Salty Matters

John Warren -Saturday March 12, 2016

Salt as a Fluid Seal
Article 3
Salt is an excellent subsurface seal

This, the third article in the series of four on salt leakage, discusses how and when salt acts as a seal. The fourth article will place this discussion in real world situations where the various salt units (especially "dark" salt) have lost long-term seal integrity and what this means in terms of CO_2 geosequestration and waste storage.

Evaporite seal character

Unlike thick shales, subsurface evaporites in the diagenetic realm better fit Hunt's (1990) definition of an actual pressure seal, which he defined as an impermeable rock with zero transmissivity maintained over long periods of geologic time. Very little subsalt fluid can escape through a salt mass that, until breached, tends to hold back all the compactional and thermohaline waters, gases or liquid hydrocarbons rising from below. In contrast, shale-seals consistently leak all these fluids to varying degrees.

In the realm of subsurface hydrocarbon exploration and development, salts (especially halite) are second only to clathrates in ability to form an effective seal to circulating pore waters and hydrocarbons, including methane. (Figure 1; Warren, 2016). Natural methane clathrates (methane-ice mixtures) are more efficient seals, but in the diagenetic realm, clathrate occurrence is limited by the inherent low-temperature stability requirement. This means clathrates act as hydrocarbon seals onshore in permafrost regions, such as some Siberian gas fields, or below clathrate layers down to depths of a hundred meters or so beneath the modern deep-sea floor, as occurs below the cold waters of the slope and rise across the halokinetic Gulf of Mexico or the non-halokinetic sediment of offshore Brunei (Warren, 2016; Warren et al., 2011a).

Like clathrates, evaporite layers can generate overpressures at very shallow burial depths, unlike clathrates they do not dissolve and dissipate in response to rising temperatures of the diagenetic burial realm. Evaporites create the highest and sharpest depth-related pressure differentials known in sedimentary basins in both overpressured and underpressured settings (Fertl 1976). Salt-sealed overpressured intervals can be as shallow as a few hundred meters below the surface or deeper than 6,000 m.

Unlike the low temperatures requirements for a clathrate seal, evaporite seals, with their extremely high entry pressures, ductility, very low permeabilities and large lateral extents, can maintain seal integrity over wide areas, even when exposed to a wide range of subsurface temperature and pressure conditions. A typical shale seal has permeability ≈ 10^{-1} to 10^{-5} md, with extreme values as low as 10^{-8} md (Figure 2). Quantitative measurement of evaporite permeability is beyond the capacity of standard instruments used in the oil industry and is mostly a topic of study for engineers working with waste-storage caverns. Their work shows the permeability of undisturbed halite is a nanodarcy or less, that is, undamaged subsurface salt has measured permeabilities that are less than 10^{-21} m^2 (10^{-6}md) with some of the tighter halite permeabilities ≈10^{-7} to 10^{-9} md. In contrast, typical massive anhydrites ≈10^{-5} md (Beauheim and Roberts, 2002). This explains 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 and anhydrite bed should be at least 10 m thick. Equally important is the reliability of the geological model of the evaporite that is used to extrapolate lateral continuity in the seal (Warren, 2016). Pore pressures in thick sealing halites can approach lithostatic (Ehgartner et al., 1998) and when exceeded salt can locally fracture and leak (as discussed in the previous article).

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 x 10^{-10} m, while the smallest molecular diameter of a hydrocarbon molecule (methane) is 3.8 x 10^{-10} m. The most frequent way that hydrocarbons migrate through an unfractured undissolved halite bed is if the halite contains impurities that render it locally porous and make it brittle during deformation.

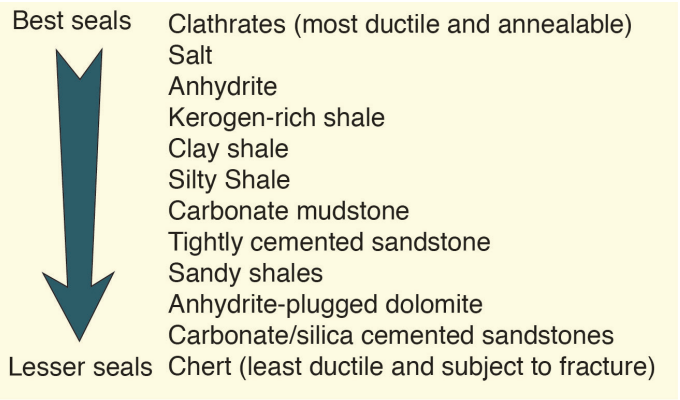

Figure 1. Differing ability to form a seal is related to a rock's inherent ductility in the subsurface (in part after Downey, 1984).

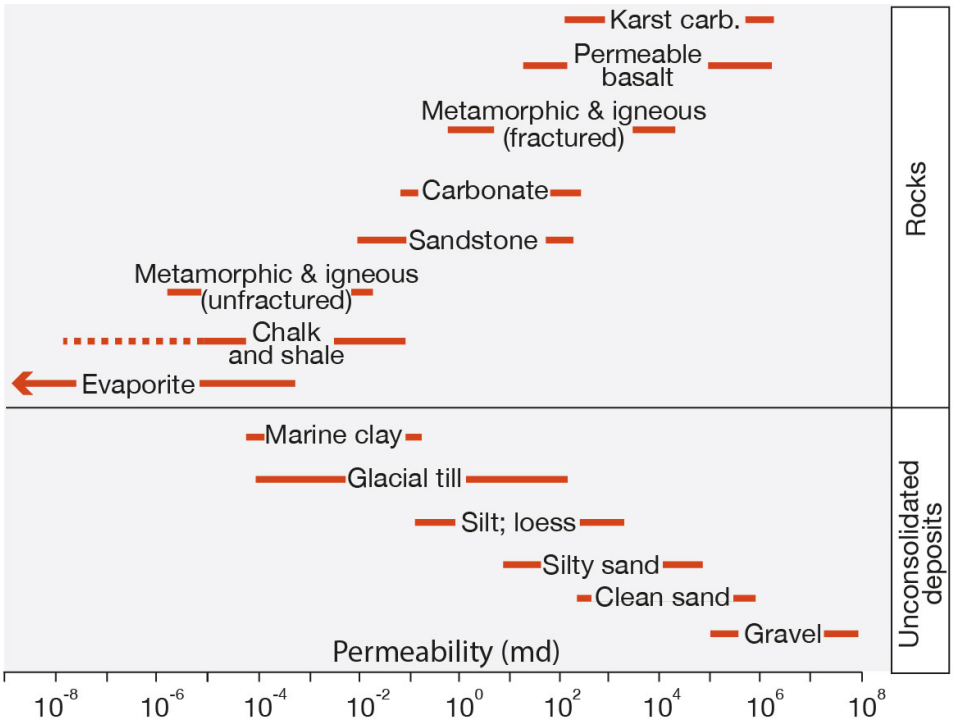

Figure 2. Relative ranking of permeability of various lithologies (in part after Beauheim and Roberts, 2002)

Seal capacity in flowing pure salt

Halite's very high ductility and its ability to flow, re-anneal and re-establish lattice bonding by solution creep when subject to stress give it a low susceptibility to fracturing even when it is deforming (Figure 3). This is why cross-salt fault and fracture patterns, as seen in most salt-entraining basins, make the industry considers salt a "crack-stopper" (Figure 4). Worldwide, seismic imaging of halokinetic realms shows that the salt has flowed, while adjacent carbonate and siliciclastics sequences fractured. Halite's ability to maintain seal integrity under stress, and so prevent the escape of hydrocarbons, reflects a combination of an ability to flow and re-anneal, and the small size of molecular interspaces in its ionically-bonded NaCl crystal lattice (Figure 5; see detailed discussion see Warren, 2016, chapters 6 and 10).

This propensity to flow under stress (tendency toward Newtonian flow) is why many laboratory tests and measurements consistently under-represent salt's flow and subsurface seal integrity responses. Inherently any lab experiment is tied to short time frames of up to weeks or a few years. However, such laboratory tests are likely more relevant to real-world subsurface situations 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 subsurface situations is 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 salt setting. That is, within observational errors, how do we quantify random versus systematic errors when we are always altering the samples and the surrounds via the process of gaining access?.

Whether, during catagenesis, buried halite beds that enclose organic intrabeds can release volatiles to sediments outside the salt mass is still a matter of some discussion among organic geochemists. The long-term lack of fracture or pore throats in buried salt beds is why organic-rich intrasalt carbonate or shale laminites tend to be inefficient source rocks

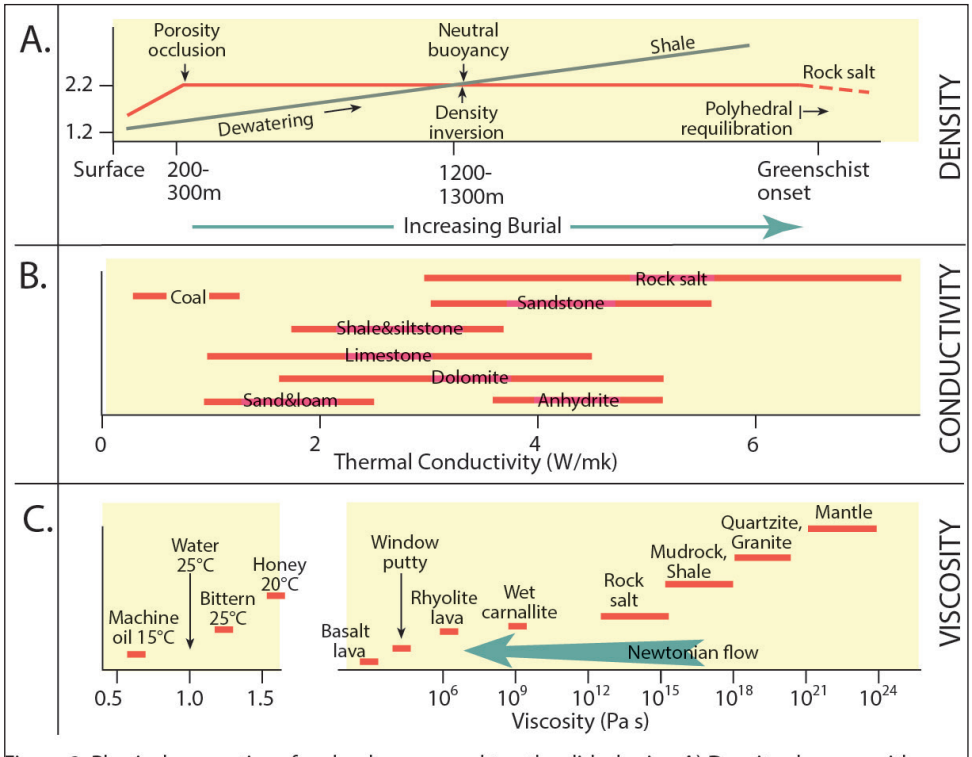

Figure 3. Physical properties of rock salt compared to other lithologies. A) Density changes with burial. B) Thermal conductivity. C) Viscosity.

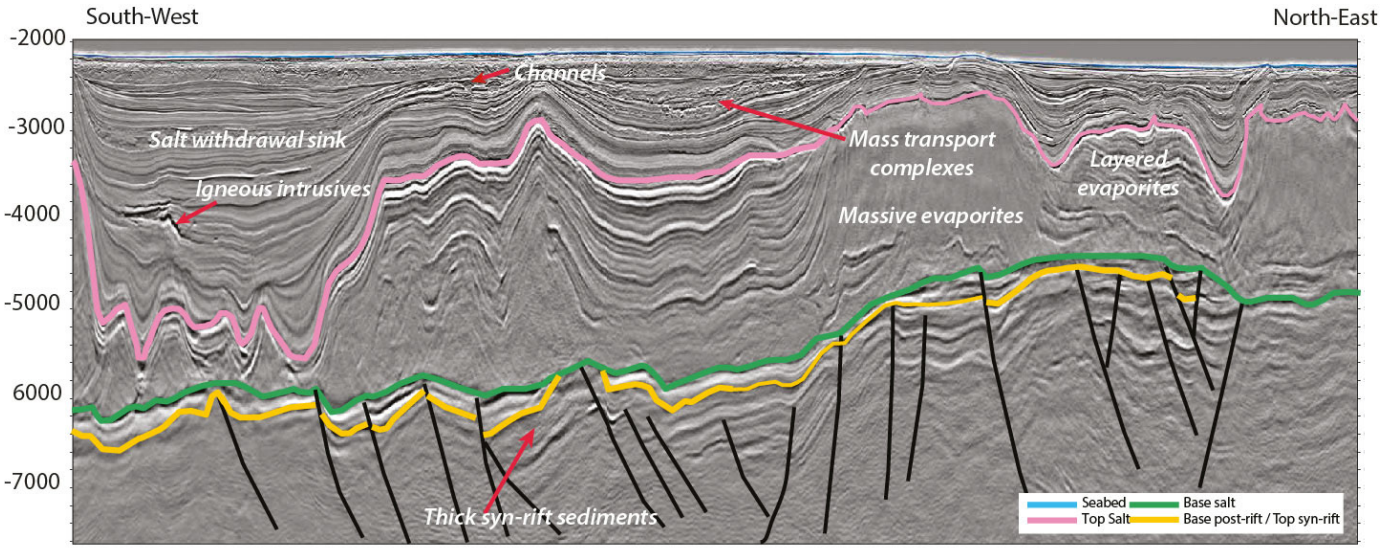

Figure 4. Typical subsalt-suprasalt relationships in the vicinity of Libra Field (Santos Basin) showing salt acting as a crack-stopper. Internally the Aptian salt shows layered versus massive character of salt in this region which is related to distinct mineralogical contrast in the intrasalt beds but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

in style 1a source rocks (Warren et al., 2011a). Likewise, possible flushing and maturation effects are poorly understood in subsurface situations where encased organic-rich beds are in contact with hydrated salts converting to their anhydrous equivalents (such as gypsum to anhydrite or carnallite to sylvite, mirabilite to thenardite). Loss of water of crystallisation in shallow burial (<0.5km) has the potential to allow organic-rich fluids to escape early as the hydrated salts transform to their anhydrous forms. Usually, such burial transformations are near complete in the first kilometre of burial and so may only allow immature hydrocarbons to escape into adjacent more porous sediments (Hite and Anders, 1991). There they must be stored, mature and remigrate during later burial if they are to act as hydrocarbon source rocks (Warren, 1986). Many intrasalt organic-rich beds survive well into the metamorphic realm and evolve into graphitic quartzites and marbles encased in meta-evaporitic albitites and scapolites.

As a general rule, even as a halite bed fractures, its inherent lack of strength and the consequent ability to flow means any microscale intercrystalline fractures quickly re-anneal by a combination of flow and pressure-solution induced recrystallisation. (Figure 5). Current consensus in the oil and gas industry is that

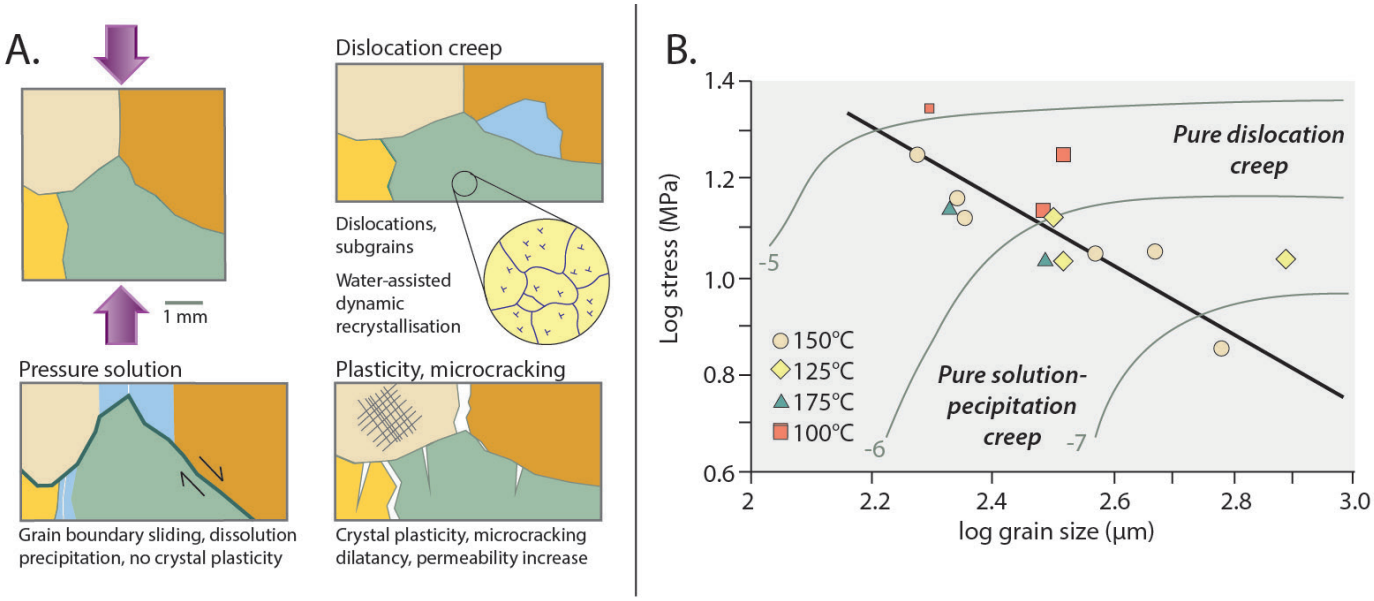

Figure 5. Crystal-scale deformation. A) Schematic showing the microstructural processes that can operated during the deformation of rock salt at temperatures in the range 20-200 °C. Different shades represent crystals with different orientation. The circular expanded inset illustrates subgrains (with 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 deformed in the transition region between dislocation creep and solution-precipitation creep, both played a role in the deformation (after Ter Heege et al. 2005; Urai et al., 2008)

some thin impurity-rich salt beds, interlayered with carrier beds, do leak small amounts of volatiles, but much less efficiently than thicker organic-rich mudstones and shales; whereas organics encased in thicker salt beds probably cannot leak from the unit until the enclosing salt dissolves or natural hydrofracturing occurs (as in the Ara Salt of Oman). Evaporite beds and salt allochthons constitute some of the strongest long-term subsurface barriers to the vertical migration of hydrocarbons in a sedimentary basin both as a seal to hydrocarbons and in CO_2 sequestration.

The next and final article in this series on salt leakage will consider; how and where does a salt seal leak in the real world of the subsurface?

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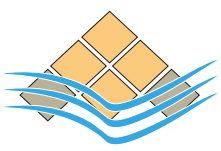

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