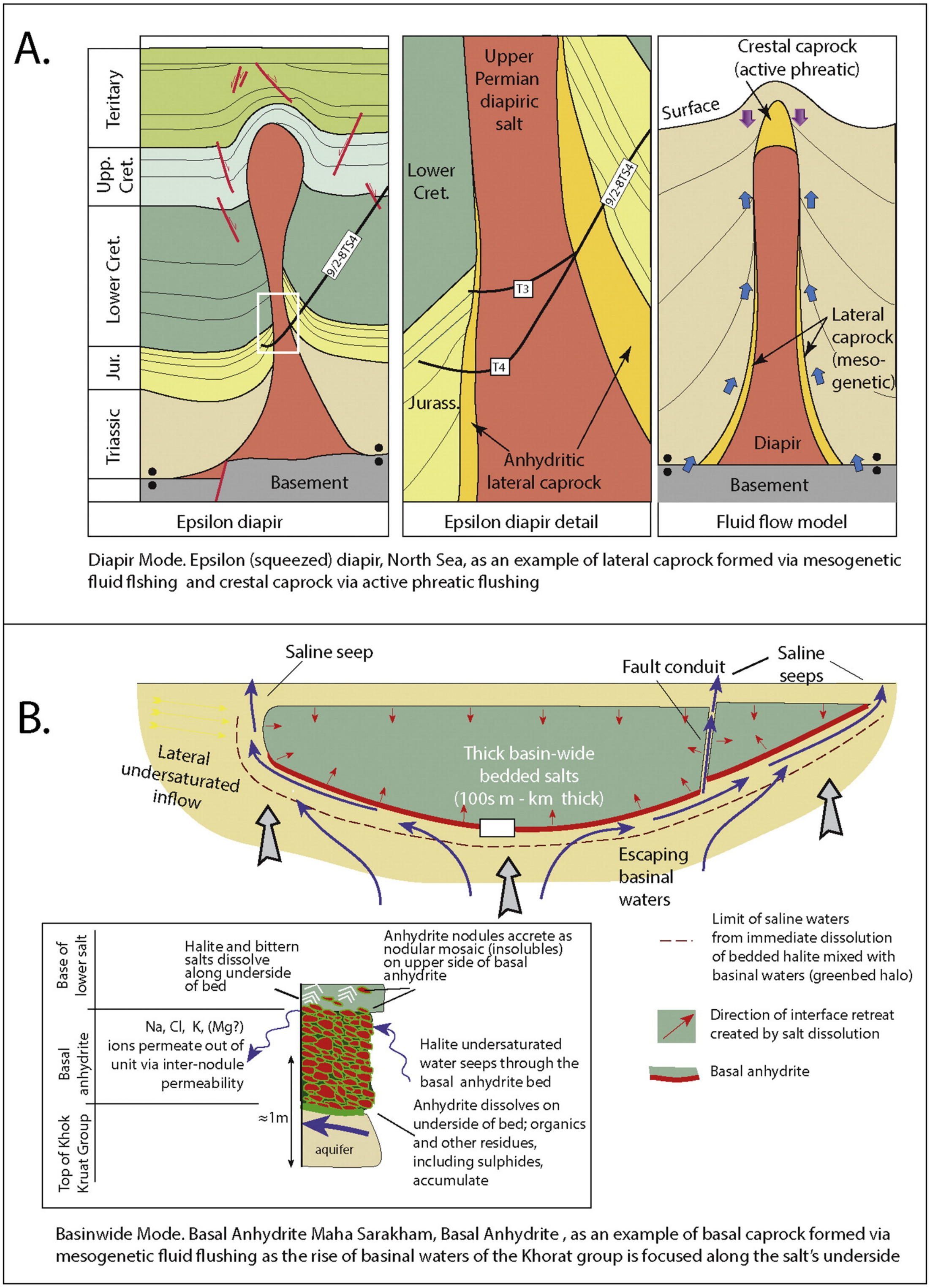

Fig. 31. Caprock also forms in various non-crestal positions. A) Lateral caprock - Epsilon Diapir, North Sea (after Jackson and Lewis, 2012). B) Basal anhydrite beneath dissolving underbelly of Maha Sarakham halite, Thailand (after Warren, 2016).

become permeable across the whole salt mass. Deeply buried and pressured salt ultimately dissolves as it transitions into various meta-evaporite indicator minerals and zones (Chapter 14, Warren, 2016).

When increasing pressure and temperature changes the halite dihedral angle in the mesogenetic realm, then supersaturated hydrocarbon-bearing brines enter salt formations to create naturally-hydrofractured "dark-salt". As we discussed earlier, pressure-induced changes in dihedral angle in the Ara Salt of Oman create black salt haloes that penetrate, from the overpressured salt-encased carbonate sliver source, up to 50 or more meters into the adjacent halite (Schoenherr et al., 2007a, 2007b). Likewise, Kettanah (2013) argues Argo Salt of eastern Canada also has leaked, based on the presence of petroleum-fluid inclusions (PFI) and mixed aqueous and fluid inclusions (MFI) in the recrystallized halite (Fig. 32 - see also Fig. 24).

Both these cases of dark-salt leakage (Ara and Argo salts) are located well within the salt mass, indicating the halokinetic salt has leaked or

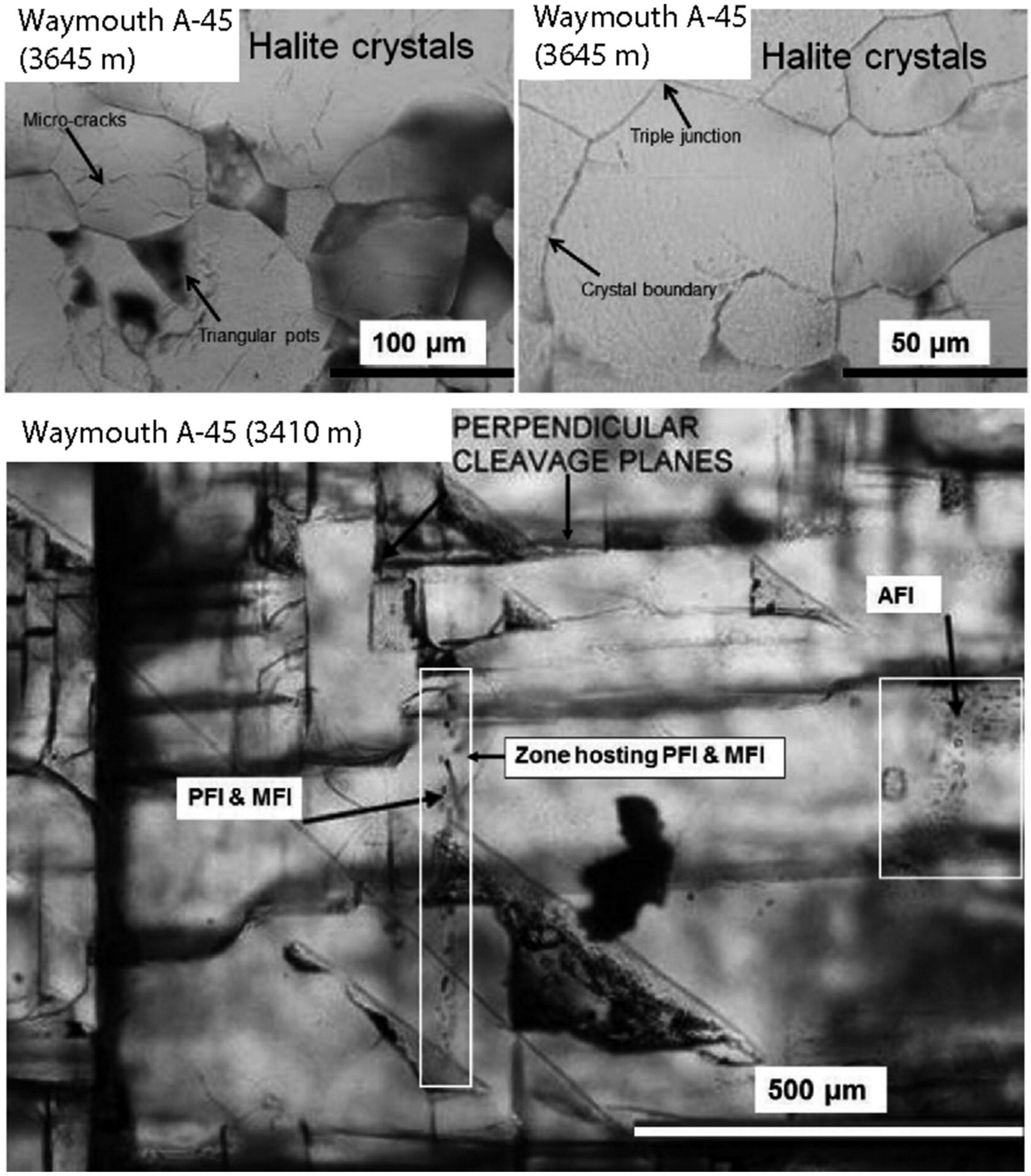

Fig. 32. Halite crystals of the Weymouth-A45 well showing halite crystal aggregates with sutured polyhedal contacts (A, B). C) shows perpendicular cleavage planes and assemblages of primary aqueous fluid inclusions (AFI) between cleavages planes that are parallel to growth zones, as well as a linearly oriented assemblages of secondary petroleum fluid inclusions (PFI) trapped along healed fractured zones (after Kettanah, 2013). The sampled halite is once again impermeable although it contains hydrocarbon inclusions.

transmitted fluids within zones now located well away from the salt edge. In the case of the Argo salt, the study is based on drill cuttings collected across 1500 m of intersected salt at depths of 3–4 km. Yet, at the three-km-plus depths in the Argo Salt where salt contains oil and bitumen, the total salt mass still acts a seal, implying it must have regained or retained seal integrity, in zones that have once leaked. Not knowing the internal fold geometries in any deeply buried salt mass, but knowing that all flowing salt masses are internally complex (as seen in salt mines and namakiers – Fig. 14), means we cannot assume how far hydrocarbon inclusions have moved or been carried within a halokinetic salt mass, post-leakage. Nor can we know if, or when, any salt contact occurred with a possible externally derived hydrocarbon-bearing fluid source, or whether subsequent salt flow lifted the hydrocarbon-inclusion-rich salt ("black" salt) off the contact surface as salt flowed back into the interior of the salt mass.

Thus, with any hydrocarbon-rich "black" salt occurrence in a halokinetic salt mass, we must ask the question; did the salt mass once hydrofracture (leak) in its entirety, or did the hydrocarbons enter locally and then as the salt continued to flow, that same hydrocarbon-inclusion-rich interval moved into internal drag and drape folds? In the case of the Ara Salt, the thickness of the black salt penetration away from its overpressured source is known as it is a core-based set of observations. In the Ara Salt at current depths of 3500–4000 m, the fluid migration zones typically extend 50–70 m out from the carbonate sliver source in salt masses that are hundreds of meters thick (Kukla et al., 2011a, 2011b; Schoenherr et al., 2007a, 2007b).

8. So how can we define leakage extent in a buried salt mass?

Dark salt, especially if it contains hydrocarbons, clearly indicates fluid entry into a salt body in the diagenetic realm. Essential to considerations of hydrocarbon trapping and long-term waste storage in salt is how pervasive is, or was, the zone of fluid entry, where did the fluid come from, and what are the likely transmission zones in the current salt body (bedded versus halokinetic)?

In an interesting recent paper documenting and discussing salt leakage, Ghanbarzadeh et al., 2015 conclude:

> "The observed hydrocarbon distributions in rock salt require that percolation occurred at porosities considerably below the static threshold due to deformation-assisted percolation. Therefore, the design of nuclear waste repositories in salt should guard against deformation-driven fluid percolation. In general, static percolation thresholds may not always limit fluid flow in deforming environments."

Their conclusions are based on lab experiments on static salt and extrapolation to a combination of mud log and wireline data collected from a number of wells that intersected salt allochthons in Louann Salt in the Gulf of Mexico. Their lab data on changing dihedral angles inducing leakage or percolation in static salt confirms the experiments of Lewis and Holness (1996). But they took the implications of dihedral angle change further, using CT imagery to document creation of interconnected polyhedral porosity in static salt at higher temperatures and pressures (Fig. 33). They utilize Archie's Law and resistivity measures on the salt to calculate inferred porosity, although it would be interesting to know what values they utilize for cementation exponent in Archies equation (depends on pore tortuosity), Sw, and saturation exponent. Assuming the standard default values of $m = 2$ and $n = 2$ when applying Archie's Law to back-calculate porosity spreads from resistivity measurements in halite, and assumed Sw are likely incorrect. The increased tortuosity created by the patchy creation of intercrystal pore connection, which is subject to ongoing re-annealment as the salt mass experiences ongoing flow would give much higher values of the cementation exponent and hence much lower interconnected porosity inputs to Archies equation; once gain underlining the limitations of static lab experiment outputs to real-world dynamic situations.

Ghanbarzadeh et al. (2015) go on to relate their experimental observations to wireline measurements and infer the occurrence of interconnected polyhedral pores in Gulf of Mexico salt based on this wireline data. Key to their interpretation is the deepwater well GC8 (Fig. 34), where they use a combination of a resistivity, gas chromatograms, and mud log observations to infer that hydrocarbons have entered the lower 1 km of a 4 km thick salt section, via dihedral-induced percolation.

I have a problem in accepting this leap of faith from laboratory experiments on pure salt observed at the static decimeter-scale of the lab to the dynamic km-scale of wireline-inferred observations in a salt allochthon in the real world scale of the offshore in deepwater salt Gulf of Mexico. According to Ghanbarzadeh et al. (2015), the three-part grey background in Fig. 34 corresponds to an upper no-percolation zone (dark grey), a transition zone (moderate grey) and a lower percolation zone (light grey). This they then infer to be related to changes in dihedral angle in the halite sampled in the well (right side column).

Across the data columns, what the uninterpreted data in the GC8 well show is: A) Gamma log; allochthon salt has somewhat higher API values at depths shallower than 5000 m; B) resistivity log; a change in resistivity to higher values (i.e., lower conductivity) with a change in the same cross-salt depth range as seen in the gamma log, beginning around 5100 m; C) gas (assuming output is from sniffer on the mud stream-not stated in paper), shows a trend of decreasing gas content from the base of salt (around 6200 m) up to a depth around 4700 m, then relatively low values to top salt, with an interval that is possibly a shalier interval (perhaps a suture - see below) that also has a somewhat higher gas content; D) gas chromatography, the methane (CH_4) content mirrors the total gas trends, as do the other gas phases, where measured/present; E) mud Log (fluorescence response), dead oil is variably present from base of salt up to 5000 m, oil staining, oil cut and fluorescence (UV) are variably present from base salt up to a depth of 4400 m.

On the basis of the presented log data, one can infer the lower kilometer of the 4 km salt section contains more methane, more liquid hydrocarbons, and more organic material/kerogen compared to the upper 3 km of salt. Thus, the lower section of the salt intersected in the GC8

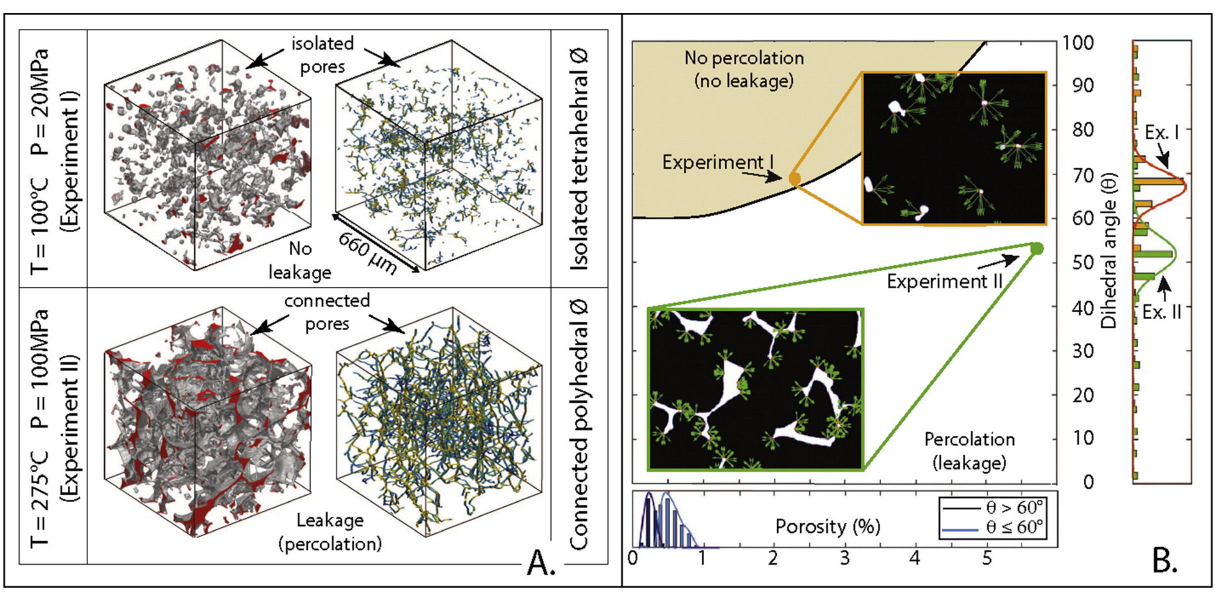

Fig. 33. Halite dihedral angle changes and the creation of connected intercrystalline polyhedal pores at higher temperatures and pressures (after Ghanbarzadeh et al., 2015). A) Hydrostatic experiments on synthetic performed at $P = 20$ MPa and $T = 100$ °C (Exp-I) and $P = 100$ MPa and $T = 275$ °C (Exp-II). Shows their 3D reconstruction of the pore network at assumed static textural equilibrium; all edges of the 3D volumes correspond to 660 mm. The skeletonized pore network was extracted from the reconstructed 3D volume; coloured according to local pore-space-inscribed radii, with warmer colours indicating larger radii. B) Distribution of apparent dihedral angles in the two experiments plotting the Exp-I and Exp-II points in a porosity to dihedral angle plot space, with the percolation threshold (brown versus white shading) calculated from static pore-scale theory. Left side inset and y axis shows the details of automated dihedral angle extraction from 2D images. They show also the median value of dihedral angles and the estimated errors based on the 95% confidence interval. Bottom inset and x axis shows their calculated porosity in natural rock salt inferred from resistivity logs using Archies Law. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

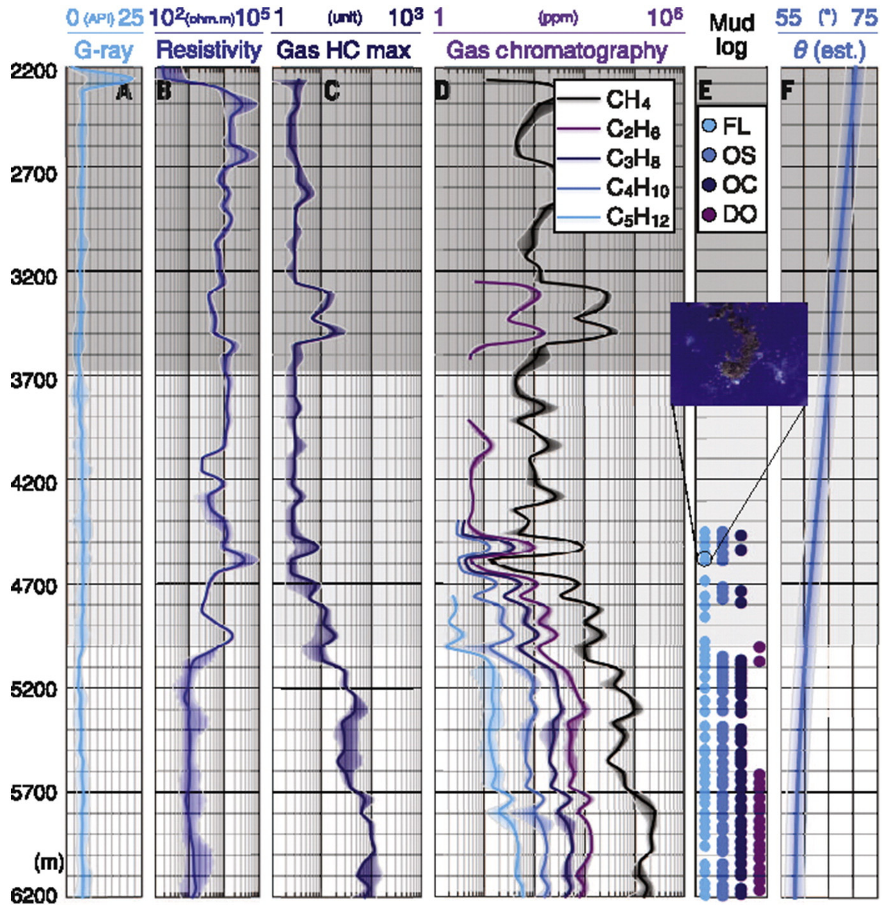

Fig. 34. Petrophysical observations using wireline well logs and mud logs data to constrain the fluid distribution and connectivity in 4 km of salt intersected in the well GC8 from the deep water Gulf of Mexico (after Ghanbarzadeh et al., 2015). (A) Gamma-ray log, (B) electrical resistivity, (C) total hydrocarbons gas, (D) gas chromatography, (E) hydrocarbon indications in the mud log (FL, fluorescence; OS, oil stain; DO, dead oil; and OC, oil cut) in mud logs, and (F) the dihedral angle inferred from experimental data. Shading around each curve shows the measurement error and average fluctuations in data.

well could be locally rich in zones of dark or anomalous salt, compared with the overlying 3 km of salt. What is not given in Fig. 34 is any information on likely levels of non-organic impurities in the salt, yet this information would have been noted in the same mud log report that listed hydrocarbon levels in the well. In my opinion, there is a lack of lithological information on the Gulf of Mexico salt in the Ghanbarzadeh et al. paper, so one must ask; "does the lower kilometer of salt sampled in the GC8 well, in addition to containing hydrocarbons, also contain other impurities like shale, pyrite, anhydrite, etc. If so, potentially leaky intervals could be present that were emplaced by sedimentological processes and local fluid entry processes unrelated to changes in the dihedral angle of the halite.

Lithological information on salt purity is widespread in the Gulf of Mexico public domain data. For example, Fig. 35 shows a seismic section through the Mahogany field and the intersection of the salt by the Phillips No. 1 discovery well (drilled in 1991). This interpreted section, tied to wireline and cuttings information, was first published in 1995 and re-published in 2010 (Harrison et al., 2010). It documents intrasalt flow complexity, which we now know typifies many sutured salt allochthon and canopy terrains across the Gulf of Mexico salt province. Internally, Gulf of Mexico salt allochthons, like others worldwide, are not composed of pure halite, just as is the case in the mined onshore structures (Figs. 16, 17 and 18). Likely, a similar lack of purity and significant structural and lithological variation typifies most if not all of the salt masses sampled by the Gulf of Mexico wells listed in the Ghanbarzadeh et al. (2015), including the key GC8 well (Fig. 34). This variation in salt purity and varying degrees of local leakage is inherent to the emplacement stage of all salt allochthons and diapirs world-wide. It is set up as the salt flows at, or just below, the seafloor (via gravity spreading or gravity gliding), fed by varying combinations of extrusion, extension and thrusting, which moves salt out and over the seabed (Fig. 36).

Salt, when it is flowing laterally and creating a salt allochthon, is in a period of rapid breakout (Fig. 36; Hudec and Jackson, 2006, 2007; Warren, 2016). Breakout describes the situation when a rising salt sheet rolls out over its base, much in the same way a military tank moves out over its track belt. As the salt spreads, the basal and lateral salt in the expanding allochthon mass is subject to dissolution, episodic retreat, collapse and mixing with seafloor sediment, along with the entry of compactional fluids derived from the sediments beneath. Increased impurity levels are particularly obvious in disturbed basal shear zones that transition downward into a gumbo zone (Fig. 37a), but also mantle the sides of subvertical salt structures, and can evolve by further salt dissolution into lateral caprocks and shale sheaths (Fig. 31a).

In expanding allochthon provinces, zones of non-halite sediment typically define sutures within (autosutures; Fig. 37b) or between salt canopies (allosutures; Fig. 37c). These sutures are encased in halite as locally leaky, dark salt intervals, and they tend to be able to contribute greater volumes of fluid and ongoing intrasalt dissolution intensity and alteration where the suture sediment is in contact with outside-the-salt fluids. Allochthon rollout, with simultaneous diagenesis and leakage, occurs across intrasalt shear zones, or along deforming basal zones. In the basal part of an expanding allochthon sheet the combination of shearing, sealing, and periodic leakage creates what is known as "gumbo," a term that describes a complex, variably-pressured, shale-rich transition along the basal margin of most salt allochthons in the

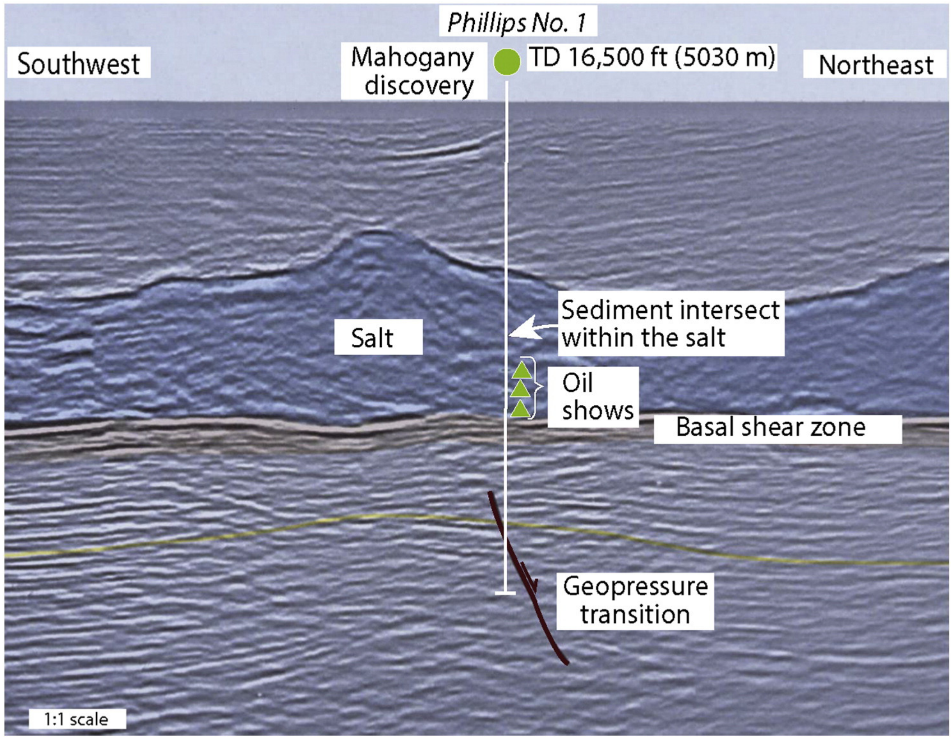

Fig. 35. Interpreted seismic across the Mahogany Discovery, Gulf of Mexico (after Harrison et al., 2010). This was the petroleum industry's first commercial subsalt oil development in the Gulf of Mexico and even in this 1990s vintage seismic, the intrasalt complexity is evident both in the seismic section and along the well trajectory. Internally, Gulf of Mexico halite is not made up of halite with only hydrocarbons as impurities.

Gulf of Mexico (Fig. 37a). Away from suture zones, as more allochthon salt rolls out over the top of earlier foot-zones to the spreading salt mass, the inner parts of the expanding and spreading allochthon body tend toward greater internal salt purity (less non-salt and dissolution residue sediment, as well as less salt-entrained hydrocarbons and fluid inclusions).

At the salt's upper contact, the spreading salt mass may carry its overburden with it, or it may be bare topped (aka open-toed; Fig. 36). In either case, once salt movement slows and stops, a caprock carapace starts to form that is best developed wherever the salt edge is flushed by undersaturated pore waters (Fig. 31a). Soon after its emplacement, the basal zone of a salt allochthon acts a focus for rising compactional fluids coming from sediments beneath. So, even as it is still spreading, the lower side of the salt sheet is subject to dissolution, and hydrocarbon entry, often with remnants of the same hydrocarbon-entraining brines leaking to seafloor about the salt sheet edge. As the laterally-focused subsalt brines escape to the seafloor across zones of thinned and leaky salt or at the allochthon edge, they can pond to form chemosynthetic DHAL (Deepsea Hypersaline Anoxic Lake) brine pools (Fig. 28a). Such seep-fed brine lakes typify the deep sea floor in the salt allochthon region of continental slope and rise in the Gulf of Mexico and the compressional salt ridge terrain in the central and eastern Mediterranean. If an allochthon sheet continues to expand, organic-rich DHAL sediments and fluids become part of the basal shear to the salt sheet (Fig. 37a).

Unfortunately, Ghanbarzadeh et al. (2015) did not consider the likely geological implications of known salt allochthon emplacement mechanisms and how this can explain much of the geological character seen in wireline signatures across wells intersecting salt in the Gulf of Mexico. Rather, they assume the salt system and the geological character they infer as existing in the lower portions of Gulf of Mexico salt masses, are tied to post-emplacement changes in salt's dihedral angle in what they consider as relatively homogenous and pure salt masses. They modelled the hydrodynamics of various salt masses in the Gulf of Mexico as static, with upward changes in the salt purity indicative of concurrent hydrocarbon leakage into salt and facilitated by altered dihedral angles in the halite.

A basic tenet for testing scientific hypotheses is "similarity does not mean equivalence." Without core from this zone, one cannot assume hydrocarbon occurrence in the lower portions of Gulf of Mexico salt sheets indicates changes in dihedral angle. Equally, if not more likely, is that the wireline signatures they present in their paper indicate the manner in which the lower part of a salt allochthon has spread. To me, it seems that Ghanbarzadeh et al. (2015) argue for caution in the use of salt cavities for nuclear waste storage for the wrong reasons.

9. Given that salt can sometimes leak, is waste storage in salt a safe, viable long-term option?

Worldwide, subsurface salt is an excellent seal, but we also know that salt does fail, that salt does leak, and that salt does dissolve, especially in intrasalt zones in contact with "outside" fluids. Within the zone of anthropogenic access for salt-encased hydrocarbon or waste storage (depths of 1–2 km subsurface) the weakest points for potential leakage in a salt mass, both natural and anthropogenic (created by attaining access to the storage), are related to intersection with, or unplanned creation of, unexpected fluid transmission zones and associated entry of undersaturated fluids that are sourced outside the salt. This intersection with zones of undersaturated fluid creates zones of weakened seal capacity and increases the possibility of exchange and mixing of fluids derived both within and outside the salt mass (see case histories in Chapter 7 and 13 in Warren, 2016). In the 1–2 km depth range, the key factor to be discussed in relation to dihedral angle change inducing percolation in the salt, will only be expressed as local heating and fluid haloes in the salt about the storage cavity. Such dihedral angle changes can be tied to a thermal regime induced by long-term storage of medium to high-level radioactive waste.

I use an ideal depth range of 1–2 km for storage cavities in salt as cavities located much deeper than 2 km are subject to compressional

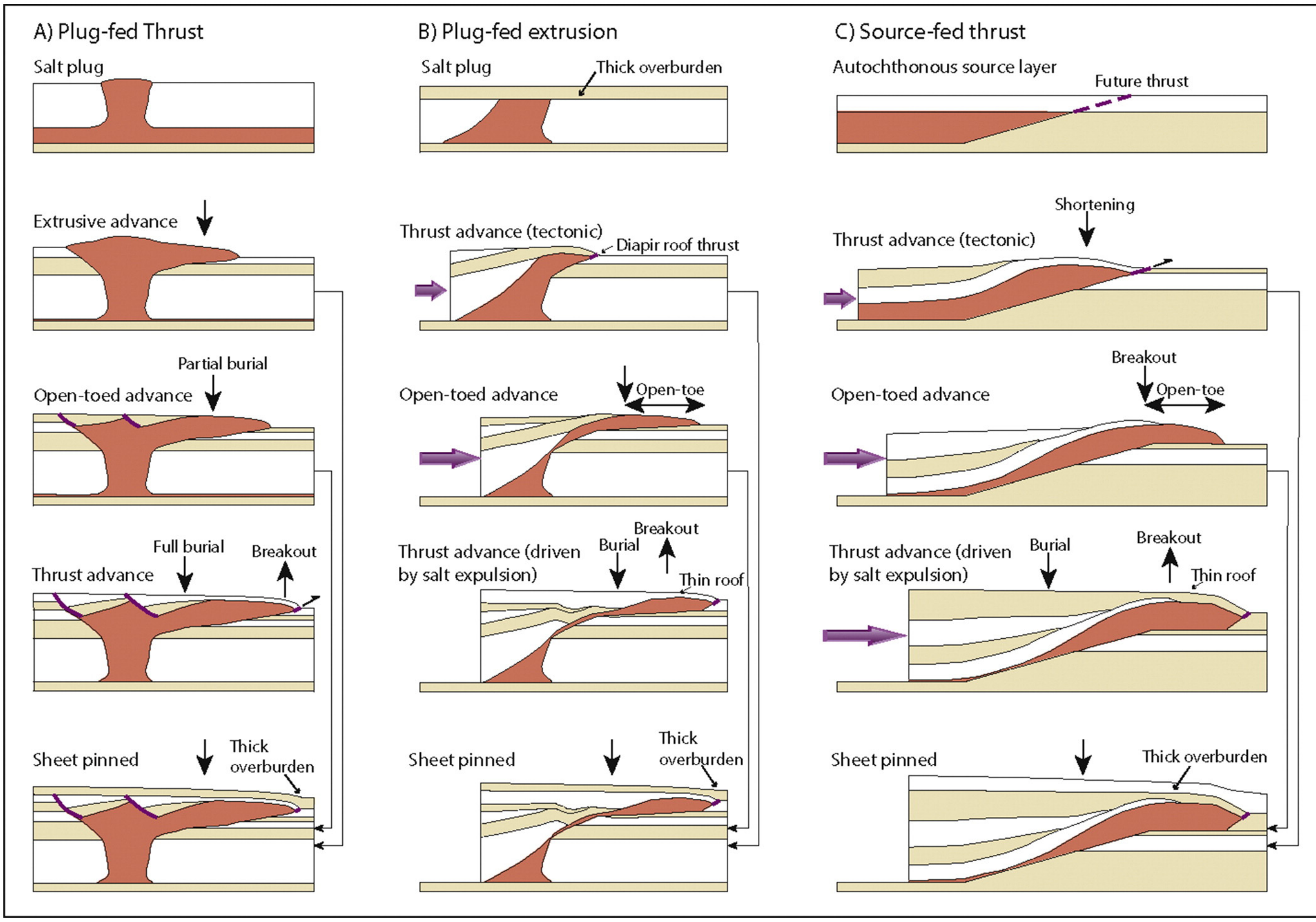

Fig. 36. Emplacement of salt sheets (allochthons; after Hudec and Jackson, 2006). Most salt sheets advance by a time-related sequence of extrusion, open-toed advance, and thrusting. These modes may combine in many ways over the life span of a salt sheet, but three evolutionary sequences (or lineages) are particularly common. (a) Plug-fed extrusions. (b) Plug-fed thrusts, and (c) Source-fed thrusts (see also Fig. 37a for detail on basal shear).

closure or salt creep during the active life of the cavity (active = time of waste emplacement into the cavity). Cavities shallower than 1 km are subject to the effects of deep phreatic circulation. Salt-creep-induced partial cavity closure, in a salt diapir host, plagued the initial stages of use of the purpose-built gas storage cavity known as Eminence in Mississippi. In the early 1970s, this cavity was subject to a creep-induced reduction in cavity volume until gas storage pressures were increased and the cavern shape re-stabilized. Cavities in salt shallower than 1 km are likely to be located in salt intervals that at times have been altered by cross flows of deeply-circulating meteoric (telogenetic) or marine-derived phreatic waters. Problematic natural percolation or leakage zones (aka anomalous salt zones), which can occur in some places in salt masses in the 1–2 km depth range, are usually tied to varying combinations of salt thinning, salt dissolution or intersection with unexpected regions of impure salt (relative aquifers).

In addition to such natural process sets, cross-salt leakage can be related to local zones of mechanical damage, tied to processes involved in excavating a mine shaft, or in the drilling and casing of wells used to create a purpose-built salt-solution cavity. Many potential areas of leakage in existing mines or brine wells are the result of poorly completed or maintained access wells, or intersections with zones of "dark salt," or with proximity to a thinned salt cavity wall in a diapir, as detailed in various case studies in Chapters 7 and 13 in Warren, 2016.

In my opinion, the history of salt ore extraction is typified by intersections with leakage zones during the life of most of the world's existing salt mines. This means conventional mine cavities in salt are probably not appropriate sites for long-term hydrocarbon or waste storage. There are simply too many potential leakage zones present in any accessible salt mine. Existing salt mines were not designed for fluid or waste storage, but to extract salt or potash, with mining operations often continuing in a particular direction along an ore seam until the edge of the salt was approached or even intersected. When high fluid transmission zones were unexpectedly intersected during the lifetime of a salt mine, two things happened; 1) the mine flooded and operations ceased, or the flooded mine was converted to a brine extraction facility (Patience Lake) or, 2) the zone of leakage was successfully grouted and in the short term (tens of years) mining continued (Warren, 2016).

For example, in the period 1906 to 1988, when Asse II was an operational salt mine in Germany, there were 29 documented water breaches that were grouted or retreated from. Over the long term, these same water-entry driven dissolution zones indicate a set of natural seep processes that continue behind the grout job. This is true in any salt mine that has come "out of the salt," and outside fluid has leaked into the mine. "Out-of-salt" intersections are typically related to fluids entering the salt mass via dark-salt or brecciated zones or shale sheath intersections.

I distinguish such "out-of-salt" fluid intersections from mesogenetic "in-salt" fluid-filled cavities. When the latter is cut, entrained fluids drain into the mine and then flow stops. Such intersections can be dangerous during the operation of a mine as there is often nitrogen, methane or CO_2 in an "in-the-salt" cavity, so there is potential for

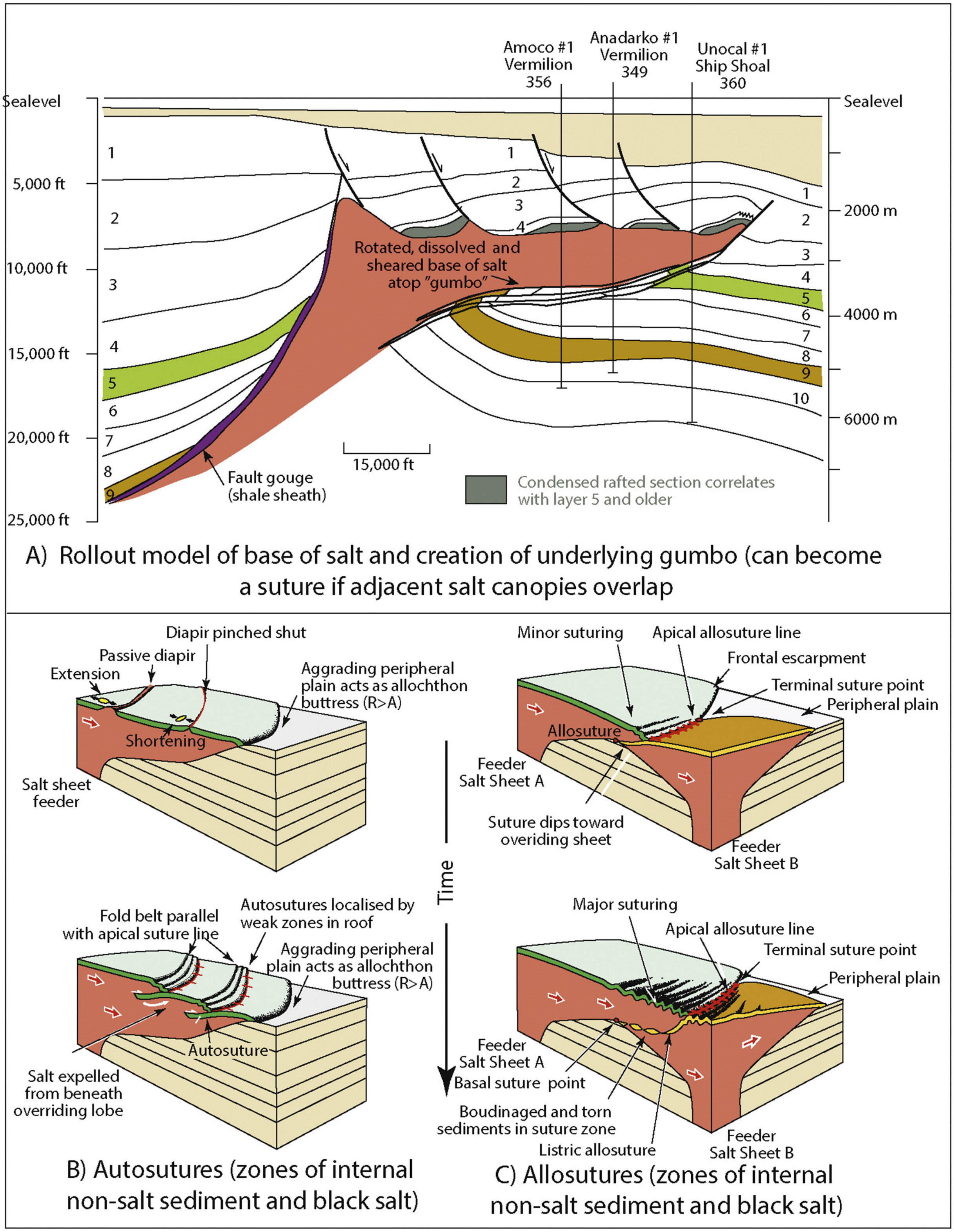

Fig. 37. Geological settings that can create "leaky" base of salt or intrasalt sediment sutures. A) Cross section view of salt allochthon with a basal thrust fault defining the rising compressional nose of the salt sheet. Relevant Gulf of Mexico wells are placed schematically on this section (after Harrison and Patton (1995). B) Autosutures: the roof of a salt sheet shortens where sheet advance is buttressed by peripheral plain or by another salt sheet. Overriding autosutures may initiate at any zone of weakness in the roof, especially pre-existing reactive diapirs formed by previous stretching as the salt sheet spreads. As it is overridden from the rear, the front of the roof depressed into the salt. C) Asymmetric allosutures. As one salt sheet overrides the other, sediments in the suture are depressed, stretched, and dismembered to form boudins in the salt. These sediments eventually tear off from the basal suture line (B and C after Dooley et al., 2012). Compare with Fig. 14b.

explosion and fatalities. But, in terms of long-term and ongoing fluid leakage, "in-salt" cavities are not a problem with respect to longterm waste storage.

Ultimately, because "out-of-salt" fluid intersections are part of the working life of any salt mine, seal integrity in any mine converted to a storage facility will fail. Such failures are evidenced by current water

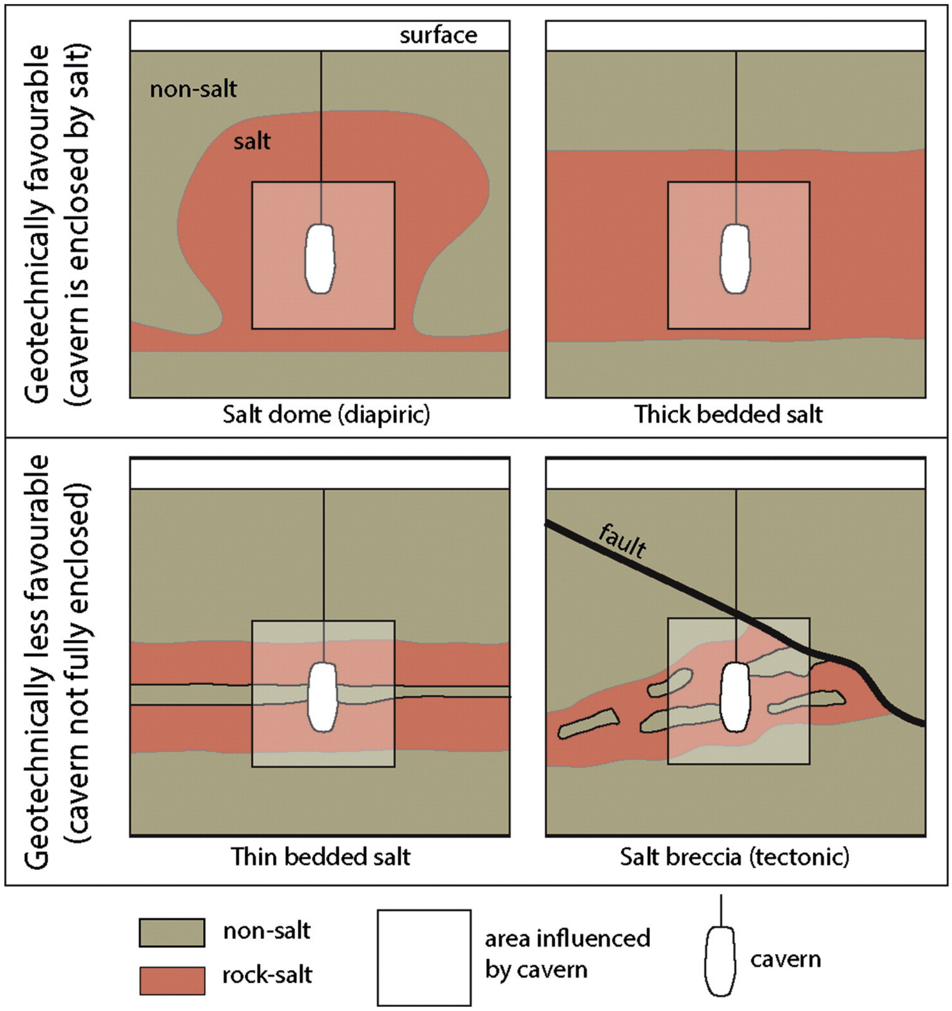

Fig. 38. Fig. 20. Schematic summarising geotechnically favourable and less favourable scenarios for mines and storage caverns in salt (after Gillhaus, 2010; Warren, 2016). Figure is not to scale. Ideally, a storage cavity or mine working should not intersect a salt anomaly and be located well away from the edge of a salt unit or any penetrative aquifer system in the target salt.

entry problems in Asse II Mine, Germany (utilised for low-medium level radioactive waste storage) and the removal of the oil formerly stored in the Weeks Island strategic hydrocarbon facility, Texas. Weeks Island was a salt mine converted to oil storage.

Worldwide, the biggest problem with converting any existing salt mine to a low to medium level nuclear waste storage facility is that all salt mines are relatively shallow, with operating mine depth controlled by temperatures where humans can work (typically 300–700 m and always < 1.1 km). This relatively shallow depth range, especially at depths above 500–600 m, is also where slowly-circulating subsurface or phreatic waters are dissolving halite to varying degrees. This is where fluids can enter the salt from outside and so create problematic dark-salt and collapse breccia zones within the salt. In the long-term (hundreds to thousands of years) these same fluid access regions have the potential to allow a portion of stored waste fluids to escape the salt mass.

Another potential problem with long-term waste storage in many salt mines, and in some salt cavity hydrocarbon storage facilities excavated in bedded (non-diapiric) salt, is the limited thickness of a halite beds across the depth range of such conventional salt mines and storage facilities. Worldwide, bedded ancient salt tends to be either lacustrine or intracratonic, and individual halite units are no >10–50 m thick in stacks of various saline lithologies. That is, intracratonic halite is usually interlayered with laterally extensive carbonate, anhydrite or shale beds, that together pile into bedded saline successions up to a few hundred meters thick (Warren, 2010). The non-halite interlayers may act as potential long-term intrasalt aquifers, especially if connected to non-salt sediments outside the halite (Fig. 38). This applies in particular if the non-salt beds remain intact and hydraulically connected to up-dip or down-dip zones where the encasing halite is dissolutionally thinned or lost. Connection to such a dolomite bed above the main salt bed, in combination with damaged casing in an access well, explains the Hutchison gas explosion (Chapter 13, Warren, 2016). Also, if there is significant local heating associated with longer term nuclear waste storage in such relatively thin (< 10–50 m) salt beds, then percolation, related to heat-induced dihedral angle changes, may also become relevant over the long-term (tens of thousands of years), even in bedded storage facilities in 1–2 km depth range.

10. Implications

Creating a purpose-built mine for the storage of low-level nuclear waste in a salt diapir within the appropriate depth range of 1–2 km is the preferred approach and a much safer option, compared to the conversion of existing salt mines in diapiric salt, but is likely to be prohibitively expensive. To minimize the potential of unwanted fluid ingress, the mine entry shaft should be vertical, not inclined. The freeze-stabilized "best practice" vertical shaft currently being constructed by BHP in Canada for its new Jansen potash mine (bedded salt) is expected to cost more than $1.3 billion. If a purpose-built mine storage facility were to be constructed for low to medium level waste storage in a salt diapir, then the facility should operate a depth of 800–1000 m, freeze-stabilized, and avoid zones of salt anomalies (salt "horses"). Ideally, such a purpose-built mine should also be located hundreds of meters away from the edges of salt mass in a region that is not part of an area of older historical salt extraction operations. At current costings, such a conventionally-mined purpose-built storage facility for low to medium level radioactive waste is not economically feasible.

In terms of higher-level nuclear waste disposal, the propensity for leakage in a conventional mine over time frames of tens of thousands of years leaves only purpose-built salt-solution cavities constructed well within the interior of thick salt domes, at depths of 1–2 km. Such purpose-built cavities should be; 1) located well away from the salt edge, as this will be experiencing natural dissolution, and 2) should be located in zones with no nearby pre-existing brine-extraction cavities or oil-field exploration wells. This precludes much of the onshore salt diapir provinces of Europe and North America as repositories for high-level nuclear waste. In addition, many of the possible sites in Europe and the USA are located beneath high population areas that can have century-long histories of poorly documented salt and brine extraction or salt intersection by petroleum wells. Contingency planning and staying "in-the-salt" over the long-term would be an ongoing problem in these regions.

The ideal site for long-term storage of high-level nuclear waste in a salt-encased cavity would be located in an arid area (minimal phreatic cross flow) with low levels of human population, underlain by kilometers-thick salt masses that are as yet undisturbed by anthropogenic activities.

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References

Anderson, E.J., 1981. Deep-seated salt dissolution in the Delaware Basin, Texas and New Mexico. In: Wells, S.G., Lamber, W., Callender, J.F. (Eds.), Environmental Geology and Hydrology in New Mexico: Special Publication Vol. 10. New Mexico Geological Society, pp. 133–145.

Andresen, K.J., Huuse, M., Schodt, N.H., Clausen, L.F., Seidler, L., 2011. Hydrocarbon plumbing systems of salt minibasins offshore Angola revealed by three-dimensional seismic analysis. Am. Assoc. Pet. Geol. Bull. 95, 1039–1065.

Autin, W.J., 1984. Geologic significance of land subsidence at Jefferson Island, Louisiana. Trans. Gulf. Coast. Assoc. Geol. Soc. 34, 293–309.

Autin, W.J., 2002. Landscape evolution of the Five Islands of south Louisiana: scientific policy and salt dome utilization and management. Geomorphology 47, 227–244.

Baar, C.A., 1974. Geological problems in Saskatchewan potash mining due to peculiar conditions during deposition of Potash Beds. In: Coogan, A.H. (Ed.), Fourth Symposium on Salt Vol. 1. North Ohio Geological Society, Cleveland, Ohio, pp. 101–118.

Balk, R., 1953. Salt structure of Jefferson Island Salt Dome, Iberia and Vermilion Parishes, Louisiana. Bull. Am. Assoc. Pet. Geol. 37, 2455–2474.

Beauheim, R.L., Roberts, R.M., 2002. Hydrology and hydraulic properties of a bedded evaporite formation. J. Hydrol. 259, 66–88.

Beckman, J., 1999. Study reveals overpressure sources in deep-lying formations. Oil Gas J. 137 (September).

Borchert, H., Muir, R.O., 1964. Salt Deposits–The Origin, Metamorphism and Deformation of Evaporites. London, D. Van Nostrand Co., Ltd. (338 pp.).

Bowman, S.A., 2011. Regional seismic interpretation of the hydrocarbon prospectivity of offshore Syria. GeoArabia 16, 95–124.

Boys, C., 1990. The Geology of Potash Deposits at PCS Cory Mine, Saskatchewan. (Master's thesis). University of Saskatchewan, Saskatoon, SK; Canada (225 pp.).

Boys, C., 1993. A geological approach to potash mining problems in Saskatchewan, Canada. Explor. Min. Geol. 2, 129–138.

Braitsch, O., 1971. Salt Deposits: Their Origin and Compositions. Springer-Verlag, New York (297 pp.).

Cartwright, J., Huuse, M., Aplin, A., 2007. Seal bypass systems. Am. Assoc. Pet. Geol. Bull. 91, 1141–1166.

Casas, E., Lowenstein, T.K., 1989. Diagenesis of saline pan halite; comparison of petrographic features of modern, quaternary and Permian halites. J. Sediment. Petrol. 59, 724–739.

Cendon, D.I., Ayora, C., Pueyo, J.P., 1998. The origin of barren bodies in the Subiza potash deposit, Navarra, Spain - implications for sylvite formation. J. Sediment. Res. A Sediment. Petrol. Process. 68, 43–52.

Choquette, P.W., Pray, L.C., 1970. Geologic nomenclature and classification of porosity in sedimentary carbonates. Bull. Am. Assoc. Pet. Geol. 54, 207–250.

Closson, D., LaMoreaux, P., Abou Karaki, N., al-Fugha, H., 2007. Karst system developed in salt layers of the Lisan Peninsula, Dead Sea, Jordan. Environ. Geol. 52, 155–172.

Coode, A.M., Strathdee, G., 1993. Mining research development and application in the Saskatchewan potash industry. In: Bawden, W., Archibald, J.F. (Eds.), Innovative Mine Design for the 21st Century: Proceedings of the International Congress on Mine Design. Balkema, Rotterdam, pp. 949–957.

Davison, I., 2009. Faulting and fluid flow through salt. J. Geol. Soc. 166, 205–216.

De Souza, E.M., 1998. Ground Control, Brine Inflow Arrest and Backfill Design in the Search for New Mining Strategies for the Potash Industry. (Doctoral thesis). Queen's University, Canada (514 pp.).

Dean, W.E., 1978. Theoretical versus observed successions from evaporation of seawater. In: Dean, W.E., Schreiber, B.C. (Eds.), Marine Evaporites. Tulsa, OK, Soc. Econ. Paleontol. Mineral., Short Course Notes vol. 4, pp. 74–85.

Desbois, G., Urai, J., Kukla, P., Wollenberg, U., Pérez-Willard, F.n., Radí, Z., Riholm, S., 2012. Distribution of brine in grain boundaries during static recrystallization in wet, synthetic halite: insight from broad ion beam sectioning and SEM observation at cryogenic temperature. Contrib. Mineral. Petrol. 163, 19–31.

Dewing, K., Obermajer, M., 2009. Lower Paleozoic Thermal Maturity and Hydrocarbon Potential of the Canadian Arctic Archipelago. Bull. Can. Petrol. Geol. 57, 141–166.

Dooley, T.P., Hudec, M.R., Jackson, M.P.A., 2012. The structure and evolution of sutures in allochthonous salt. Bull. Am. Assoc. Pet. Geol. 96, 1045–1070.

Ehgartner, B.L., Neal, J.T., Hinkebein, T.E., 1998. Gas releases from salt. Report SAND98-1354, Sandia National Laboratories, Albuquerque, NM, June 1998.

Fertl, W.H., 1976. Abnormal Formation Pressures. Elsevier Scientific, Amsterdam (382 pp.).

Ford, D., Williams, P.D., 2007. Karst Hydrology and Geomorphology. John Wiley and Sons, Ltd, New York (562 pp.).

Gendzwill, D., Martin, N., 1996. Flooding and loss of the Patience Lake potash mine. CIM Bull. 89, 62–73.

Gendzwill, D.J., Wilson, N.L., 1987. Form and distribution of Winnipegosis mounds in Saskatchewan. In: Peterson, J.A., Kent, D.M., Anderson, S.B., Pilatzke, R.H., Longman, M.W. (Eds.), Williston Basin; Anatomy of a Cratonic Oil Province vol. 118.

Ghanbarzadeh, S., Hesse, M.A., Prodanović, M., Gardner, J.E., 2015. Deformation-assisted fluid percolation in rock salt. Science 350, 1069–1072.

Gillhaus, A., 2010. Natural gas storage in salt caverns - Summary of worldwide projects and consequences of varying storage objectives and salt formations. In: Zou, Z.H., Xie, H., Yoon, E. (Eds.), Underground Storage of CO_2 and Energy. CRC Press, Boca Raton, Fl, pp. 191–198.

Goldman, M.I., 1933. Origin of the anhydrite caprock of American salt domes. US Geol. Surv. Prof. Pap. 175, 83–114.

Graham, B., Reilly, W.K., Beinecke, F., Boesch, D.F., Garcia, T.D., Murray, C.A., Ulmer, F., 2011. Deep Water; The Gulf Oil Disaster and the Future of Offshore Drilling; Report to the President, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, January 2011.

Gwynn, J.W., 1984. Mining conditions and problems encountered within the TexasGulf-Cane Creek potash Mine near Moab, Utah: and potential mining conditions at Gibson Dome, Utah. Utah Geological and Mineral Survey Report of Investigation, No. 184 (12 pp.).

Hanna, M.A., 1930. Secondary salt-dome materials of coastal plain of Texas and Louisiana. Bull. Am. Assoc. Pet. Geol. 14, 1469–1475.

Harrison, H., Patton, B., 1995. Translation of salt sheets by basal shear: Proceedings of GCCSEPM Foundation 16th Annual Research Conference. Salt Sediment and Hydrocarbons, pp. 99–107 (Dec 3-6).

Harrison, H., Moore, D.C., Hodgkins, P., 2010. A geologic review of the Mahogany Subsalt Discovery: a well that proved a play (The Mahogany Subsalt Discovery: a unique hydrocarbon play, Offshore Louisiana). Search and Discovery Article #60049 Posted April 28, 2010, Adapted from Presentation at AAPG Annual Convention, 1995, and from an Extended Abstract Prepared for Presentation at GCSSEPM Foundation 16th Annual Research Conference, "Salt, Sediment and Hydrocarbons," December 3–6, 1995.

Harville, D.G., Fritz, S.J., 1986. Modes of diagenesis responsible for observed successions of potash evaporites in the Salado Formation, Delaware Basin, New Mexico. J. Sediment. Petrol. 56, 648–656.

Hite, R.J., Anders, D.E., 1991. Petroleum and evaporites. In: Melvin, J.L. (Ed.), Evaporites, Petroleum and Mineral Resources. Developments in Sedimentology vol. 50. Elsevier, Amsterdam, pp. 477–533.

Hite, R.J., Anders, D.E., Jing, T.G., 1984. Organic-rich source rocks of Pennsylvanian age in the Paradox Basin of Utah and Colorado. In: Woodward, J., Meissner, F.F., Clayton, J.L. (Eds.), Hydrocarbon Source Rocks of the Greater Rocky Mountain Region. Rocky Mountain Assoc. Geologists, Denver, pp. 255–274.

Hobbs, B., Ord, A., 2015. Structural Geology: The Mechanics of Deforming Metamorphic Rocks. Principles vol. 1. Elsevier, New York (656 pp.).

Holness, M.B., Lewis, S., 1997. The structure of the halite-brine interface inferred from pressure and temperature variations of equilibrium dihedral angles in the halite-H_2O-CO_2 system. Geochim. Cosmochim. Acta 61, 795–804.

Holt, R.M., Powers, D.W., 2011. Synsedimentary dissolution pipes and the isolation of ancient bacteria and cellulose. Geol. Soc. Am. Bull. 123, 1513–1523.

Hovorka, S.D., Holt, R.M., Powers, D.W., 2007. Depth indicators in Permian Basin evaporites. Geol. Soc. Lond., Spec. Publ. 285, 335–364.

Hudec, M.R., Jackson, M.P.A., 2006. Advance of allochthonous salt sheets in passive margins and orogens. Am. Assoc. Pet. Geol. Bull. 90, 1535–1564.

Hudec, M.R., Jackson, M.P.A., 2007. Terra Infirma: understanding salt tectonics. Earth Sci. Rev. 82, 1–28.

Hunt, J.M., 1990. Generation and migration of petroleum from abnormally pressured fluid compartments. Bull. Am. Assoc. Pet. Geol. 74, 1–12.

Hunt, J.M., Whelan, J.K., Eglinton, L.B., Cathles III, L.M., 1998. Relation of shale porosities, gas generation, and compaction to deep overpressures in the US Gulf Coast. In: Law, B.E., Ulmishek, G.F., Slavin, V.I. (Eds.), Abnormal Pressures in Hydrocarbon EnvironmentsMemoir Vol. 70. American Association Petroleum Geologists, Tulsa, OK, pp. 87–104.

Jackson, C.A.L., Lewis, M.M., 2012. Origin of an anhydrite sheath encircling a salt diapir and implications for the seismic imaging of steep-sided salt structures, Egersund Basin, Northern North Sea. J. Geol. Soc. 169, 593–599.
Johnson, K., 2008. Gypsum-karst problems in constructing dams in the USA. Environ. Geol. 53, 945–950.
Kettanah, Y.A., 2013. Hydrocarbon fluid inclusions in the Argo salt, offshore Canadian Atlantic margin. Can. J. Earth Sci. 50, 607–635.
Kukla, P., Urai, J., Warren, J.K., Reuning, L., Becker, S., Schoenherr, J., Mohr, M., van Gent, H., Abe, S., Li, S., Desbois, G., Schléder, Z., de Keijzer, M., 2011a. An integrated, multi-scale approach to salt dynamics and internal dynamics of salt structures. AAPG Search and DiscoveryArticle #40703 (2011).
Kukla, P.A., Reuning, L., Becker, S., Urai, J.L., Schoenherr, J., 2011b. Distribution and mechanisms of overpressure generation and deflation in the late Neoproterozoic to early Cambrian South Oman Salt Basin. Geofluids 11, 349–361.
Kupfer, D.H., 1974. Boundary shear zones in salt stocks. Fourth Symposium on Salt. Northern Ohio Geological Survey vol. 1, pp. 215–225.
Kupfer, D.H., 1976. Shear zones inside Gulf Coast salt stocks help to delineate spines of movement. Bull. Am. Assoc. Pet. Geol. 60, 1434–1447.
Kupfer, D.H., 1980. Problems associated with anomalous zones in Louisiana salt stocks, USA. In: Coogan, A.H., Lukas, H. (Eds.), Fifth Symposium on Salt (Hamburg, Germany, June 1978) vol. 1. Northern Ohio Geological Society, Cleveland OH, pp. 119–134.
Kupfer, D.H., 1990. Anomalous features in the Five Islands salt stocks, Louisiana. Trans. Gulf. Coast. Assoc. Geol. Soc. 40, 425–437.
Kupfer, D.H., Lock, B.E., Schank, P.R., 1998. Anomalous zones within the salt at Weeks Island, Louisiana. Trans. Gulf. Coast. Assoc. Geol. Soc. 48, 181–191.
Leitner, C., Neubauer, F., Urai, J.L., Schoenherr, J., 2011. Structure and evolution of a rocksalt-mudrock-tectonite: the haselgebirge in the northern calcareous alps. J. Struct. Geol. 33, 970–984.
Lewis, S., Holness, M., 1996. Equilibrium halite-H_2O dihedral angles: high rock salt permeability in the shallow crust. Geology 24, 431–434.
Linn, K.O., Adams, S.S., 1966. Barren halite zones in potash deposits, Carlsbad, New Mexico. Second Symposium on Salt, pp. 59–68.
Lock, B.E. (Ed.), 2000. Geologic mapping of salt mines in salt diapirs: approaches and examples from South LouisianaTrans. Gulf. Coast. Assoc. Geol. Soc. 50, 567–582.
Looff, K.M., 2000. Geologic and microstructural evidence of differential salt movement at Weeks Island Salt Dome, Iberia Parish, Louisiana. Trans. Gulf. Coast. Assoc. Geol. Soc. 50, 543–555.
Looff, K.M., Rautman, C., 2010. Salt spines, boundary shear zones and anomalous salts: Their characteristics, detection and influence on salt dome storage caverns. Paper Presented at Solution Mining Research Institute Spring 2010 Technical Conference, Grand Junction, Colorado, USA, 26–27 April 2010 (23 pp.).
Looff, K.M., Looff, K.M., Rautman, C., 2010. Salt spines, boundary shear zones and anomalous salts: Their characteristics, detection and influence on salt dome storage caverns. Paper presented at Solution Mining Research Institute Spring 2010 Technical Conference, Grand Junction, Colorado, USA, 26-27 April 2010 (23 pp.).
Macgregor, D.S., 1996. Factors controlling the destruction or preservation of giant light oil fields. Pet. Geosci. 2, 197–217.
Mackintosh, A.D., McVittie, G.A., 1983. Geological anomalies observed at the Cominco Ltd. Saskatchewan potash mine. Potash '83; Potash Technology; Mining, Processing, Maintenance, Transportation, Occupational Health and Safety, Environment, pp. 59–64.
Martinez, J.D., Johnson, K.S., Neal, J.T., 1998. Sinkholes in evaporite rocks. Am. Sci. 86, 38.
McIntosh, R.A., Wardlaw, N.C., 1968. Barren halite bodies in the sylvinite mining zone at Esterhazy, Saskatchewan. Can. J. Earth Sci. 5, 1221–1238.
Mohr, M., Warren, J.K., Kukla, P.A., Urai, J.L., Irmen, A., 2007. Subsurface seismic record of salt glaciers in an extensional intracontinental setting (Late Triassic of northwestern Germany). Geology 35, 963–966.
Molecke, M.A., 2000. Final state of the Strategic Petroleum Reserve (SPR) Weeks Island Mine Washington, D.C. United States. Dept. of Energy; Oak Ridge, Tenn.: Distributed by the Office of Scientific and Technical Information, U.S. Dept. of Energy, 2000 (56 pp.).
Muehlberger, W.R., Clabaugh, P.S., 1968. Internal structure and petrofabrics of Gulf Coast salt domes. AAPG Mem. 8, 90–98.
Neal, J.T., 1994. Surface features indicative of subsurface evaporite dissolution. Implications for Storage and Mining: Solution Mining Research Institute, Meeting Paper, 1994 Spring Meeting, Houston Texas.
Neal, J.T., 1995. Supai salt karst features: Holbrook Basin, Arizona. In: Beck, B.F. (Ed.), Karst Geohazards: Engineering and Environmental Problems in Karst Terrane. Proc. 5th Conference, Gatlinburg 1995, Balkema, pp. 53–59.
Neal, J.T., Myers, R.E., 1995. Salt dissolution sinkhole at the Weeks Island, Louisiana, strategic petroleum reserve storage site. In: Beck, B.F. (Ed.), Karst Geohazards: Engineering and Environmental Problems in Karst Terrane. Proc. 5th Conference, Gatlinburg 1995, Balkema, pp. 61–65.
Neal, J.T., Bauer, S.J., Ehgartne, B.L., 1995. Sinkhole progression at the Weeks Island, Louisiana, Strategic Petroleum Reserve (SPR) Site. Solution Mining Research Institute, Fall Meeting, San Antonio, Texas, October 1995. Sandia National Laboratories, Albuquerque, NM.
Neal, J.T., Ballard, S., Bauer, S.J., Ehgartner, B.L., Hinkebein, T.E., Hoffman, E.L., Linn, J.K., Molecke, M.A., Sattler, A.R., 1997. Mine-induced sinkholes over the U.S. Strategic Petroleum Reserve (SPR) storage facility at Weeks Island, Louisiana: geologic mitigation prior to and during decommissioning, SAND96-2387A. Presented at 6th Multidisciplinary Conference on Sinkholes and the Engineering & Environmental Impacts of Karst, Springfield, Missouri, April 6–9, 1997. Sandia National Laboratories, Albuquerque, NM.
Nof, R.N., Baer, G., Ziv, A., Raz, E., Atzori, S., Salvi, S., 2013. Sinkhole precursors along the Dead Sea, Israel, revealed by SAR interferometry. Geology 41, 1019–1022.
O'Brien, J., Lerche, I., 1994. Understanding subsalt overpressure may reduce drilling risks. Oil Gas J. 92, 28–29 (32-34).
Paine, W.R., Mitchell, M.W., Copeland Jr., R.R., Gimbrede, L.d.A., 1965. Frio and Anahuac sediment inclusions, Belle Isle Salt Dome, St. Mary Parish, Louisiana. Am. Assoc. Pet. Geol. Bull. 49, 616–620.
Peach, C., Spiers, C.J., 1996. Influence of crystal plastic deformation on dilatancy and permeability development in synthetic salt rock. Tectonophysics 256, 101–128.
Plimpton, H.G., Foster, R.K., Risbeck, J.S., Rutherford, R.P., King, R.F., Buffington, G.L., Traweek, W.C., 1980. Final report of mine explosion disaster Belle Isle Mine Cargill, Inc. Franklin, St. Mary Parish, Louisiana June 8, 1979. Dept. of Labor, Mine Safety and Health Administration, Report No. MINE ID 1600246 (135 pp.).
Popp, T., Kern, H., Schulze, O., 2001. Evolution of dilatancy and permeability in rock salt during hydrostatic compaction and triaxial deformation. J. Geophys. Res. B: Solid Earth 106, 4061–4078.
Prugger, F.F., Prugger, A.F., 1991. Water problems in Saskatchewan potash mining–what can be learned from them? CIM Bull. 84, 58–66.
Schenk, O., Urai, J.L., 2004. Microstructural evolution and grain boundary structure during static recrystallization in synthetic polycrystals of sodium chloride containing saturated brine. Contrib. Mineral. Petrol. 146, 671–682.
Schoenherr, J., Littke, R., Urai, J.L., Kukla, P.A., Rawahi, Z., 2007a. Polyphase thermal evolution in the Infra-Cambrian Ara Group (South Oman Salt Basin) as deduced by maturity of solid reservoir bitumen. Org. Geochem. 38, 1293–1318.
Schoenherr, J., Urai, J.L., Kukla, P.A., Littke, R., Schleder, Z., Larroque, J.-M., Newall, M.J., Al-Abry, N., Al-Siyabi, H.A., Rawahi, Z., 2007b. Limits to the sealing capacity of rock salt: a case study of the infra-Cambrian Ara Salt from the South Oman salt basin. Bull. Am. Assoc. Pet. Geol. 91, 1541–1557.
Schofield, N., Alsop, I., Warren, J., Underhill, J.R., Lehné, R., Beer, W., Lukas, V., 2014. Mobilizing salt: magma-salt interactions. Geology 42, 599–602.
Schulze, O., Popp, T., Kern, H., 2001. Development of damage and permeability in deforming rock salt. Eng. Geol. 61, 163–180.
Shaker, S., 2008. The double edged sword: the impact of the interaction between salt and sediment on subsalt exploration risk in deep water. Trans. Gulf. Coast. Assoc. Geol. Soc. (v.).
Talbot, C.J., Stanley, W., Soub, R., Alsadoun, N., 1996. Epitaxial salt reefs and mushrooms in the southern Dead Sea. Sedimentology 43, 1025–1047.
Ter Heege, J.H., De Bresser, J.H.P., Spiers, C.J., 2005. Dynamic recrystallization of wet synthetic polycrystalline halite: dependence of grain size distribution on flow stress, temperature and strain. Tectonophysics 396, 35–57.
Thrasher, J., Fleet, A.J., Hay, S.J., Hovland, M., Düppenbecker, S., 1996. Understanding geology as the key to using seepage in exploration: spectrum of seepage styles. In: Schumacher, D., Abrams, M.A. (Eds.), Hydrocarbon migration and its near-surface expression. AAPG Memoir vol. 66, pp. 223–241.
Urai, J.L., Schléder, Z., Spiers, C.J., Kukla, P.A., 2008. Flow and transport properties of salt rocks. In: Littke, R. (Ed.), Dynamics of Complex Intracontinental Basins: The Central European Basin System. Elsevier, pp. 277–290.
Walden, W., Jacoby, C.H., 1963. Exploration by horizontal drilling at Avery Island, Louisiana. In: Bersticker, A.C. (Ed.), Symposium on Salt (First). Northern Ohio Geo-logical Society, Cleveland, OH, pp. 367–376.
Waltham, T., Bell, F., Culshaw, M., 2005. Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction. Springer Praxis Books, Berlin Heidelberg (382 pp.).
Warren, J.K., 1986. Shallow water evaporitic environments and their source rock potential. J. Sediment. Petrol. 56, 442–454.
Warren, J.K., 2008. Salt as sediment in the Central European Basin system as seen from a deep time perspective (Chapter 5.1). In: Littke, R. (Ed.), Dynamics of Complex Intracontinental Basins: The Central European Basin System. Springer-Verlag, Berlin-Heidelberg, pp. 249–276.
Warren, J.K., 2010. Evaporites through time: tectonic, climatic and eustatic controls in marine and nonmarine deposits. Earth Sci. Rev. 98, 217–268.
Warren, J.K., 2011. Evaporitic source rocks: mesohaline responses to cycles of "famine or feast" in layered brines. Doug Shearman Memorial VolumeIAS Special Publication Number 43. Wiley-Blackwell, pp. 315–392.
Warren, J.K., 2016. Evaporites: A Compendium (ISBN 978-3-319-13511-3). Springer, Berlin (1854 pp.).
Woods, P.J.E., 1979. The geology of Boulby mine. Econ. Geol. 74, 409–418.
Závada, P., Desbois, G., Urai, J.L., Schulmann, K., Rahmati, M., Lexa, O., Wollenberg, U., 2015. Impact of solid second phases on deformation mechanisms of naturally deformed salt rocks (Kuh-e-Namak, Dashti, Iran) and rheological stratification of the Hormuz Salt Formation. J. Struct. Geol. 74, 117–144.
Zimmermann, J.L., Moretto, R., 1996. Release of water and gases from halite crystals. Eur. J. Mineral. 8, 413–422.