Salty Matters

John Warren -Friday 22 January, 2016

Salt as a Fluid Seal Article 2

Introduction

The previous article in this series on salt leakage focused on black and dark salt created by ingress or interaction of undersaturated waters with relatively shallow halokinetic salt masses, with entry zones often tied to intervals of salt shear. The resulting black or dark salt textures are one style of "anomalous" salt. This article looks at fluid entry into salt in subsurface intervals of high pore pressure, exemplified by the "black salt" in the Ara salt seals of Oman. Such intervals are often tied to burial-pressure and temperature-related changes to the dihedral angle of salt (halite).

Dihedral angle changes and the permeability of salt

Permeability in intercrystalline pore networks in re-equilibrating and crystallising subsurface salt is tied to the dihedral angle θ at solid-solid-liquid triple junctions (Figure 1; Lewis and Holness, 1996, Holness and Lewis, 1997). When the halite dihedral angle is higher than 60° under static laboratory conditions, this contact angle equates to the maintenance of closure of polyhedral grain boundaries by halite precipitation, and so at these lower temperatures both bedded and halokinetic recrystallized salt is impermeable (Schenk and Urai, 2004; Holness and Lewis, 1996). In this temperature range, the small amount of brine present in the salt 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 pressurised polyhedral halite attain dihedral angles that are less than 60° then the fluid-inclusion filled intercrystal cavities link up and the salt mass becomes permeable.

At burial temperatures >100°-150°C and pressures of 70 MPa or more, the dihedral angle has decreased to values <60°, driving a redistribution of the fluid into a thermodynamically stable network of connected, fluid-filled channels or fused fluid strings at grain boundary triple junctions. This transition may be related to 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 experiments demonstrated

$$\theta = 2\cos^{-1}[\gamma_{ss}/(2\gamma_{sl})\}$$

θ = dihedral angle solid-solid-liquid triple junction

γ_{ss} and γ_{sl} are the solid-solid and solid-liquid surface energies

that buried salt masses, subject to high pressures and elevated temperatures, can acquire intercrystalline or polyhedral permeability comparable to associated with intergranular permeability in sand.

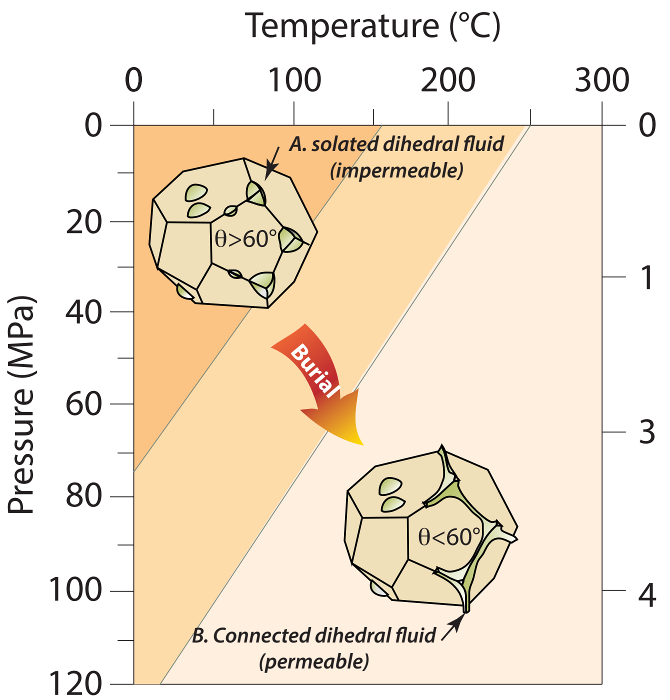

Figure 1. Effect of dihedral angle on pore connectivity in texturally equilib monomineralic and isotopic polycrystalline mosaic halite. Background sha shows two polyhedral porosity fields and transition zone calculated for th Salt (black salt or leaking halite plots in transition zone), Oman. A) Isolated ty for dihedral angle > 60°. B) Connected polyhedral porosity for dihedral 60° (after Lewis and Holness, 1996; Kukla et al. 2011b; Warren, 2016).

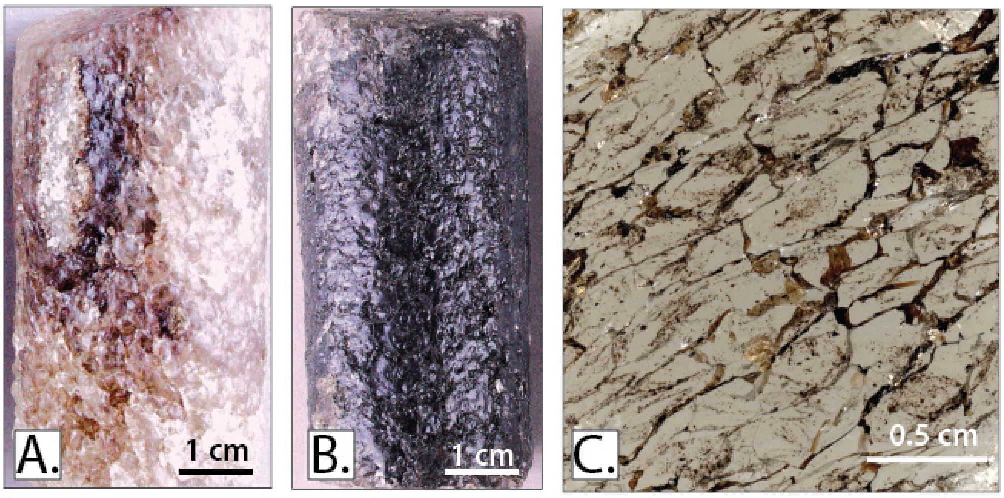

Figure 2. Hydrocarbon-impregnated halite ("black halite") from the Ara Salt, South Oman Salt basin. A) Lightly impregnated salt core, B) Heavily impregnated zone in salt core, this is classic Omani "black salt". C) Photomicrograph of naturally-impregnated salt showing interconnected polyhedral porosity outlined by the darker hydrocarbons (all images courtesy of Janos Urai)

carbon-rich formation waters. According to Lewis and Holness, the depth at which the recrystallization occurs may begin as shallow as a few kilometres (Figure 1). But, their pressure bomb laboratory-based static-salt experiments did not completely encompass the ability of natural salt to pressure creep and self-seal by longer-term diffusion-controlled pressure solution (Warren 2016, Chapter 6). Even if the changing dihedral angles alter and open up permeability at such shallow depths, there is no guarantee that subsequent flowage associated with pressure solution will not re-anneal these new pores. The ability of salt to continue to act as a highly efficient hydrocarbon seal to depths of 6-10 km means, in my opinion, that bedded salt does may become a relative aquifer until attaining depths of 6-10 km or more. This occurs certainly at temperatures and pressures where the sequence is entering the greenschist realm. In extremely overpressured situations the transition of dihedral angles is much shallower, as in the 40-50m thick black salt rims that typify the salt-encased hydrocarbon-charged carbonate stringers in the Ara Salt of Oman (Kukla et al., 2011b). Once it does transform into polyhedral halite, a former aquiclude becomes an aquifer flushed by chloride-rich brines, likely carrying other volatiles.

This typically occurs at higher temperatures and pressures where intercrystal water positions link within flowing or static, but texturally re-equilibrated, salt and so creates continuous fluid strings along evolving intercrystalline junctions in the burial-recrystallised salt. The newly attained intercrystal configuration allows penetration and throughflow of hot, dense brines or hydrocarbons into and through the altered mass of salt polyhedrons. In Oman has created characteristic haloes of black salt about pressurised salt-encased carbonate slivers (next section).

At the same time as a recrytallising salt mass passes into the earlier stages of the greenschist facies, the salt is dissolving and altering to sodic scapolite (Warren, 2016; Chapter 13). Thus, through the later stages of diagenesis and into early to medium grades of metamorphism, the salt 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 evolves from a dense impermeable salt mass into permeable salt with higher dihedral angles and so explains salt's significant role in the creation of many of massive base metal and IOCG deposits (Warren, 2016; Chapters 15, 16).

A release of entrained inclusion (±intercrystalline) water at temperatures > 300-400°C (early greenschist) 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. Figure 3

Black salt and overpressure in Oman

The transition in dihedral angle with increasing pressure and temperature explains the occurrence of black (bitumen-charged) haloes in salt encasing some carbonate-sliver reservoirs in the Ara Salt of Oman (Figure 2; Kukla et al., 2011a, b). Once this recrystallization occurs, the previous lower P&T mosaic halite loses its ability to act as an aquitard or aquiclude (seal) and can instead serve as a permeable conduit for escaping highly-pressurised and hydro-

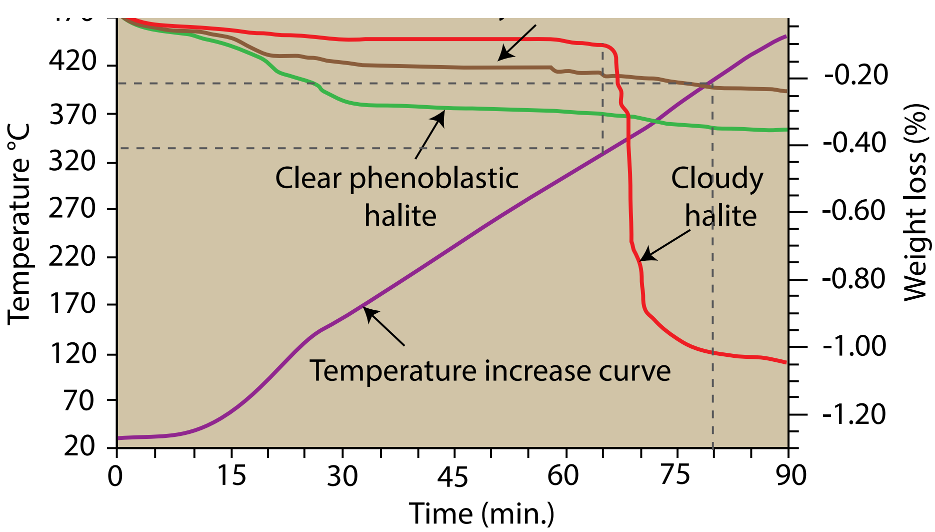

Figure 3. Weight loss of three pure halite samples upon heating from ambient temperature to 470 °C. Most of the weight loss corresponds to water loss from entrained inclusions, which are more common in cloudy halite (after Zimmermann and Moretto, 1996).

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 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 (Zimmermann and Moretto, 1996).

The influence of overpressure driving changes in the dihedral angle of pressurised salt is most clearly seen in black-salt encased Late Neoproterozoic to early Cambrian intra-salt Ara (stringer) reservoirs of the South Oman Salt Basin (Figures 2, 4, 5; Kukla et al., 2011b). These carbonate bodies are isolated in salt and frequently contain low-permeability dolomites and are characterised by high initial hydrocarbon production rates due to overpressure. But not all stringers are 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 (Figure 4).

The black staining of the halite is caused by intragranular microcracks and grain boundaries filled with solid bitumen formed by the alteration of oil (Figures 2, 5). The same samples show evidence for crystal plastic deformation and dynamic recrystallization. Subgrain-size piezometry indicates a maximum differential paleostress of less than 2 MPa. 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. In Schoenherr et al.'s (2007b) model, the oil pressure in the carbonate stringer reservoirs reservoir increases until it is equal to the fluid pressure in the low, but interconnected, porosity of the Ara Salt, plus the capillary entry pressure (Figure 5). When this condition is met, oil is expelled into the rock salt, which dilates and increases its permeability by many orders of magnitude. Sealing capacity is lost, and fluid flow will continue until the fluid pressure drops below te minimal principal stress, at which point rock salt will reseal to maintain the fluid pressure at lithostatic values. Inclusion studies in the halite indicate ambient temperatures at the time of entry were more than 90°C, implying hydrocarbons could move into interconnected polyhedral tubes in the halite. These conduits were created in response to changes in the polyhedral angle in the halite in response to elevated temperatures (Lewis and Holness, 1996).

Hydrocarbon-stained "black salt" can extend up to 100 metres from the pressurised supplying stringer into the Ara salt of Oman (Figure 2, 5). It indicates a burial-mesogenetic pressure regime and is not the same process set as seen in the telogenetic "black salt" regions of the onshore Gulf of Mexico. The latter is created by dissolution, meteoric water entry, and clastic contamination, as in the crests of nearsurface diapirs such as Weeks Island (Warren 2015). An Ara stringer enclosed by oil-stained salt but now below the lithostatic gradient likely indicates a later deflation

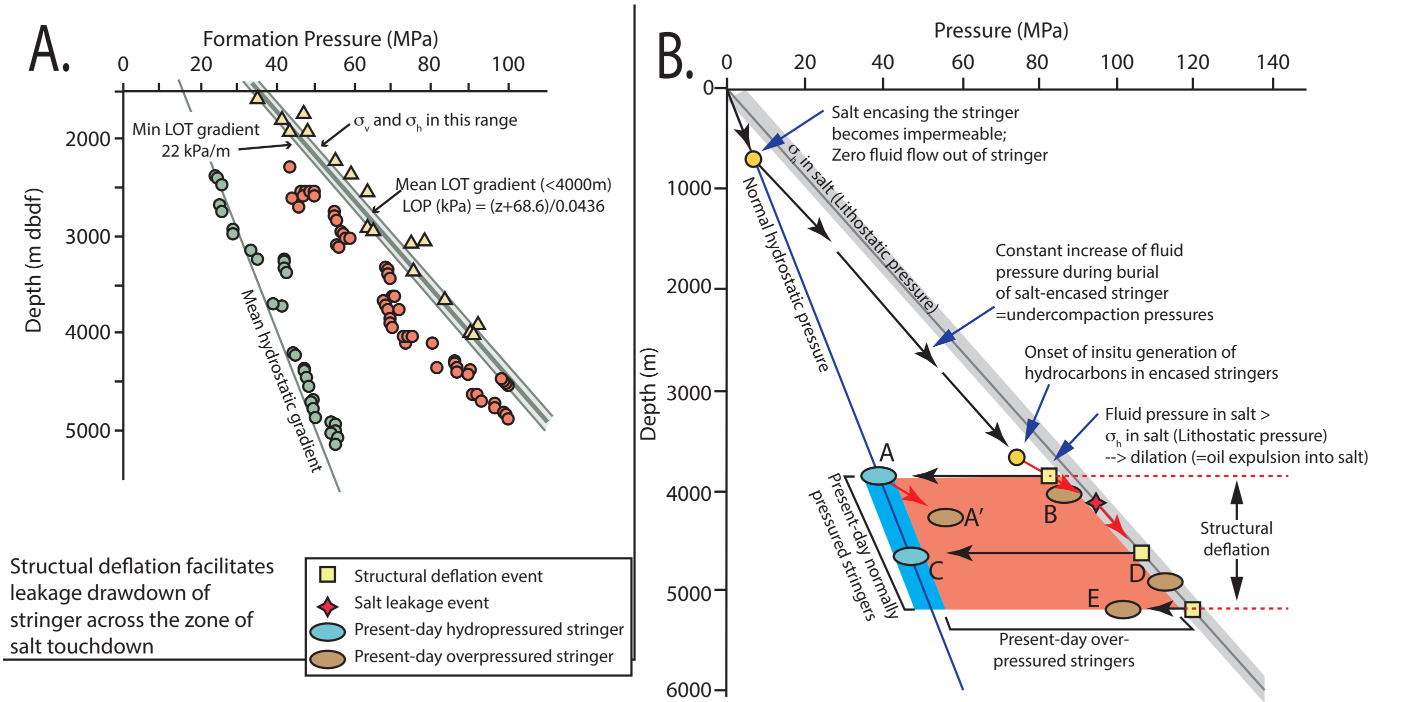

Figure 4. Overpressure in the carbonate stringers of the South Oman Salt Basin (after Kukla et al., 2011a, b). A) Measured formation pressures in the Ara carbonates (circles) versus depth. The plot shows two different pressure populations: one at near-hydrostatic pressures, with a mean pore-pressure coefficient λ = 0.49 (green circles), and one at near-lithostatic pressures, with a mean pore-pressure coefficient λ = 0.87 (grey circles). Brown triangles are leakoff test (LOT) data, and z is depth in metres. The thick black band represents the range of differential stress difference (σ_1–σ_3 [maximum principal stress - minimum]) in rock salt as derived from integrated density logs and subgrain size piezometry. tvdbdf = 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).

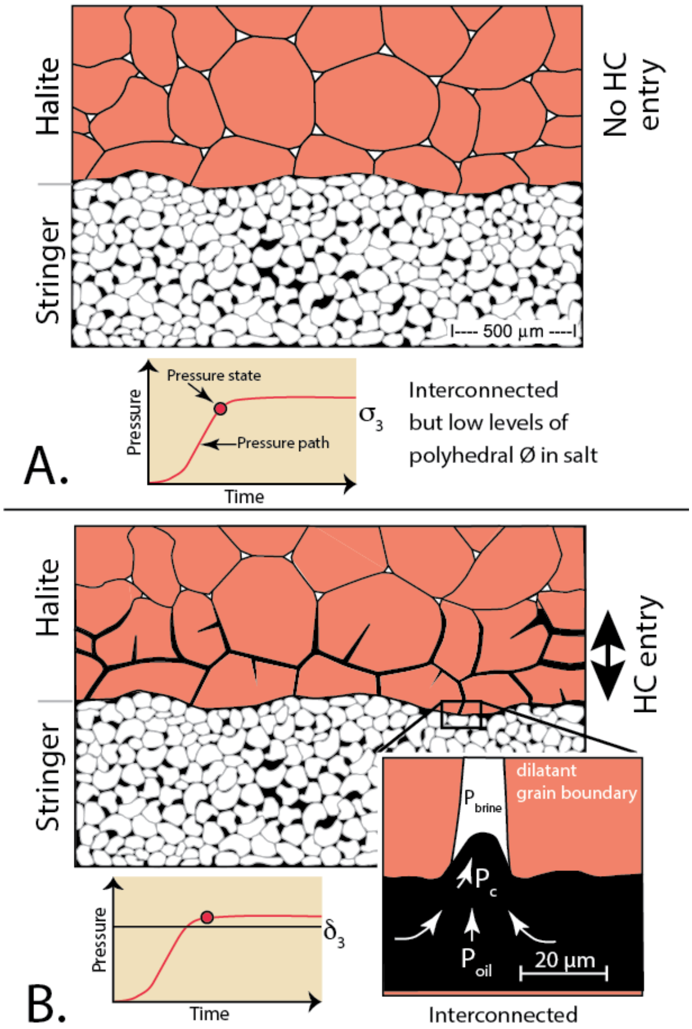

Figure 5. Entry of pressurised hydrocarbons (HC) into polyhedral salt pores. A) schematic cross section in (a) shows the interface of stringer reservoir and Ara Salt. Halite has an interconnected but low porosity represented by the triangular white spaces between the salt crystals (cut perpendicular 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, Poil in the stringer exceeds the minimum principal stress (σ_3) of the salt by the capillary entry pressure (Pc), 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).

event that caused either complete (C) or partial (E) loss of overpressures. Alternatively, stringers showing overpressure, but below the lithostatic gradient (E), might be explained by regional cooling or some other hitherto unexplained mechanism (Figure 4a; Kukla et al., 2011a, b).

Structural, petrophysical and seismic data analysis suggests that overpressure generation in the Ara is driven initially by rapid burial of the stringers in salt, with a subsequent significant contribution to the overpressure from thermal fluid effects and kerogen conversion of organic-rich laminites with the stringer bodies. If the overpressured stringers come in contact with a siliciclastic minibasin, they will deflate and return to hydrostatic pressures (A) in Figure 4. When the connection between the minibasin and the stringers is lost, they can regain overpressures because of further oil generation and burial (A'). If hydrocarbon production in undeflated stringers stops relatively early, the fluid pressures do not reach lithostatic pressures (B). If hydrocarbon generation continues, the fluid pressures exceed the lithostatic pressure (red star), leading to dilation and oil expulsion into the rock salt to what is locally known as "black salt" (D and E).

As well as these examples of overpressure associated with older evaporites, overpressure readily develops in salt-sculpted Tertiary basins. For example, overpressure occurs in salt shear (gumbo) transitions beneath some, but not all, shallow salt allochthons in Green and Mahogany Canyon regions in the Gulf of Mexico (Beckman, 1999: Shaker 2008). Where salt allochthons are climbing the stratigraphy, subsalt sealing and associated overpressure can occur beneath the salt mass at shallower levels than is 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 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 terranes. Salt buoyancy often acts upward and has the tendency to accelerate and decelerate the principal stress above and below the salt, respectively. A distinctive shift of the pore pressure envelopes and normal compaction trends takes place across the salt body in several wells drilled trough salt below 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. On the salt-rooted minibasin scale, a high-gradient was also observed in areas where the salt was emplaced and a lower gradient where the salt withdrew (Shaker and Smith, 2002). On the other hand, in the compressional 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.

Extreme overpressuring is commonplace in subsalt settings in the Gulf of Mexico at depths of 3000-4000 m and its variability creates drilling problems, as evidenced by the BP Horizon spill and explosion on April 20, 2010. Gas generated at greater depths in these regions can be trapped under the salt seal at pressures approaching lithostatic. It means drilling under the allochthonous salt on the Gulf Coast slope can intersect undercompacted sediments that are moderately to extremely overpressured and friable (Hunt et al., 1998). The influence of highly effective Jurassic salt seals on pressure gradients in 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 by the drill (Table 1). Many wells intersecting salt allochthons in the deepwater realm of the Gulf of Mexico and the circum-Atlantic Salt basins are overpressured at some depth

Well	Top salt (m)	Base salt (m)	Total salt thick-ness (m)	Total well depth (m)	Mud weight above salt (ppg)	Mud weight below salt (ppg)	Density profile (gm/cc) (above/in salt/below	Sonic log below salt (μsec/ft)
West Cameron, Block 505, No.2	4,300	4,780	480	5,640	12	18	2.45/2.05/2.25	140
Garden Banks, Block 171, No. 1	2,590	2,925	335	3,230	12	14	2.15/2.05/2.25	140
Vermillion, Block 356, No. 1 South	2,592	3,231	639	5,180	13	18	no data	140
South Marsh Island, Block 200, No.1	2,685	2,987	302	n/a	15.6	17.2	2.15-2.25/2.05/2.15-2.25	130

below the base of salt with mud weights controlling pressures ranging from 14 to 17.5 ppg.

Implications

This and the previous article (Warren, 2015) demonstrate that black salt is a form of anomalous salt that indicates salt has leaked, however, the locations and conditions where leakage has occurred are distinct. The black salt encountered in the salt mines of the US Gulf Coast are indicative of meteoric water entry in relatively shallow conditions in regions where the salt is in contact with the surrounding shales of muds that enclose the diapir salt core. In other words, fluid entry is from the outside of the salt mass and fluids move into the salt from its edges and likely enhance the porosity in the intercrystalline salt. In contrast, the black salt occurrences in the Ara Salt of Oman are indicative of overpressure haloes, generated internally via hydrocarbon and fluid expulsion in carbonate slivers, which are 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. The two settings of black salt formation are distinct.

There is not a single mechanism that creates black salt in a halokinetic salt mass. We shall discuss the implications of this in the next article which will include a look at leakage models in halokinetic salt systems both in terms of their seal integrity and the implications for short and long term storage of hydrocarbons and nuclear waste.

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