SOLUTION MINING RESEARCH INSTITUTE

679 Plank Road
Clifton Park, NY 12065, USA

Telephone: +1 518-579-6587
www.solutionmining.org

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Aldbrough Hydrogen Storage - Legacy Data for New Caverns in Deep Bedded Zechstein Salt

Silvan Hoth[1], Hendrik Wilke[2], Patryk Tomaszewski[2], Farideh Sarikhany[1], Heinz Michael Springer[1], Dirk Knaust[1], Janiche Beeder[1], Christopher McMichael[2], Fritz Wilke[2], Jamie Slingsby[3], Victoria Spooner[3]

[1]Equinor ASA, [2]AtikinsRéalis, [3]SSE Thermal

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Abstract

Hydrogen storage in salt caverns is increasingly vital to facilitate the energy transition and allow for hard to abate industry decarbonisation. This paper focuses on the Aldbrough Hydrogen Storage (AHS) project in East England and the development of a hydrogen storage field south of the existing Aldbrough natural gas storage facility, utilising the same layered Zechstein salt deposits at a depth of ~1,800 m b.g.l. The observed vertical and lateral heterogeneity of the Zechstein deposits require a detailed and integrated subsurface characterisation. Such a multidisciplinary approach integrates (i) legacy data, including well data (e.g., wireline logs and cores), (ii) 2D seismic sections, (iii) solution mining histories, (iv) cavern development records, (v) brine samples, (vi) bromide analysis, and (vii) microbiological data to ensure safe, efficient and economic development of the cavern field, its operation and abandonment. In particular, the correlation between petrophysical log responses and core observations provided valuable insights into salt stratigraphy, salt composition, presence of insoluble, e.g. shale, anhydrite and highly soluble salt intervals, e.g. carnallite.

In the first phase, wireline petrophysical logs, in conjunction with core analysis, formed the basis for a lithostratigraphic subdivision of the encountered Zechstein Group deposits. Depth maps for key horizons were generated on the basis of these interpretations. In the next step, well data were linked with 2D seismic lines to understand the structural position of the wells, and to extrapolate well information into 3D. Isochore maps for several Zechstein Group intervals were calculated, constraining palaeogeography during Zechstein deposition to (i) identify suitable cavern design and locations, (ii) determine operating pressures, and (iii) estimate storage capacity.

The early phase cavern design involved a thermodynamic assessment, coupled thermal-mechanical analysis, and a development of a solution mining concept. The latter was specifically designed for the local geology and involved the analysis of historical solution mining records and brine chemistry data to predict leaching behaviour, to finally achieve optimal cavern development.

Integration of petrophysical logs with brine sample analysis and microbiological growth experiments, revealed a direct connection between salt rock composition, brine chemistry, its degree of chaotropicity, i.e. the ability of certain substances (chaotropes) to disrupt the structure of macromolecules, and the growth of hydrogen consuming microbes.

Results presented here, highlight the need to define a site-specific leaching concept, requiring operational and organisational flexibility during execution and operation. This emphasises that geology directly influences infrastructure, which in turn affects the storage capacity, operational flexibility, and ultimately the economic viability of the project. Lastly, a tight integration with topside facility planning and finance is required, to ensure safe and efficient operations.

Key words: Hydrogen salt cavern storage, salt geology, seismic interpretation, petrophysical analysis, leaching concept, rock mechanics

1. Introduction

As part of a joint venture with Equinor, SSE currently operates nine gas storage caverns at its Aldbrough site in East Yorkshire, UK. During the leaching process challenges were realised on some of the caverns, which were attributed to the presence of non-halite salt (carnallite and kieserite) within the bedded Permian Zechstein Group. Although these challenges were overcome and all caverns successfully entered natural gas storage operation, they have left a legacy which has impacted ongoing operations and hence informs the planning for the adjacent Aldbrough Hydrogen Storage (AHS) site. Besides the Aldbrough Gas Storage (AGS) facility, the Zechstein salt deposits are widely used for salt cavern storage along the UK east coast with the 9 caverns at the SSE Thermal Atwick site (~15km north of Aldbrough), and over 100 caverns in Teesside, including three high purity hydrogen storage caverns in operation since the 1970s (Figure 1).

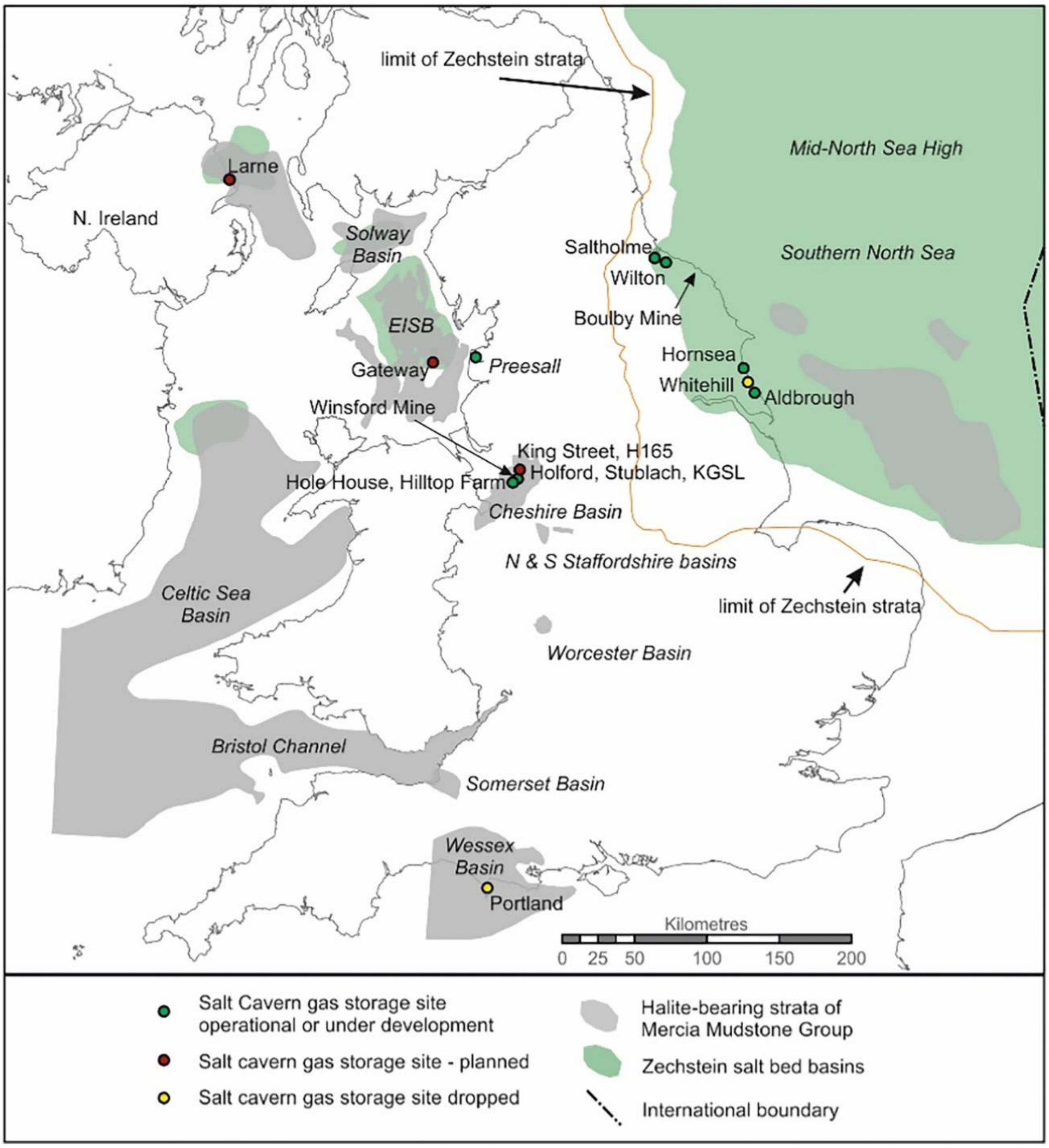

Figure 1: Diagrammatic map of UK sedimentary basins containing massive, bedded halite deposits and the location of operational, planned, and cancelled UK gas storage facilities. EISB – East Irish Sea Basin; KGSL – Keuper Gas Storage Limited. Taken from Williams, et al. (2022).

The commonly observed high lateral and vertical heterogeneity of the Zechstein deposits requires a detailed subsurface characterisation to ensure safe efficient and economic development of the AHS cavern field, its operation and abandonment. This is achieved through a multidisciplinary approach integrating (i) legacy data, including well data (e.g., wireline logs and cores), (ii) 2D seismic sections, (iii) solution mining histories, (iv) cavern development records, (v) brine samples, (vi) bromide analysis, and (vii) microbiological data. To develop the AHS cavern field a stepwise approach is chosen as outlined below:

1. Petrophysical logs, in conjunction with core analysis, form the basis for a lithostratigraphic subdivision of the Zechstein Group in the Aldbrough area (Chapter 4 & 5). Based on this interpretation, depth maps for key horizons were generated. To better constrain the subsurface geometries in the AHS area, a reinterpretation of a selection of 2D seismic lines was conducted and the resulting horizons were gridded to obtain time structure and isochore maps (Chapter 3).
2. The above information was used to (i) identify suitable cavern design and locations, (ii) determine operating pressures, and (iii) estimate storage capacity. Correlation between geophysical log responses and core observations provided valuable insights into salt stratigraphy, salt composition, presence of insoluble, e.g. shale, anhydrite and highly soluble salt intervals, e.g. carnallite. Furthermore, microbiological samples from existing caverns were used to constrain the rate and magnitude of H_2 consumption and H_2S production during H_2 storage operations (Chapter 7). This will also inform the technical requirements for well materials and surface installations.
3. This information fed into the early phase cavern design, involving a (i) thermodynamic assessment, (ii) a coupled thermal-mechanical analysis, and (iii) the development of solution mining concepts. The latter were specifically designed to account for the local geology and involved the analysis of historical solution mining records and brine chemistry data to predict leaching behaviour to finally achieve optimal cavern development (Chapter 8).
4. In the next phase, a planned 3D seismic survey in conjunction with new well data will refine existing geological understanding of salt stratigraphy and purity.
5. The AHS project development will follow a phased strategy, including real-time monitoring of pressure, brine composition and structural stability, with continuous re-assessment of cavern locations, cavern shape development and operational parameters, as the project progresses.

This approach underlines (i) the crucial role of legacy data, (ii) the incorporation and follow through of lessons learned, (iii) the acquisition of new geological and geophysical data, (iv) as well as thorough integration of geology, geophysics, petrophysics, geomechanics, solution mining and microbiology to reduce uncertainties and optimise planning for and operations of H_2 storage in deep salt layers. Thereby the scale and potential impact of heterogeneity observed on 2D seismic section, wireline log data and cores on solution mining and cavern stability need to be continuously assessed. This will feed into a thorough subsurface understanding, including a robust subsurface safety assessment ensuring safe and efficient operations.

2. Geological Setting

The Aldbrough Gas Storage (AGS) cavern site is located on the coast of the East Riding of Yorkshire coast, UK. *Figure 2* shows a schematic W-E stratigraphic profile through the Aldbrough area with the main acoustic boundaries mapped in the available 2D reflection seismic data. Both the Atwick and AGS salt caverns are located within the Z2 Fordon Evaporites, which will also be utilised to construct salt caverns for the Aldbrough Hydrogen Storage (AHS) project. A summary of the geological evolution of the greater Aldbrough area spanning from the Carboniferous to the Cretaceous as evidenced by geological and geophysical data is given below.

During the Carboniferous the study area was located on the distal margin of the Variscan foreland basin, with the Variscan mountains to the east and the Laurasian continent to the west and north (Ziegler, 1990). The Upper Carboniferous Coal Measure is characterised by a thick paralic succession, being unconformably overlain by the Permian Rotliegend Group (Pharaoh et al., 2010). This Variscan unconformity dips eastwards from ~ 1 km in the west to 2.2 km in the east (UKOGL).

Following the late Carboniferous to Early Permian assembly of Pangea with the Variscan mountain chain in the west of the study area, the intracontinental Southern and Northern Permian Basin (SPB, NPB) formed in response to thermal subsidence north of the Variscan orogen. Although the Arctic-North Atlantic rift system between Greenland and Scandinavia had commenced in the late Carboniferous, its southward propagation took place during late Permian and Early Triassic as indicated by the Triassic development of the Viking and Central grabens, transecting the NPB and SPB (Pharaoh et al., 2010). At the same time, northward directed Tethyan rifting propagated into the SPB and the central North Sea. By the Middle Triassic, both rift systems became linked, giving rise to an orthogonal fault pattern with NW-SE oriented Arctic-Atlantic extension and NE-SW trending Tethyan extension (Coward et al., 2003).

Permo-Triassic depositional environments in the Northern and Southern Permian basins reflect the northward migration of Pangea from equatorial latitudes in the Carboniferous to 30°N by the Early

Triassic (Pharaoh et al., 2010). The SPB was hence located within the equatorial arid and semi-arid climatic belts. The vast continental interior of Pangaea created extreme continentality, with a pronounced monsoonal seasonality and dry winters and summer wet conditions along the northern Tethyan margin (McKie 2014). By the beginning of the Late Permian, the Northern and Southern Permian Basins had apparently subsided below global sea level. Although repeated temporary marine incursions into the SPB during late Rotliegend times have been recorded (Legler & Schneider, 2008), the deposition of the Kupferschiefer (Copper Shale) is evidence of catastrophic and permanent flooding of the Permian basins by the Zechstein transgression derived from the Arctic Ocean. This highly organic unit was deposited in basinal areas well below wave base under permanently stagnant (euxinic) bottom-water conditions in water depths of 200 to 300 m or more (Ziegler, 1990).

According to Pharaoh et al., (2010) the Late Permian evolution of the SPB continued to be dominated by thermal relaxation of the lithosphere with crustal extension playing only a minor role. Cyclical glacioeustatic sea-level variations controlled sedimentation patterns in both the NPB and the SPB. During sea-level highstands, carbonate and evaporite beds formed along the basin margins and on intra-basinal highs, while the basinal areas received no sediments; during sea level lowstands, basinal areas were filled with thick halite deposits. Richter-Bernburg (1955) recognised up to seven depositional cycles containing Carbonate, Anhydrite, Halite and Potassium salts within the Zechstein Group, with each cycle representing renewed flooding of the SPB from the north, followed by evaporation of the seawater and the resultant precipitation of salt minerals. A correlation between the offshore UK Zechstein (distal) and the onshore UK Zechstein deposits (proximal) is shown in Figure 3. Following the deposition of the Zechstein Group a thick succession of Triassic Sherwood Sandstone and Mercia Mudstone was deposited. This was followed by open sea mudstones of the Jurassic period (Lower Lias), a period of uplift and erosion, and Cretaceous sandstones (Carstone) which are in turn overlain by Red Chalk and later by white Chalk. The succession is finally unconformably overlain by Quaternary glacial clays, sands and gravels (Kent et al, 1980).

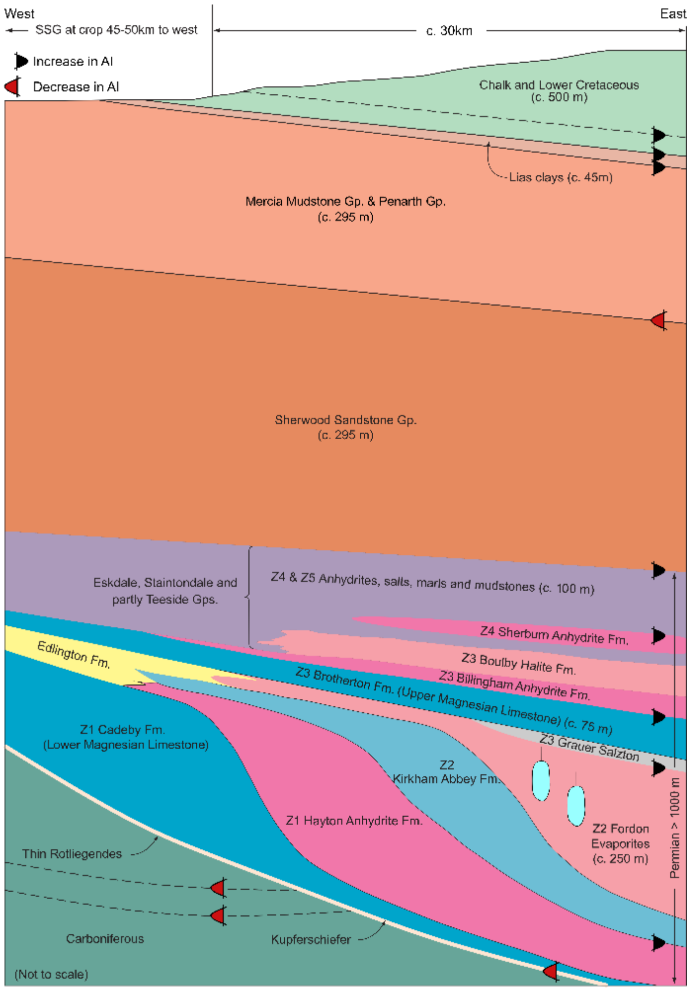

Figure 2: Schematic stratigraphic summary chart of the Aldbrough area. Modified after Evans (2008). Seismic wavelets indicate stratigraphic horizons with main acoustic impedance contrast, which have been mapped. AI refers to acoustic impedance contrast.

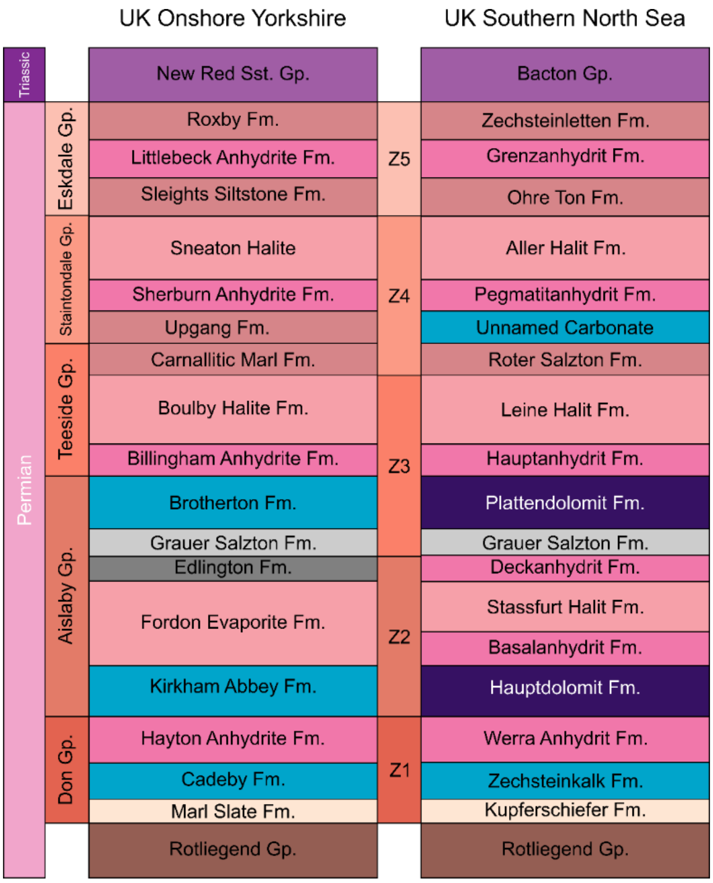

Figure 3: UK onshore offshore Zechstein nomenclature. Modified after Peryt et. al (2010).

3. Geophysics

For subsurface evaluation purposes 2D seismic lines (TWT) belonging to the HUMB-2011 survey were purchased (Figure 4). Altogether 10 seismic lines trending either E-W or N-S were selected from this survey for interpretation to gain a regional understanding of the thickness and structuration of the Zechstein sequence. Following the ‘tying-the-loop’ approach all 10 lines were interpreted and the resulting horizons were gridded to obtain time structure maps. In a next step, these were used to calculate isochore maps. As shown in Figure 4 there is only one line which is within the area of interest, providing valuable but limited information about subsurface geometries. Therefore, a 3D seismic acquisition is planned for the near future, to fully cover the AGS and AHS areas to obtain a 3D understanding of the subsurface geometries, but also to extrapolate the geological information from AGS towards the south to lastly optimise the development of AHS.

To establish a link between geological well information in depth with seismic reflections in two-way-travel time a sonic and a density log is needed which should cover the entire well length. Furthermore, the well should be located either at or in close vicinity to the seismic section to reduce projection uncertainty. This is especially important, when geology is changing laterally at a scale of a few hundred meters, as observed in Aldbrough (Chapter 5). Since none of the AGS wells meet this criterion, offset wells from the West Newton area, 6 km to the northwest of Aldbrough had to be used.

Seismic mapping indicates (i) a gentle east to southeasterly tilt of the Zechstein sequence in the Aldbrough area (Figure 5) and (ii) the presence of a kilometre-scale embayment with observed thinning towards the west and south (Figure 6). This embayment is fringed by a carbonate shelf prograding from west to east and from south to north respectively. This is supported by the West Newton wells encountering carbonate shelf deposits, but almost no mobile salt (UKOGL, Chapter 5). It follows, that Aldbrough is only a few kilometres east and north of the paleo-shoreline during the Zechstein 2 cycle. Figure 6 and related seismic sections indicate furthermore the presence of east-west trending pinch and swell structures, suggesting salt flow. This boudinage could be explained by gravity gliding of the Zechstein Group deposits along the regional gentle eastward slope (ca. 2°) during and/or shortly after deposition of the Zechstein salt. Mild north-south directed folding in the Triassic is also observed.

Figure 4: Satellite image of the Aldbrough area, showing the existing AGS plant, with AHS towards the south. Black lines are 2D lines from the HUMB-2011 survey, which have been used for interpretation.

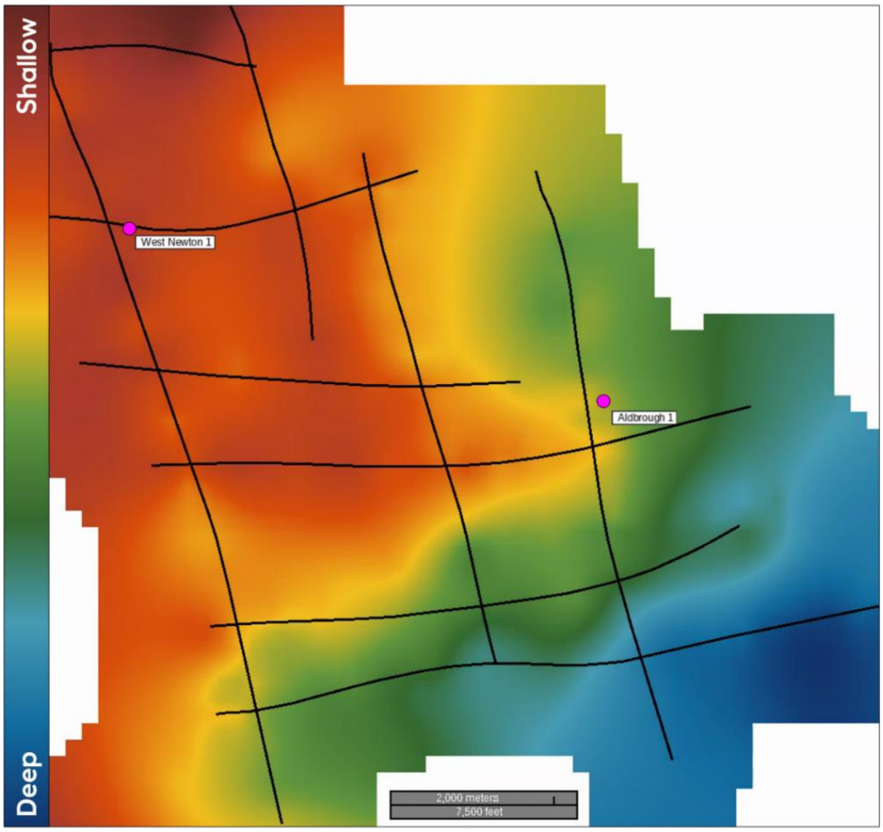

Figure 5: Time structure map in ms [TWT] of Top Brotherton, equivalent to Top Plattendolomit.

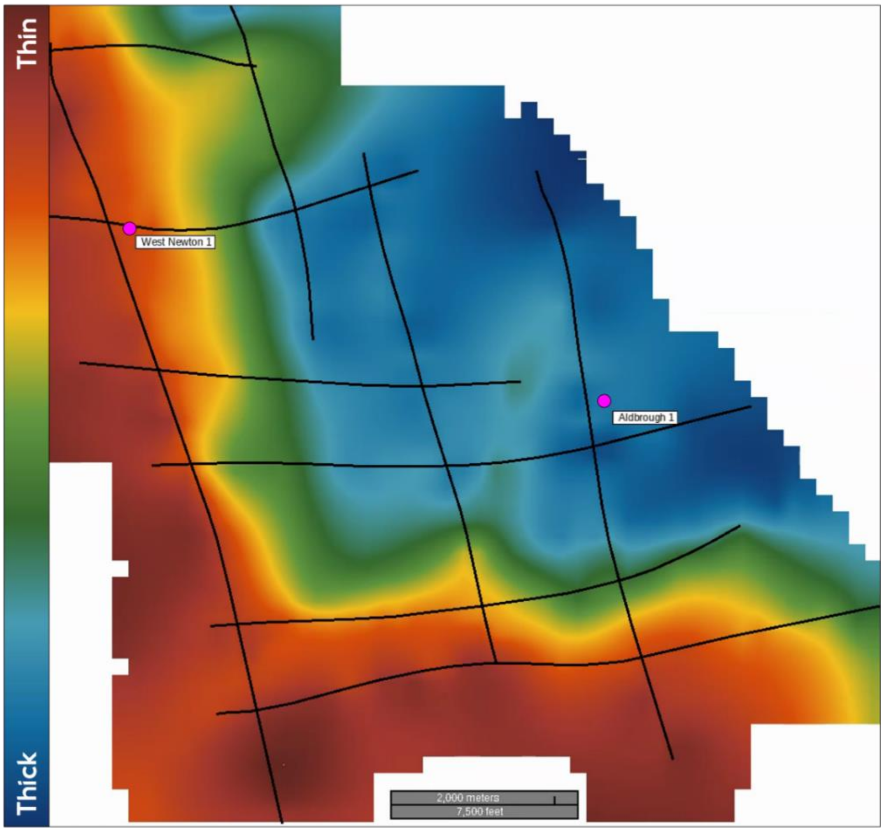

Figure 6 Time thickness map for the interval Top Kupferschiefer – Top Brotherton/Top Plattendolomit.

Besides seismic-scale deformation of the Permian Zechstein Group sonar and core data provide further evidence for intra-salt deformation and non-layer cake geometries. Interpretation of sequential 3D sonar surveys suggests the presence of planar features, for which dip and dip-direction could be estimated (McMichael 2022). Although, these might derive from solution mining or rock mechanic processes, there is apparent consistency between dips observed in the cores and the ones interpreted from sonar surveys. While the cores from Aldbrough-2 did not indicate significant structures, the base of the Aldbrough-1 cored interval shows localised structural dip of up to 45° for an up to 10 m long section, including shear-zones and boudinage.

Given that (i) individual layers within the Zechstein sequence show significant thickness changes at a lateral scale of a few hundred meters, (ii) the presence of boudinage at seismic and core scale, and (iii) significant structural dip, more deformation at the scale of the caverns is expected. This necessitates the development of a site-specific definition of a leaching concept for each individual cavern.

4. Petrophysics

Wireline log data have been used to subdivide and describe the evaporite sequences. Based on this zonation, regional maps of the evaporite sequences could be derived. The thickness of the Z2 Halite, which hosts the AGS caverns, ranges from about 160 to 200 m. In the next step wireline log data have been used for a quantitative evaluation of the main halite section. Most evaporites can be clearly distinguished from each other and from other consolidated sedimentary rocks by their log responses. While e.g. anhydrite has relatively high density and sonic velocity, halite and carnallite are characterized by low density and low sonic velocities. Relative to sandstone and shales anhydrite has a higher density, whereas halite and carnallite have lower densities. The Aldbrough wells show log responses within the main Z2 Halite section which are interpreted by different amounts and distributions of carnallite, kieserite, polyhalite, anhydrite and halite.

The thickness and distribution of the carnallitic zone varies from west to east in the AGS area. While the western wells show no carnallite, neither in the petrophysical log response nor in the cores, wells in the centre of the AGS cavern field show carnallite stringers, which are ca. 1-3 m thick. Towards the east, the carnallitic zone increases in thickness, thereby showing a gradual up-section increase in the inferred carnallite content, culminating in an up to ~15 m thick zone of high carnallite content. This has been estimated to reach > 60% carnallite (Figure 7). These estimates align well with observations from the potash Boulby mine, located to the north of Aldbrough. In the Boulby mine carnallite seams within the Z3 show an average carnallite content of 58% with halite and insoluble salts accounting for 42%. These seams range in thickness between 3 – 15 m (pers. Com. Thomas Edwards).

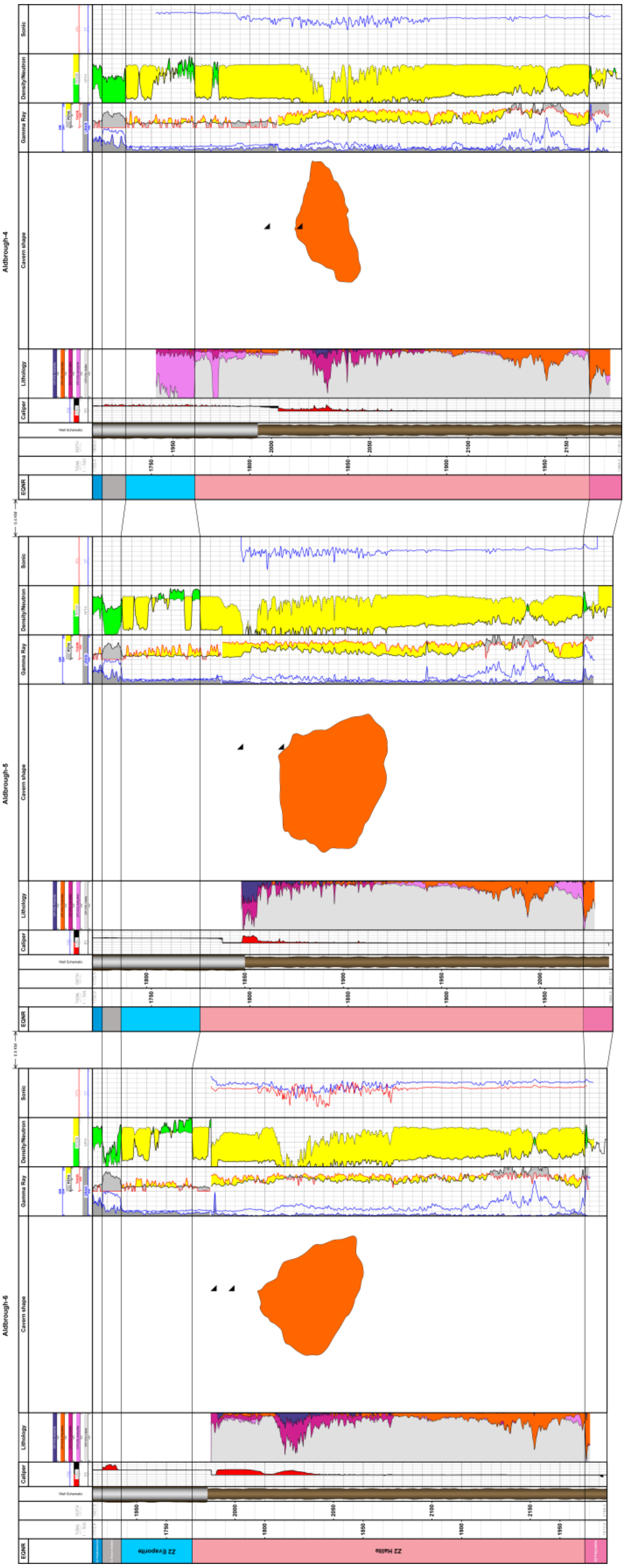

Figure 7 N-S cross section through the eastern Aldbrough wells -4, -5 and -6 showing the cavern placement relative to wireline log responses and the log derived mineral model. Cavern geometries are taken from last sonar survey in brine, prior to gas first fill.

5. Geology

Based on well observations and correlations, Smith (1989) reconstructed the palaeo-environment during Zechstein deposition along the Yorkshire coast, UK, suggesting a depositional setting of marginal carbonate platforms, prograding from west to east and transitioning into a slope setting. The Z2 and lower Z3 cycles – as relevant for this study – can be subdivided into the following formations:

- Z3 Plattendolomit
- Z3 Grauer Salzton
- Z2 Deckanhydrit
- Z2 Stassfurt Halite
- Z2 Basalanhydrit.

Given the wide spectrum of lithologies in each formation, different lithological terms have been applied in previous stratigraphical evaluations, such as polyhalite, main salt, evaporite (Figure 8). Grant et al. (2019) showed that the Z2 carbonate shelf-margin on the southwestern margin of the Southern Permian Basin comprises a series of corrugated embayments and promontories, which extend up to 5 km into the basin and locally have a palaeobathymetric relief of >200 m.

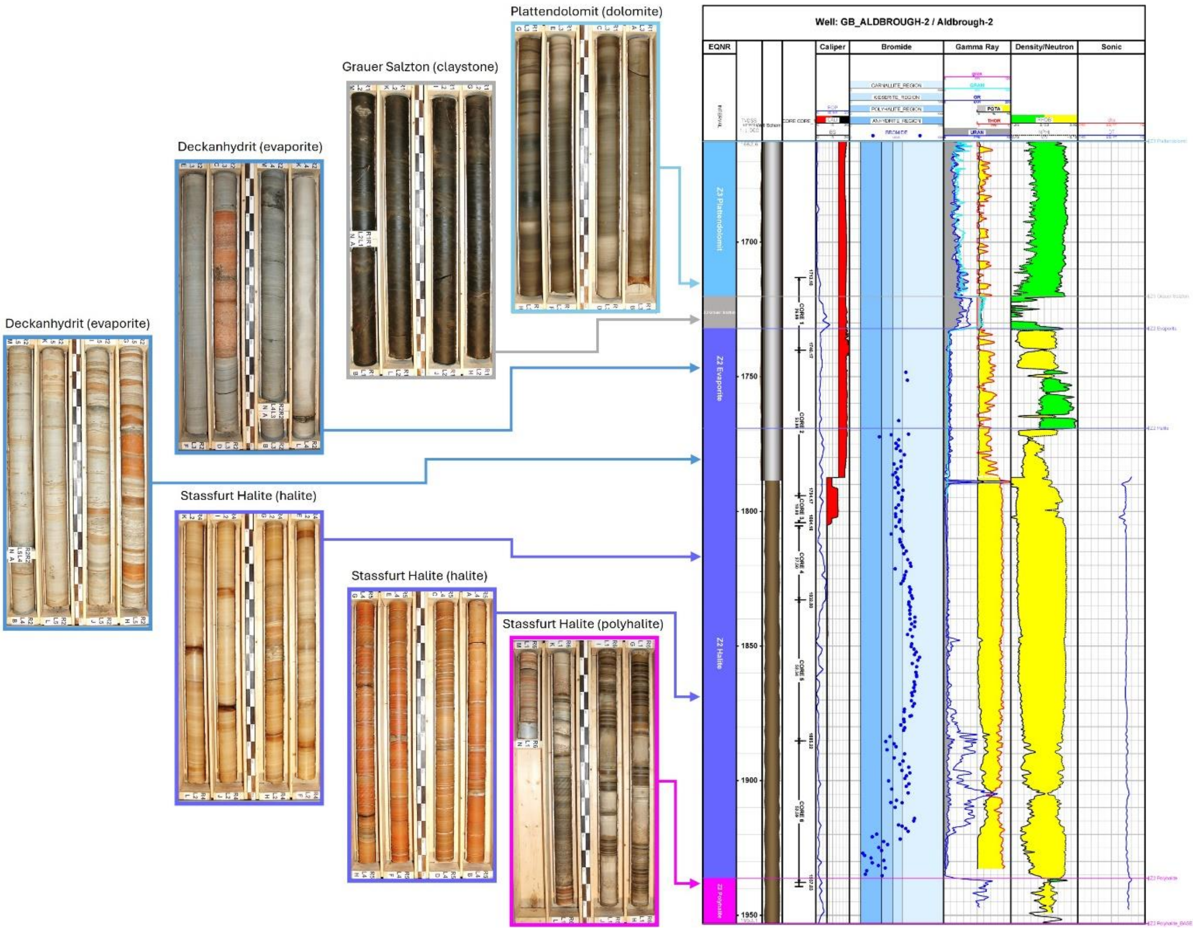

Figure 8 Representative core examples from the Z2 cycle in Aldbrough-2, their stratigraphical and lithological terms, and their position aligned with log curves.

Cores from Aldbrough and Atwick wells were investigated to establish a link with petrophysical logs, to refine the stratigraphic interpretation and correlation as well as to aid the extrapolation of lithologies into non-cored intervals. This analysis showed that while lithological changes appear rather gradual in core, they are more apparent in petrophysical logs (Figure 8). Aldbrough-1 and -2 cores were sampled to refine the mineralogical characterization, including potential traces of carnallite as well as to establish a bromide profile (Chapter 6). Sections of increased kieserite content were identified, and tests were conducted to evaluate the reaction potential with hydrogen (Chapter 7). Key findings comprise:

1. The presence of key stratigraphic units, including sections of “cleaner halite”, i.e. with a lower insoluble content at the base of the Z2 Main Salt, polyhalitic and kieseritic salts were confirmed.

2. A good overall correlation of salt units between the two wells, underpinning the feasibility of the geological prediction into the AHS site.
3. Both cored Aldbrough wells show a cleaner salt section near the base, which was either not utilized or exploited inefficiently for leaching in most of the Aldbrough caverns and presents thus an upside for future cavern development (Chapter 8).
4. Both cored wells did not contain a carnallitic zone, which agrees with the prediction from petrophysical logs. Hence, the carnallite distribution, i.e. as seams or dispersed in a halite matrix, remains unknown in the eastern part of the AGS cavern field. Therefore, inferences about carnallite distribution hinge on petrophysical log interpretation. An understanding of the latter will be detrimental to refine the solution mining concept, with the future data acquisition strategy aimed at sampling the carnallitic zone.
5. Intervals of meter-scale deformation, including structural dip above 10° were recorded and potential links to cavern shape as derived from sonar surveys were established.

Comparison with the Atwick cores showed a similar lithological sequence. However, the cores exhibited significantly more structural deformation features such as shear fabrics and brecciation. The carnallitic zone as inferred from petrophysical logs could not be observed in the available cores.

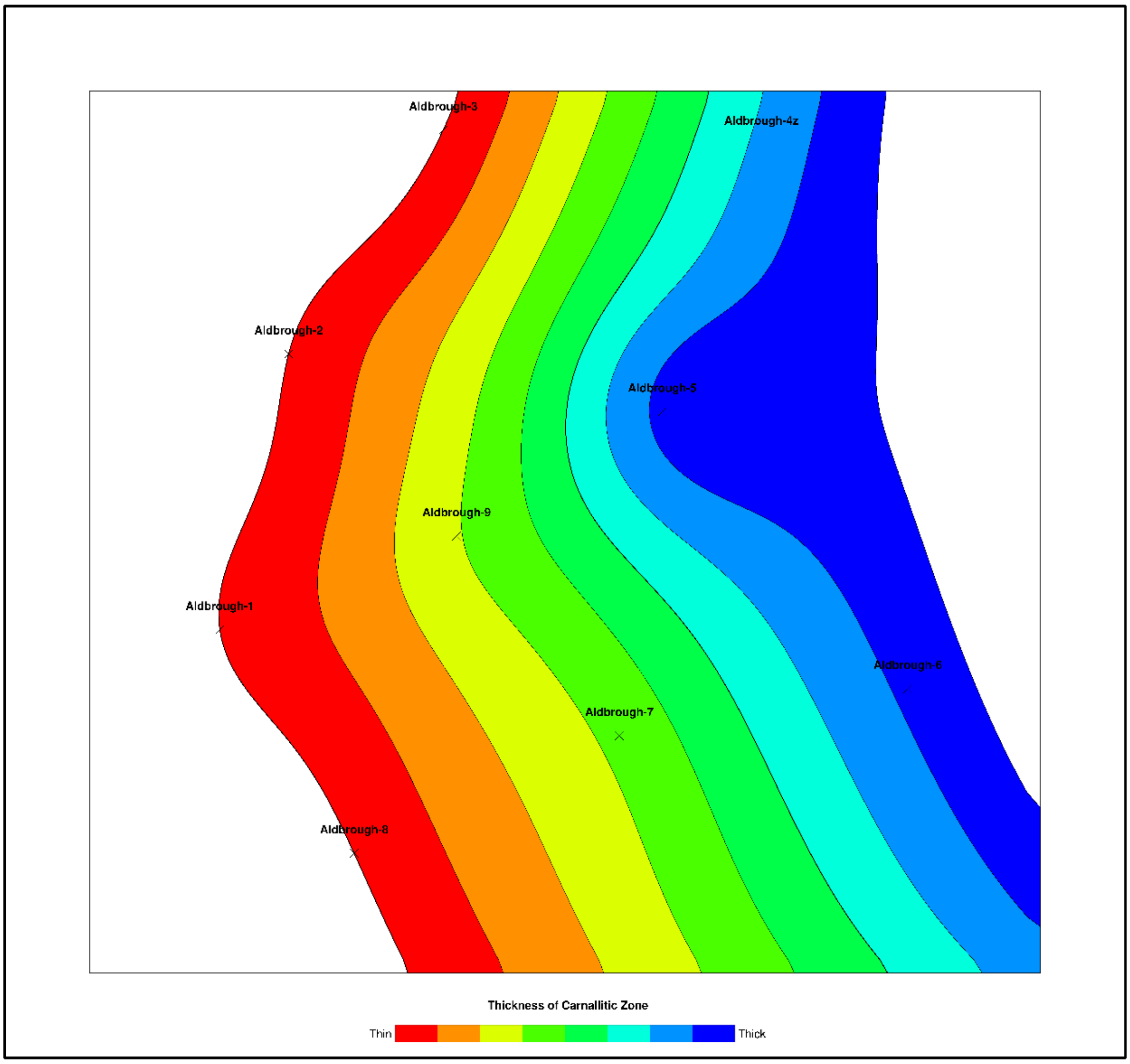

Figure 9 Distribution of the carnallitic zone in the drilled Aldbrough area.

Two subsurface requirements are crucial for the development and operation of salt caverns, (1) a reasonable thickness of halite, and (2) its purity, relating to the thickness and distribution of insoluble or highly soluble salts, e.g. carnallite. Therefore, an understanding of the stratigraphic position, in particular of the Z2 Halite, in the AGS site is necessary to assess and extrapolate both parameters towards the adjacent AHS site in the south.

Re-evaluation of all wells and a unification of the well database provides the basis for an enhanced interpretation of the Z2 thickness and lateral distribution, including the carnallitic zone. Three NE-SW correlation panels of selected wells that are aligned in dip direction with respect to the palaeo-coastline, refine the regional cross section of Fyfe and Underhill (2023) and show a basin-to-onshore trend from NE to SW. The thickness of the Z2 Halite as potential host unit of the planned caverns ranges from ca. 160 to 200 m in the existing Aldborough wells. Potential reasons for the observed thickness variation of the Z2 Halite in the study area include, (1) primary deposition above a swell or mild topographic high, (2) salt-tectonic movement and deformation, or (3) a combination of both.

Secondly, the presence and thickness distribution of insoluble and highly soluble salts within the Z2 Halite have been investigated with a special emphasis on the latter. Overall, the carnallitic zone thickens to the east (Figure 9), which could reflect more marine influence towards the basin center in the east and more marginal condition in the west, where carnallite is largely absent. In the central part of the AGS cavern field, the carnallitic zone is 29-33 m thick and consists of several thin layers of carnallite that are recognizable by the log response (Gamma Ray, Density, Sonic). In contrast, in the east, the carnallitic zone reaches a thickness of 63-72 m and petrophysical log curves suggest a dense intercalation of carnallite beds with halite. Here the thickness of beds with high or very high carnallitic content may exceed 10 m. A subsurface analogue of deformed carnallitic layers within halite has been investigated in the underground potash mine Boulby (Chapter 4) to the north of Aldbrough, as well as in the salt mines Bernburg and Teutschenthal in Germany (Figure 10).

Figure 10 Carnallitic layers (pink) within the Z2 Halite (grey) in the underground salt mine Teutschenthal, Germany. Note the strong deformation into pygmatic folds and en-echelon clasts due to halokinesis.

6. Bromide analysis

A common procedure to detect the progressive evaporation of sea water within a Zechstein cycle, including the carnallite at its top, is a bromide analysis, which has been performed on available core material from Aldbrough-1 and -2 wells. The rationale is that during progressive evaporation of the Zechstein seawater, the trace element bromine underwent an increase in concentration within the residual seawater. Consequently, the chloride anion (Cl-) in the crystal lattice of precipitated halite (rock salt, NaCl) was progressively replaced by bromide (Br-). Consequently, bromide profiles of the bedded Zechstein 2 rock salts in the SPB demonstrate a continuous increase in bromide content from the base to the top, culminating in a peak of the bromide levels around the potash seam (equivalent to 'Kaliflöz Staßfurt') at the top of the unit (Küster et al, 2008). This pattern of increasing bromide content has been utilized in salt domes as a relative age-dating tool, thereby supporting the development of 3D geological models (Schramm et al. 2002; Küster et al., 2008).

For Aldbrough-1 and Aldbrough-2 a rather atypical bromide distribution is observed, with numerous deviations from the idealized increasing-upward bromide trend as expected for the Z2 cycle. Nevertheless, bromide curves for both wells exhibit similar trends within comparable ranges of absolute bromide content in halite confirming the correlations observed from core and wireline logs. In addition, bromide values reach values commonly interpreted to represent the carnallite field. However, no evidence of carnallite could be found in the cores at these depths or further up-section. This aberrant bromide distribution may be explained by a secondary event of brine migration, being enriched in bromide and possibly potassium (and magnesium) overprinting the primary deposition and concentration of bromide. Comparable studies performed in the German part of the SPB confirm the redistribution of bromide in the Z2 Halite and a homogenization of the originally varying bromide contents (Küster et al., 2008; Warren, 2016). Furthermore, correlation with UK offshore wells indicate a similar carnallite distribution as observed in Aldbrough and Atwick. This might either require semi-regional fluid migration, redistributing potassium and magnesium or the presence of sub-cycles within the Z2 evaporation cycle if the carnallite is of primary origin.

7. Microbiology and geochemistry

Hydrogen is one of the most attractive energy sources, i.e. electron donor for many different microorganisms in oxygen-free subsurface environments such as salt caverns. Hydrogen-oxidizing enzymes, called hydrogenases, split the hydrogen into protons and electrons, which provide the energy for many cellular reactions. In principle, microbial hydrogen consumption can be coupled to the reduction of nitrate, ferric iron, sulphate, elemental sulphur, or carbon dioxide to produce nitrogen, ferrous iron, hydrogen sulphide (H_2S), acetate or methane (Dopffel et al., 2024). It is anticipated that the majority of microbial reactions with hydrogen will take place at the surface of the sump, i.e. brine-gas interface and along the moist cavern walls. While the main metabolisms are understood, the *scale of these reactions* in the subsurface remains elusive, given the unknown upscaling of these reactions from laboratory to cavern scale and the presence of self-enforcing and self-limiting feedback processes (Dopffel et al. 2024). One of the latter has been documented by Dopffel et al. (2023), recording an increase in pH-value related to microbial consumption of hydrogen, leading eventually to a decrease in microbial hydrogen consumption. Hence, pH monitoring in the hydrogen withdrawal stream will inform about the severity of microbial reactions in the salt cavern and if any mitigating actions, e.g. biocides are effective (Beeder et al. 2024).

Since retrieval of microbiological samples from salt caverns is costly and laboratory incubation times can take up to one year, the number of samples and hence the data from which conclusions regarding microbial consumption of hydrogen are made, must remain limited. It remains to be shown that available results are *representative*, and if these results are *repeatable*. To address this questions, two caverns, i.e. Aldbrough-5 and Aldbrough-9 have been sampled for microbial analysis and will be resampled in the near future. After several months of incubation time, first results suggest that hydrogen consumption and H_2S production rates are very low.

Furthermore, observed cell numbers in Aldbrough-9 are low, while those in Aldbrough-5 are very low. This can be tentatively linked to the different salt stratigraphy in which both caverns were constructed. Based on the well log interpretation, Aldbrough-9 has almost no carnallite, while Aldbrough-5 shows significantly more carnallite. This notion is supported by the available sump composition analysis, indicating an order of magnitude higher K^+ and Mg^{2+} content in Aldbrough-5 compared to Aldbrough-9. It is understood that the presence of Mg^{2+} in a solute has an adverse effect on cell metabolism, i.e. magnesium chloride ($MgCl_2$) is a chaotropic salt. Thereby, chaotropicity refers to the ability of certain substances, known as chaotropes, to disrupt the structure of macromolecules. In microbial cells, chaotropes can alter membrane permeability, causing leakage of cellular contents and disruption of essential processes. They can also cause proteins to unfold and lose their functional conformation, inhibiting enzyme activity, and other critical protein functions. The destabilization of macromolecules can interfere with metabolic pathways, reducing the efficiency of energy production and other metabolic processes. In contrast, kosmotropicity refers to the ability of certain substances, known as kosmotrophs, that stabilize the structure of water and enhance the stability of macromolecules. They promote water-water interactions, leading to a more ordered structure. Common kosmotropic salts include magnesium sulfate ($MgSO_4$) and sodium sulfate (Na_2SO_4). Measuring the degree of chaotropicity/kosmotropicity as outlined in Hoth et al. (2025) would have the following benefits:

1. Screening of geological salt accumulations with a higher content of chaotropic salts prior to the development of salt cavern fields to a priori reduce microbial risks
2. When building new salt caverns, the chaotropic/kosmotropic impact of the salt stratigraphy on microbial activity can be assessed early
3. When converting existing salt caverns from hydrocarbon to hydrogen storage, measuring the degree of chaotropicity/kosmotropicity of the salt cavern brine provides an indication of cavern specific microbial risks, which can then be reduced by adding a chaotropic agent
4. Should the initial salt cavern brine be kosmotropic, chaotropic agents can be added to subdue or even inhibit microbial growth
5. Should adverse microbial activity emerge during salt cavern operations, addition of chaotropes might provide an easy and cost-efficient way to reduce microbial activity

Lastly, hydrogen may also directly react with rocks exposed along the cavern walls, especially those containing sulphur, i.e. kieserite ($MgSO_4 \cdot H_2O$), anhydrite ($CaSO_4$) and pyrite (FeS_2), where the latter is commonly contained within organic shales.

8. Solution mining

The solution mining process is a key component of cavern storage development and has a significant impact on the overall project timeline and the longevity of the caverns. Each cavern requires a tailored leaching strategy to account for site-specific geological conditions, including salt purity, insoluble content, leaching velocity, and rock mechanical properties. To achieve the desired cavern geometry, operational flexibility is required to adjust critical operational variables throughout the leaching process. These include leaching rate, mode of leaching, i.e. direct or indirect injection, and the depths at which the leaching strings and blanket interface are positioned. Continuous monitoring, including sonar surveys, pressure measurements, and chemical analysis of the brine, ensures the process is refined in response to new data, optimizing cavern development. This should be done in an iterative process, where the findings from one cavern guide the positioning and timing of solution mining measures for the next cavern. Key implications of this approach comprise:

1. The leaching sequence is specifically structured to accommodate the impact of highly soluble salts on cavern stability and geometry. Initially, the cleaner halite sections near the bottom of the Z2 Halite are targeted to achieve a wide cavern base, enabling the collection of insoluble from overlying, less pure salt sections.
2. To enhance structural integrity, wide-span flat roof sections as developed in AGS are avoided, both during the initial leaching phase and throughout the main development of the cylindrical cavern section. Therefore, cavern geometries with a bell-shaped roof as developed in Atwick are aimed for.
3. Preferential leaching is controlled to maintain compliance with rock mechanical design principles, ensuring that the final cavern diameter and inter-cavern spacing adhere to established safety parameters.
4. Special attention is given to the selection of the blanket medium, as hydrocarbons such as diesel are avoided to prevent contamination of the stored hydrogen and to avoid adding nutrients for hydrogen consuming bacteria.

The design of the solution mining strategy utilized the lessons learned from the development of the existing AGS and Atwick cavern sites. This included a thorough evaluation of the solution mining records and carrying out leaching history match assessments. The latter provided additional evidence for the presence of highly soluble salt, e.g. carnallite, based on the observed cavern growth and brine concentration, contrasted against the expected leaching behavior in the absence of highly soluble salt.

9. Thermodynamic and coupled thermo-mechanic analyses

A thermodynamic study with the objective of evaluating the thermodynamic behavior of the planned storage operation was conducted. This was based on the desired cavern geometry and volume requirements, as well as the operating regime, with the aim of determining whether the current cavern design can successfully accommodate the intended storage regime. The model was used to employ a thermodynamically coupled rock mechanical model in order to ensure that the AHS caverns will operate in a pertinent geomechanical operating envelope and that the caverns long-term integrity is thoroughly investigated.

The operation pattern employed for these models was utilized to represent a high gas injection and withdrawal rate, based on a maximum allowable pressure change rate of 20 bar/day, transitioning directly from maximum pressure to minimum pressure and back to maximum pressure. This approach was used to understand temperature variation under extreme operation conditions, even if the actual cavern operations may differ. Rock mechanical properties of the Z2 Halite were derived from laboratory tests of cores from the AGS wells. The main results of this study are summarized as follows:

1. Successful simulation of subsurface stress concentrations
2. The overlaying Sherwood Sandstone helped reduce vertical convergence and ensure cavern wall stability.
3. Temperature changes were primarily limited to the cavern's periphery.
4. Compressive stresses were observed at the modelled cavern roof rendering tensile failure practically unattainable.
5. Shear stresses were within the shear strength limit of the salt, and the maximum shear strain did not exceed 10%.

It was therefore concluded that the caverns could maintain their structural integrity and effectively contain hydrogen over the long term, despite the conservative assumptions regarding the operational regime.

10. Summary

The joint venture partners Equinor and SSE plan to develop a cavern field for hydrogen storage (AHS) near the existing natural gas storage (AGS) plant at Aldbrough, UK. Geological, petrophysical, geomechanical data, as well as lessons learned from AGS solution mining and cavern operations will be critical to optimize AHS cavern development in the Z2 Fordon Evaporites of the Permian Zechstein Group. A stepwise approach is advocated, highlighting the need for a thorough integration of the existing data to define site- and cavern-specific leaching concepts, requiring operational and organisational flexibility during execution and operation. Consequently, site specific geological conditions directly control storage volume, infrastructure, operational flexibility, and ultimately the economic viability of the project. Lastly, a tight integration of the subsurface project implementation with above-ground facility planning and finance is required, to ensure safe and efficient operations.

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