A geological reappraisal of the Preesall Saltfield, Lancashire, United Kingdom: recognizing geological factors relevant to gas storage

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Abstract

Bedded salts are characteristic of halite developed in onshore UK, and are hosts or proposed hosts for underground gas storage sites in Cheshire, Dorset, Lancashire and Yorkshire. Geological assessments of proposed storage sites provide information that influences aspects of the planning, design and construction of facilities, including cavern and infrastructure placement and operational parameters. The Preesall Saltfield is located near Blackpool in north-west England and has been an area of interest for the underground storage of gas in solution mined caverns in thick bedded halite for over a decade. Interest in this area continues, driven by UK Government's need for additional gas storage in a bid to stabilize supply as the UK makes a transition to become a net importer of natural gas.

A comprehensive reassessment of the Preesall Saltfield has greatly improved the understanding of the structure, geology and processes that affect the area, providing key data that may influence the design of a proposed UGS facility. 3D modelling of the saltfield reveals it to be a north-trending half-graben, bound to the west by the Burn Naze Fault, preserving some of the thickest known halite deposits found onshore in the UK. Wet rockhead conditions are developed in the eastern part of the saltfield and were exacerbated during the 1900s due to poor brining techniques. Further migration of wet rockhead, which is now thought to be under a protective 'brine blanket', is unlikely if the current hydrogeological conditions persist. A detailed stratigraphy is proposed for the salt body based on the down-hole geophysical signature and geological core logging. Sedimentological studies indicate the halite predominantly crystallised in shallow to moderate water depths that periodically dried out, from foundered mats of halite crystals, with minor zones of cumulate development. This understanding addresses some of the geological factors relevant to an assessment of the suitability of the Preesall Saltfield as a host for UGS.

Key words: Bedded Salt Deposits; Computer Modeling; Computer Software; Geology; Seismic; Solution Mining and Salt History; United Kingdom; Preesall Halite; Triassic

Introduction

In 2004 the UK became a net importer of natural gas (DTI, 2006), with Norway and Qatar supplying the greatest proportions of natural gas and LNG respectively (DECC, 2011a). UK demand is high, principally for domestic supply and power generation, although indigenous natural gas production in the North Sea continues to fall. Against this background of continued and rising demand, and in a bid to improve energy security, UK Government policy currently supports the need for increased gas storage, as laid out in a 2007 UK Government White Paper (DTI, 2007), further clarified by a UK National Policy Statement (DECC, 2011b). There is a need for increased storage capacity in the UK to provide security of supply and financial stability of the gas market, especially in the winter, when strategic seasonal demand typically peaks.

There are 4 main halite formations, all of bedded, not domal salt, that are currently thick enough to host economically viable UGS schemes in the UK (Evans & Holloway, 2009). Currently in the UK, there are 5 operational UGS schemes in solution-mined caverns in halite, with a further 9 that have been granted planning permission (Table 1). Plans for one scheme, located within the Preesall Saltfield, are currently under consideration by the Infrastructure Planning Commission. Geological factors have played an important, but variable, role in the consideration of planning consent. At the King Street scheme, which was the subject of a public inquiry in 2009, geological factors were not contested (Burden, 2009). At Byley they were a consideration, but geological factors were not questioned to the extent they were in the case of the proposed Preesall scheme, where the failure to demonstrate the proposed development would not represent an unacceptable risk of gas migration was considered a major reason for justifying the refusal of planning permission (Simpson, 2007). While the Preesall inquiry was underway, a planning application was made for the Stublach development (Dec. 2005) and unopposed (in terms of the geological factors) received planning approval by June 2006. Of the major onshore halite formations in the UK, the Preesall Halite remains the only one without active storage facilities or approved plans to develop such schemes.

Table 1. Status of solution cavity underground gas storage schemes in the UK. Partly sourced from Evans (2008) and Evans & Holloway (2009).

Site name	Saltfield	Status	Storage Horizon
Hole House Farm	Cheshire	Operational	Northwich Halite
Holford H165	Cheshire	Operational	Northwich Halite
Holford (Byley)	Cheshire	Planning approved; under development	Northwich Halite
Stublach	Cheshire	Planning approved; under development	Northwich Halite
King Street	Cheshire	Planning approved	Northwich Halite
Hill Top	Cheshire	Planning approved; under development	Northwich Halite
Parkfield Farm	Cheshire	Planning approved	Northwich Halite
Portland	South Dorset	Planning approved; under development	Dorset Halite
Gateway	Morecambe Bay	Planning approved; under development	Preesall Halite
Preesall	Preesall, Lancashire	Pre-planning with UK infrastructure Planning Commission	Preesall Halite
Teeside	Billingham/Wilton	Operational	Permian salt
Whitehill	Aldbrough	Planning approved	Permian Fordon Evaporites
Hornsea	Atwick	Operational	Permian Fordon Evaporites
Aldbrough 1&2	Aldbrough	Operational	Permian Fordon Evaporites

The Preesall Saltfield is Triassic (Anisian) in age (Warrington *et al*., 1980; Plant *et al*., 1999), and located in the English county of Lancashire about 70 km north-west of Manchester. The halite body is also known offshore in the East Irish Sea Basin, and elsewhere onshore at shallow depths to the north near Barrow in south Cumbria, and further south, to the east of Leyland, Lancashire. The saltfield is approximately 4 km by 4 km, and is located in a down-faulted north-trending asymmetric, westerly-tilted-graben (Figure 1). The Preesall Saltfield has been investigated as a possible host for underground gas storage in solution-mined salt caverns since the mid 1990s (Daran Petroleum, 1996; Jenyon, 1997). The saltfield was one of the first to be commercially exploited, with serious exploitation having commenced in 1889 (Thompson, 1908) and during the early 1900s, was worked for both brine, via numerous brine wells, and (dry) rocksalt, by the Preesall Saltmine, located in the shallower, eastern part of the brinefield. The field is of particular interest in the part it played in the development of the technique of controlled brine-pumping (solution-mining), which was adopted in other UK saltfields and came to dominate the industry in Britain (Wilson & Evans, 1990).

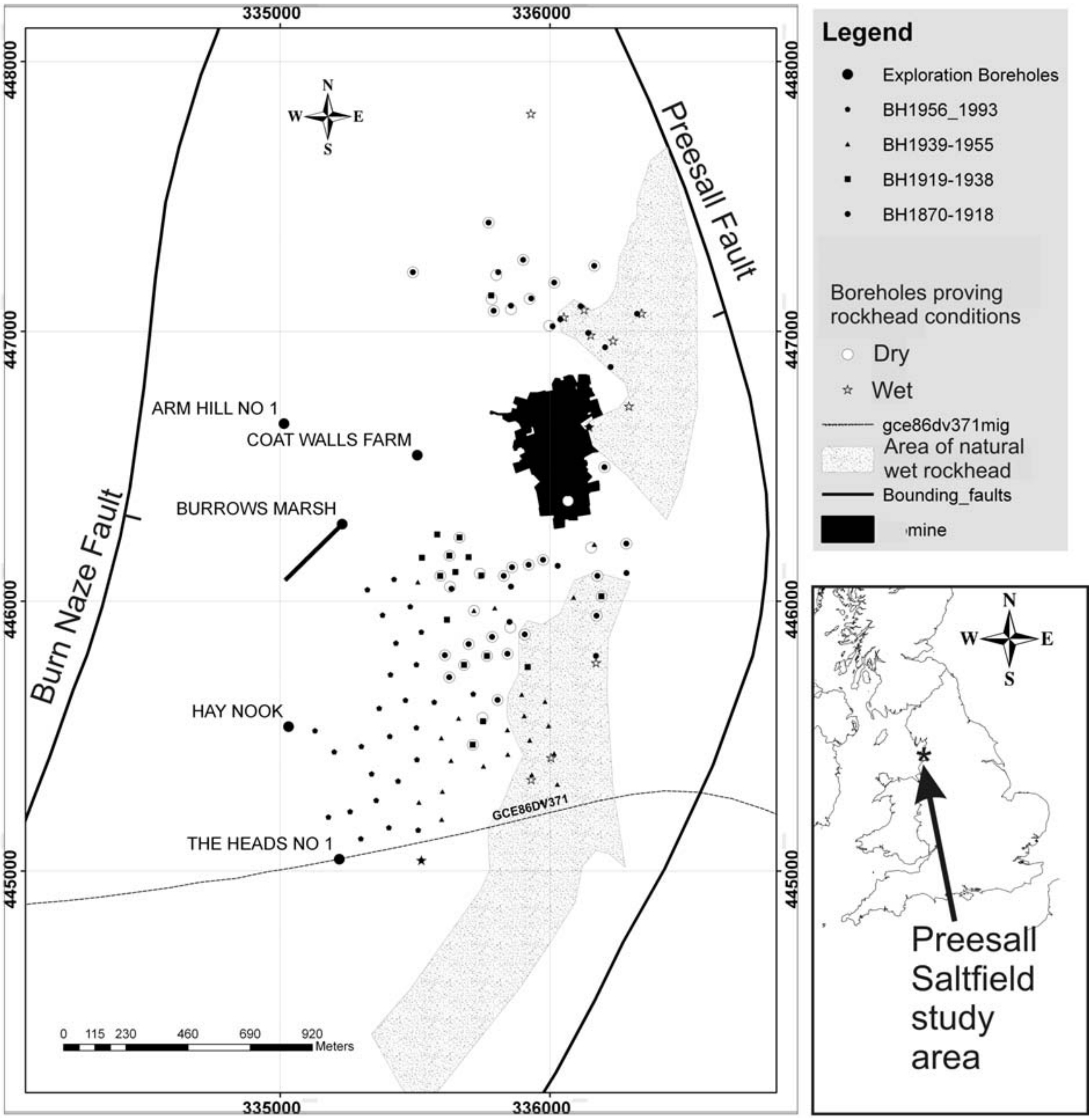

Figure 1. Main datasets and geological features of the Preesall Saltfield referred to in the text. The saltfield is bound to the east by the Preesall Fault, and to the west by an antithetic to this, the Burn Naze Fault. Natural wet rockhead (stippled grey) is developed in the eastern part of the saltfield. Overburden to the halite has been characterized by the BGS Coat Walls Farm Borehole. The halite has been proved by a series of exploration and brine wells. The halite was worked from two levels during the 1890s - 1930s by the Preesall Salt Mine. Seismic reflection lines, including Gas Council line GCE-86-DV371, were shot during the 1970s – 1990s, for hydrocarbon exploration and latterly to prove the halite interval in efforts associated with developing solution-mined cavities for underground gas storage. The latest phase of exploration (Arm Hill # 1, Burrows Marsh, shown with deviation, Hay Nook and The Heads # 1 boreholes) were also associated with UGS proposals.

This paper gives a geological overview of the Preesall Saltfield, including a fresh understanding of the stratigraphy, structure and sedimentology, and addresses critical parameters relevant to the development of solution-mined caverns that are primarily influenced by the geology. These include the depth and thickness of the halite body, the structural complexity of the saltfield, and the likely extent and development of natural and human-influenced dissolution of the upper salt surface (wet rockhead). The sedimentology of the Preesall Halite, and inferences on the depositional environment, give confidence to correlation of the salt body locally within the Preesall Saltfield, and regionally with the Northwich Halite of the Cheshire region, some 75 km to the south (see Evans *et al*., 2011).

Solution cavity underground gas storage schemes rely on a complex interplay of economics (including the volatile gas markets and investor backing), technology (such as drilling and pipeline techniques) and science (including geology and thermodynamics) to succeed. However, favorable geological conditions can prove critical to the eventual success of a scheme. Although some unfavorable geological scenarios, such as poor foundation conditions in the shallow subsurface, can be engineered around and planned for, other geological factors cannot, and could cause a scheme to fail before it has got further than a desk study. These include the integrity of interbedded mudstone/other insoluble lithologies within the halite unit, a poor understanding of the variation in thickness and depth of the halite body, and the presence or migration of wet rockhead conditions into the storage area. Engineering geology considerations such as the presence, and properties of faults and fractures, or concerns regarding seismicity, can cause concerns to populations local to proposed schemes. At the very least, if present within a prospective area, these factors will influence the siting of surface infrastructure, the location of pipelines or the location of the solution cavities. Other geological considerations that can affect how a scheme develops (and importantly for developers, may affect the ultimate storage capacities) include the behavior of interbedded mudstones when solution-mined, and the potential effect of halite crystal texture coupled with local/regional stress regimes on the morphology of developed caverns.

Additionally, the identification of gas pathways that may be created by human activity from storage infrastructure to a receptor fall into the remit of a geological investigation: mine voids and known and unknown boreholes within a proposed storage area are examples. If fully considered at an early stage, geological factors relevant to storage schemes can be identified and where possible, incorporated in mitigation strategies. This allows representation of geological factors in risk assessment strategies and incorporation in pre-construction and pre-operational safety plans, which are key steps in the pre-operational phase in the UK. When handled appropriately, a full understanding of the geological factors relevant to solution cavity underground gas storage schemes at an early stage can significantly reduce the overall financial burden and development time needed to engineer safe, efficient, fully operational facilities.

Review of the exploitation of the Preesall Brinefield

The history and development of the Preesall Brinefield is outlined by Thompson (1908), and Landless (1979). Brief accounts are also given by Wilson & Evans (1990) and Evans & Holloway (2009). Halite was discovered by accident in the Preesall Saltfield when, in 1872, a mineral exploration programme targeting iron ore, which at that time was known from the area north of Morecambe Bay, to the north of Preesall, proved thick, bedded halite (Thompson, 1908). The halite proved at depth was not obviously apparent at the surface: bedrock exposure and features are not present. Thick deposits in excess of 20 m of interbedded tills and sands and gravels were deposited during the Devensian glaciation. Following this, the modern course of the River Wyre developed across the western part of the saltfield, depositing tidal deposits of silt and clay, further mantling the mudstone and halite bedrock. Tell-tale signs, including linear subsidence features, and subsidence hollows in which peat accumulated in the superficial deposits are, however, present at surface. These were identified during geological surveying of the area in the 1960's (IGS, 1968), but very similar surface features are typically developed in the ice-marginal setting that covered the area at the end of the Devensian glaciation. These glacially-related features are developed in response to processes that both involve collapse of unconsolidated material into voids, one scenario involving the solution of halite, the other melting of ice trapped within superficial deposits. Linking the surface features to the dissolution of halite in the shallow subsurface was only possible once the presence of halite was known (Wilson & Evans, 1990).

The complex development of the Preesall Brinefield can be catalogued and displayed in a GIS, which allows for a quick and clear understanding of the spatial relationships between disparate datasets (e.g., Figure 1). Following the discovery of halite deposits, an exploration shaft was sunk, and brining commenced via this and subsequent brine wells, principally located immediately north and south of the Preesall mine (Figure 1), which opened in 1894 in the shallower, eastern part of the brinefield. Rocksalt was taken from two different horizons within the Preesall Halite, at approximately 143 and 274 m below ground level. Despite efforts to the contrary including pumping and the sinking of additional shafts, brine entered the mine through the roof in 1920, possibly sourced from the original exploration shaft. The mine eventually closed in 1930, due in part to the dissolution of pillars within the mine (Landless, 1979). Part of the mine subsequently collapsed in 1934, with a 5 acre area eventually subsiding and flooding with the formation of a surface subsidence pond or 'flash'.

A series of 8 wells were drilled into the disused mine workings in 1941, associated with the World War II war effort. Unpublished archival maps held by the British Geological Survey (BGS) (Figure 2) indicate that 7 of these wells were drilled to pump fresh water into the mine void, and one well, down dip of the others, was employed to extract the denser brine. The BGS holds an extensive range of often unique archive material that may be relevant to the development of many aspects of UGS. This includes documents that may constitute corroborative data, historic borehole log records (most of which are now available through the BGS GeoRecords online service), and background studies to published BGS work. The BGS also holds other data that may have little apparent geological value, but nonetheless are of potential relevance, such as photographs (many of which are available through the BGS OpenGeoscience service) and written manuscripts. Of particular relevance to the Preesall Saltfield is an unpublished study completed in September 1939; by the then Geological Survey (Geological Survey, 1939), to assess the halite resource and condition of the brinefield immediately prior to the start of World War II.

Following World War II, brine well development continued in a broadly south-westerly direction, with the shallower halite exploited in the decades before the deeper deposits, which were more costly and the brine technologically more difficult to win. In response to the closure of the local chemical plant at Hillhouse in Fleetwood (Landless, 1979; BGS, 2006), exploitation of halite ceased in 1993 (Wilson & Evans, 1990). During the active life of the brinefield, 113 brine wells are known to have been completed. Poor solution mining practice (due to a lack of knowledge regarding the development of stable brine caverns) resulted in some of the earlier caverns being developed until all the salt up to the lower boundary of the mudstone overburden was removed. On abandonment these caverns were left filled with brine, the deleterious effect of which to marls causes further weakening of the cavern roof. The roofs of such caverns tend to be unstable and fall into the cavern void. Some of these brinewells have continued to migrate upwards through the mudstone overburden, in some cases to surface, facilitated by the low bulking factor of the mudstone overburden, which precludes choking of the migrating collapse void/chimney. Preesall has some dramatic examples e.g. the Northfield collapse of 1901, and more recently in 1974, the Agglebys Crater (refer Table 2 and Evans & Hough, 2008b). Over the years, however, problems with subsiding brine wells were recognized to be influenced by the brining method and techniques of maintaining the pressure-tightness and stability of the cavities, both during and after use were developed by the United Alkali Company Limited and its ICI successor. The successfully developed solution-mining techniques were transferred to, for example, workings of the Northwich Halite in the Cheshire Brinefield.

Stratigraphical reappraisal of the Preesall Halite

Interest in the geology of the Preesall area continued after closure of the brinefield, with attention focused initially on hydrocarbon exploration, followed subsequently by investigations associated with the creation of underground caverns in the halite for the storage of natural gas. This has resulted in the acquisition and interpretation of a large volume of data describing the Mercia Mudstone Group, within which the Preesall Halite occurs. The Mercia Mudstone Group is a thick succession of primary red-bed mudstone and siltstone lithologies, with regionally developed accumulations of halite. The Preesall Halite is developed in the East Irish Sea Basin, in the Lancashire district onshore. The unit is assigned member status, within the Sidmouth Mudstone Formation of the Mercia Mudstone Group (Howard *et al*., 2008; Table 3).

Analysis of downhole geophysical log data (e.g., Dobbs *et al*, 2009 a & b; Evans *et al*. 2009 a & b), augmented by detailed lithological logging has permitted the development of a robust stratigraphy for the Preesall Halite. The bedded nature of the halite unit is revealed in downhole geophysical logs as a series of up to 7 high-gamma responses (Figure 3), confirmed by both borehole cuttings and core from the saltfield. The mudstones and mud-prone halite beds are correlated between boreholes and split the halite succession into distinctive packages. Log analysis indicates that the Preesall Halite is gradational with the underlying Thornton Mudstone, with thin beds of halite present in the upper part of the Thornton Mudstone, and thin beds of mudstone, such as the locally developed Bed A (Figure 3), present in the lower part of the Preesall Halite. The log responses of the lower part of the Preesall Halite vary, with mudstone Bed A identified in some, but not all, boreholes. Further borehole or detailed interpretation of high resolution seismic reflection data may confirm whether the junction is diachronous, or if small-scale local faulting affects the lower part of the succession in some areas. Overlying Bed A, which is developed in the central part of the basin, are a further 5 mudstone beds, with Bed 5 split into two discrete leaves locally within the thicker, deeper parts of the salt basin.

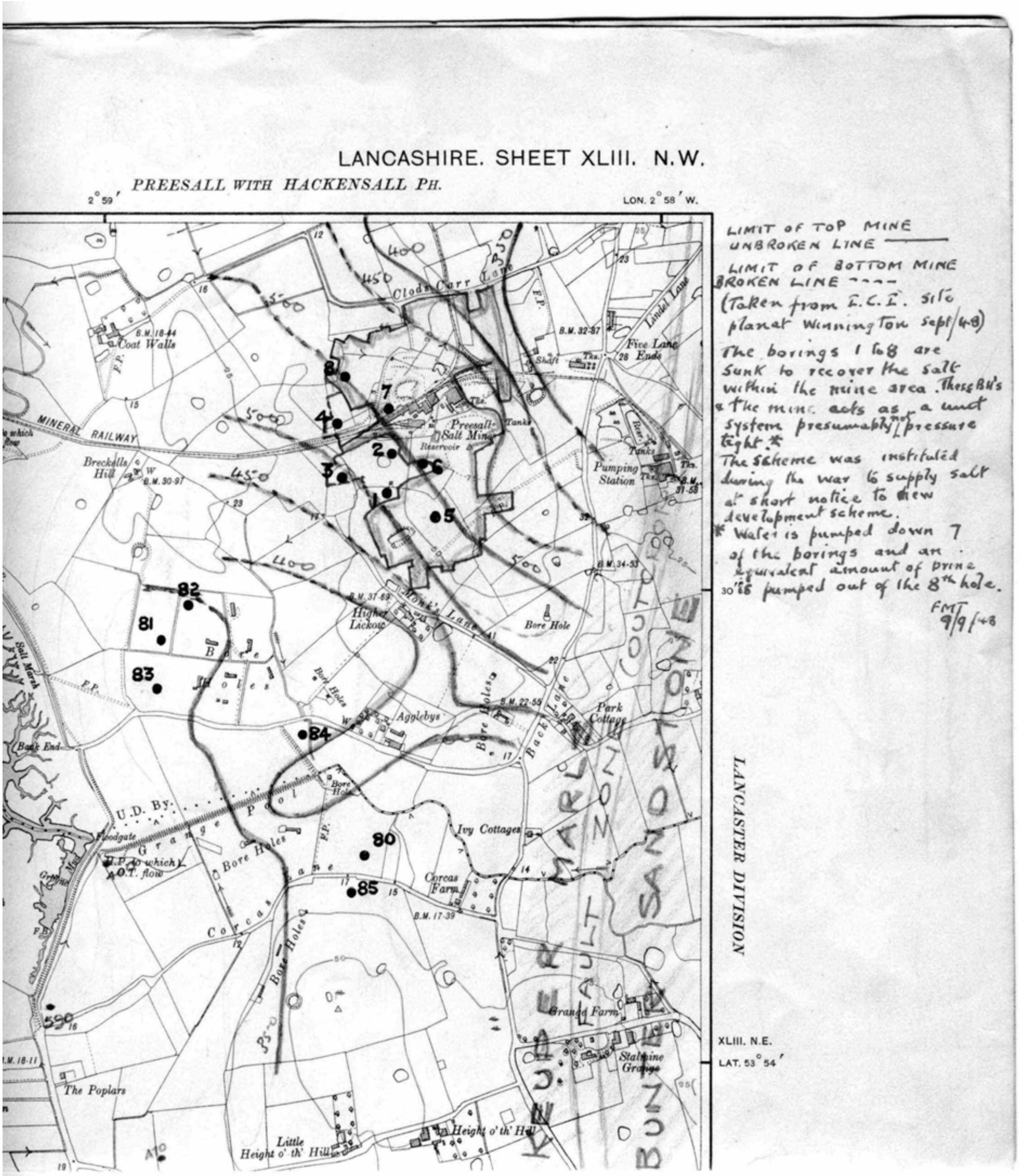

Figure 2. Archival information such as this manuscript map, produced by BGS and dating from 1948 (Geological Survey, 1948), is likely unique, and is an obvious resource for any desk study carried out in the initial stages of the commissioning a project for solution cavity UGS.

Table 2. Collapsed brine wells in the Preesall Brinefield. Most of these were developed early in the development of the brinefield, before it became best practice to maintain a halite roof to brine caverns. Partly sourced from Thompson (1908) and unpublished ICI records (ICI, 1997).

Year of collapse	*Brine well* (ICI brine well number)	Local name/British National Grid Reference
1891	BW-23	[336170 445798]

[Type text]

1901	BW-28, 29	Northfield [336062 447046]
1911/1965	BW-48	[336170 445798]
1923	BW-54	Westfield [336148 447256]
1930	BW-21, 26, 37	The Flash [336186 446910]
1934	BW-24, and part of the Preesall Mine	Preesall Mine [336130 446700]
1974	BW-52, 53	Agglebys [335864 445910]
1994	BW-88	Height'o'th'Hill [335846 445437]

Table 3. Stratigraphic nomenclature of the Preesall Halite and adjacent rock units in the onshore extent of the East Irish Sea Basin.

<table>
<tr><td colspan="5">Current nomenclature (after Howard et al., 2008)</td><td colspan="2">Former Nomenclature (Wilson & Evans, 1990)</td><td>Typical thickness at Preesall (m)</td></tr>
<tr><td rowspan="7">TRIASSIC</td><td rowspan="6">Mercia Mudstone Group</td><td rowspan="6">Sidmouth Mudstone Formation</td><td>Breckells Mudstone Member</td><td></td><td colspan="2">Breckells Mudstones</td><td>188</td></tr>
<tr><td rowspan="3">Kirkham Mudstone Member</td><td>Coat Walls Mudstone</td><td rowspan="3">Kirkham Mudstones</td><td>Coat Walls Mudstones</td><td>173</td></tr>
<tr><td>Pressall Halite</td><td>Preesall Halite</td><td>Up to 433</td></tr>
<tr><td>Thornton Mudstone</td><td>Thornton Mudstones</td><td>106 - 112</td></tr>
<tr><td>Singleton Mudstone Member</td><td rowspan="2"></td><td colspan="2">Singleton Mudstones (includes Rossall salt in lower part and Mythop salts in upper part)</td><td>181 - 311</td></tr>
<tr><td>Hambleton Mudstone Member</td><td colspan="2">Hambleton Mudstones</td><td>30 - 37</td></tr>
<tr><td>Sherwood Sandstone Group</td><td colspan="3"></td><td colspan="2">Sherwood Sandstone Group</td><td>>500</td></tr>
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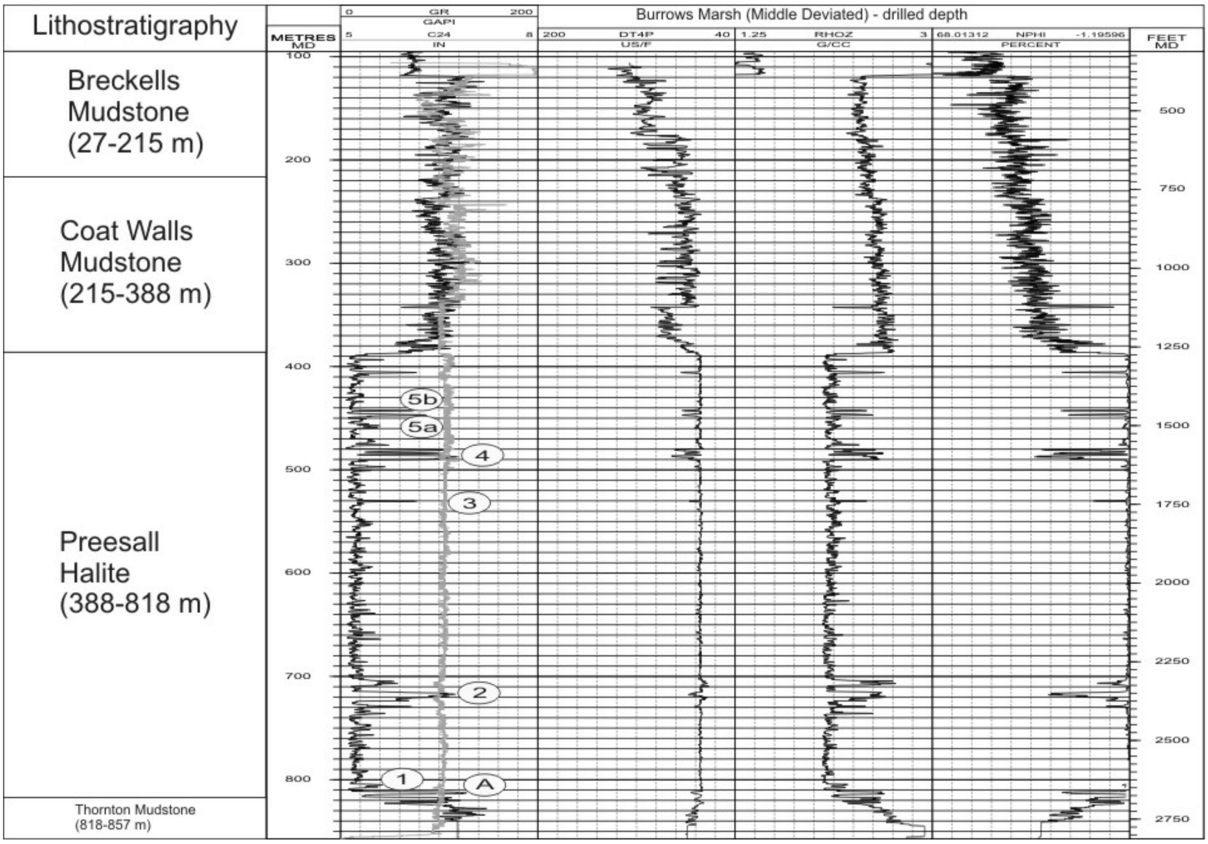


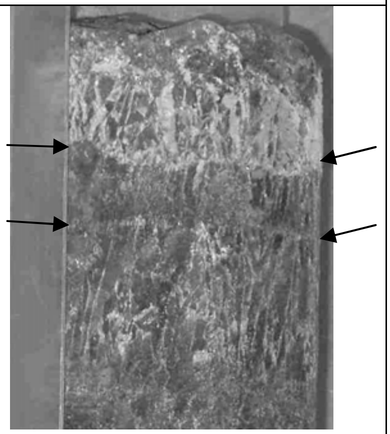
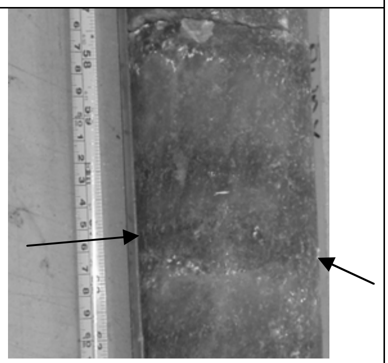
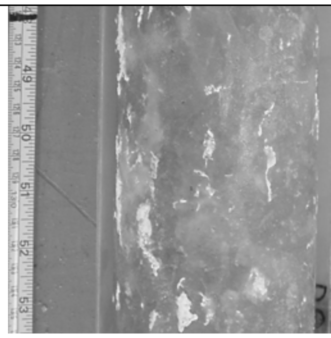
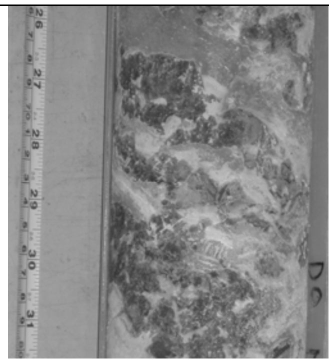
Figure 3. Geophysical logs (uncorrected for well deviation) from the Burrows Marsh Borehole, drilled between November 2008 and January 2009. The borehole was deviated up to 28 degrees to the south-west to prove the stratigraphy, depth and thickness of the Preesall Halite. The geophysical logs allow the halite to be split up based on high gamma (mudstone) intervals, with 6 main picks identified across the saltfield (Beds 1 – 5a and 5b), and with one further pick (Bed A) developed locally in the lower part of the halite unit.

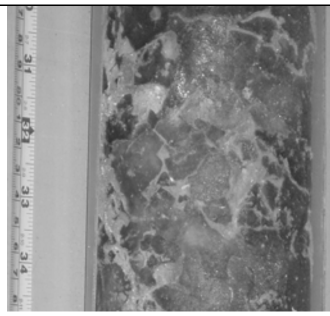
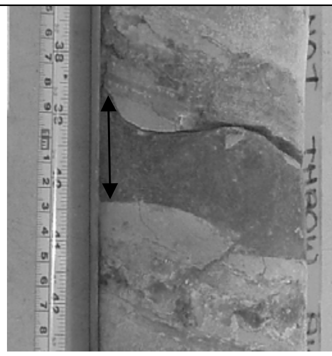
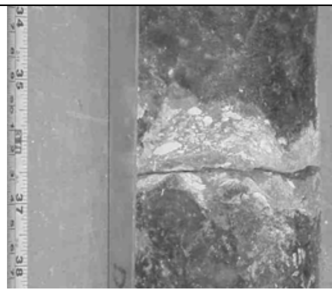
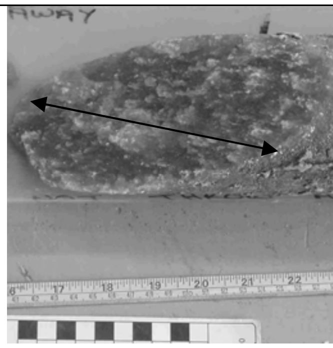
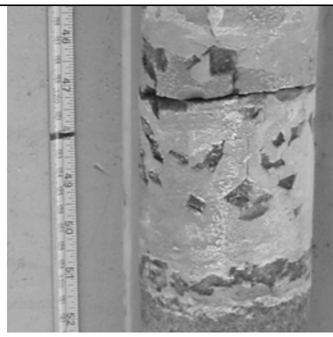
Sedimentology of the Preesall Halite from the Arm Hill #1 Borehole

The Arm Hill #1 Borehole (BGS reference number SD34NE/169) was vertically drilled in 2003 – 4 by Canatxx Gas Storage Limited, approximately 400 m to the west of Cote Walls Farm, close to Arm Hill, in the central part of the brinefield. The borehole was drilled to prove the Preesall Halite, and was fully cored from 349.60 m to terminal depth at 613.50 m, proving halite below 366.88 m (core logging indicates that the base of the Preesall Halite was not proved in this well). Nine main lithofacies and tectonic fabrics have been identified within the halite interval (Table 4), based on detailed core descriptions and lithological logging. These facies and fabrics may be considered end-members, with proven lithologies grading between two or even three facies/fabrics.

The lithofacies allow the depositional environment of the halite unit to be characterized as a primarily shallow, perennial brine pan that was only very rarely emergent. The development of cumulate intervals indicates that there were occasional periods when the water depth in the brine pan deepened enough to allow the brine from which the halite was crystallizing to stratify. Solution seams, typically less than 1 mm thick, indicate the influx of fresher water into the brine pan. Periods when halite crystallization ceased are represented by mudstone intervals; these are typically structureless through complete brecciation. Brecciation of the halite can be through a variety of geological processes, the principal being autobrecciation through haloturbation, where repeated halite dissolution and recrystallization soon after deposition churns the sediment pile. Other processes, such as emergence and desiccation may also play a part in brecciating the unconsolidated sediment, while structural effects can affect lithified strata. Zones of massive (structureless) halite are present; these are of indeterminate origin. Spectacular zones of high-angle recrystallized halite are present in ten zones throughout the halite interval. These are characterized by halite crystal elongation, producing a schistose fabric and apparent extension lineation suggestive of mylonites developed in ductile sheared zones. A near identical fabric has been described from cores of the Boulby Halite in a great number of boreholes on Teesside (Smith, 1996).

Table 4. Lithofacies and tectonic fabrics identified in the Arm Hill #1 Borehole core.

Lithofacies or tectonic fabric	Characteristics	Image of characteristic example of lithofacies
Primary bedded/laminated halite	Halite exhibiting primary depositional sedimentary structures including primary crystal laminae with elongate, upward-oriented crystals. May include a minor mud constituent as beds, laminae or blebs. Brecciation features are common, forming penecontemporaneously or shortly after deposition through the dissolution and recrystallisation of halite. Rare solution seams (arrowed on image) may be present.	
Primary banded halite	Halite bands in thick laminae/thin beds, with light and dark bands. Solution seams (arrowed on image) may be present.	
Massive (structureless) halite	Halite with no apparent sedimentary structure; possibly fully recrystallised.	
Haselgebirge: halite and mudstone	Halite with approximately 20 – 80% mud content. Mud may be present as beds, laminae (pictured) or blebs. Of primary sedimentological origin but brecciation features are common, forming penecontemporaneously or shortly after deposition through the dissolution and recrystallisation of halite.	

Chickenwire halite	Halite with approximately 20 – 80% mud content. Mud present between halite crystals has been squeezed creating a ‘chickenwire’ texture.	
Halite fracture infill	Fracture infills (arrowed on image) of halite, ranging up to tens of cm in width.	
Anhydrite-dominated halite	Halite and up to approximately 20% mud, with anhydrite present as nodules (pictured, in a mud-dominated matrix), laminae and amorphous blebs. Teepee-type structures may be present.	
Recrystallised/ mylonitic halite	Halite with distinctive recrystallisation with a schistone ‘mylonitic’ flow texture; crystal elongation and extension lineation direction arrowed in image.	
Mudstone	Mudstone with up to 20% halite, present as individual crystals (pictured), thin beds or thick laminae.	

At Teesside, the fabric was found forming sheets ranging from a few millimetres to 3.8 m in thickness and give rise to anastomosing networks around less deformed halite ‘pods’. They were interpreted as the flow lineated sheets, some of which were also closely associated with breccias of anhydrite. Both fabrics were interpreted as the result of ductile flow of the halite due to differential extension within the halite body, the sheets having acted as 'glide planes' (Smith, 1996). The precise mechanism by which the flow-lineated sheets in the Boulby Halite evolved is as yet unclear, but the flow of the halite was probably driven by pressure gradients (Talbot et al, 1982; Smith, 1996). These at Preesall may have developed as ductile deformation zones in response to intrahalite body stresses, or be associated with fault development: the latter having been identified immediately to the west of the Arm Hill #1 Borehole location (Evans & Hough 2008a).

The identification of the internal stratigraphy of the Preesall Halite in the Preesall Saltfield has allowed it to be correlated with the offshore Preesall Halite succession, and importantly the Northwich Halite in the Cheshire Basin (Jackson & Johnson, 1996; Evans *et al*., 2011). This correlation indicates that the Preesall and Northwich halite units accumulated in a linked depositional basin, and periods of mud deposition were occurring over a wide area across the basin at similar times.

Structural reappraisal of the Preesall Saltfield

The understanding of the structure within which the Preesall Saltfield is situated has evolved since the original geological survey work published in the 1870s (De Rance, 1875), as more data has been evaluated. Seismic reflection data of varying vintage and energy source have been acquired across the saltfield and adjacent areas. During the early-mid 1980's, the Gas Council acquired seismic reflection data as part of their onshore oil and gas exploration programme. These data were reprocessed in 1996 as part of a study into salt cavern gas storage by Daran Petroleum Consultants Limited for British Gas Hydrocarbon Resources Limited (Daran Petroleum, 1996).

In 1997 three seismic reflection lines were acquired by IMC Geophysics for Canatxx Gas Storage Limited as part of investigations into the salt of the Preesall area for gas storage purposes. As part of a later phase of oil and gas exploration in this area, two further seismic lines were acquired and processed in 1999 by IMC Geophysics for Independent Energy Lancashire Plains (IELP). One of these runs E-W, close to the Arm Hill #1 Borehole, providing a good seismic calibration point. A number of the regional Gas Council and IELP hydrocarbon exploration lines and the three 'Canatxx' lines were again reprocessed during 2005 (Evans et al., 2005). This was in order to attempt the best resolution for the Preesall Haite interval for development of a 3D model of the saltfield.

Prior to the acquisition of seismic reflection data in the 1980s and 1990s, the saltfield was thought to be located in a downfolded syncline, with an axis running broadly northwards beneath the Wyre Estuary, partly fault-bounded to the east by the down-west Preesall Fault (Wilson & Evans, 1990). This interpretation was based primarily on borehole provings of halite, although Wilson & Evans (1990) did raise the possibility that the western margin of the saltfield could be faulted. The interpretation of seismic reflection data associated with hydrocarbon exploration led to the structural model of the saltfield being reinterpreted as a faulted half graben or westerly tilted asymmetric graben, with the western margin bounded by the Burn Naze Fault, antithetic to the Preesall Fault (Daran Petroleum, 1996) (Figure 4). The presence of the Burn Naze Fault has further been confirmed in Evans & Hough (2009a):

In the Burn Naze area, on the western bank of the River Wyre, the Burn Naze Fault is imaged on seismic reflection data from line GCE-86-DV371 (Figure 4) and proved by adjacent borehole provings (ICI exploration borehole B1 (SD34SW/2) which did not prove the Preesall Halite, spudding in older mudstones, and Borehole No. 27, Thornton (SD34SW/3), which proved the top of the halite at a depth of 174 m)

The fault has been tentatively identified on the western ends of two of the 'Canatxx' lines (CAN97-F and Can97-G) shot to the west of The Heads

ICI exploration borehole E1 (SD34NW/4), also known as the Hackensall Hall Borehole, proved only 81 m of halite, and experienced poor borehole conditions in the lower part, including lost core and poor quality of core recovered. It is interpreted as having passed through the fault, although it is possible that it intersected a parallel, subsidiary fault located just to the east of the Burn Naze Fault

A full reappraisal of the structure of the saltfield was undertaken by BGS in 2005 and was updated during 2008 - 10 on behalf of Canatxx Gas Storage Limited and Halite Energy Group Limited. The purpose of the work was to characterize the Preesall Saltfield as a potential host to solution-mined caverns for underground gas storage purposes (e.g., Evans *et al*., 2005; Evans & Hough, 2008a). The structural reappraisal comprised the following steps: literature review; data review; seismic reflection reprocessing and interpretation; 3D modeling. The process was iterative, with the model evolving to incorporate new data as it was acquired and interpreted.

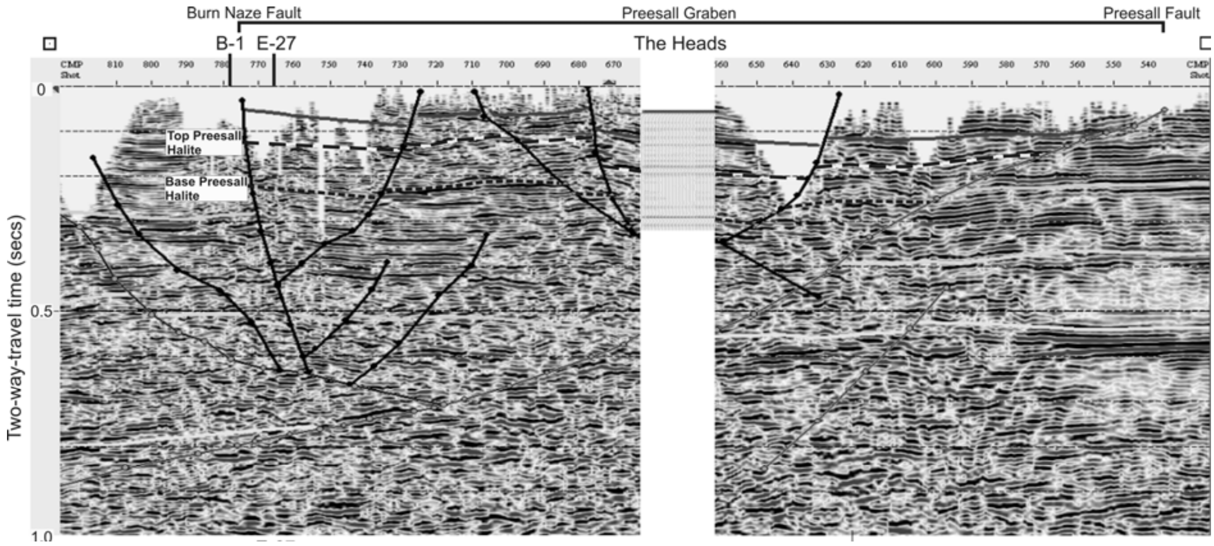


Figure 4. Reprocessed, migrated and interpreted seismic reflection line Gas Council GCE-86-DV371. The line confirmed the Preesall Fault marking the eastern boundary of the Preesall Saltfield, and also importantly the presence of the Burn Naze Fault which bounds the western margin of the saltfield. The line also images a series of northerly trending intrabasinal faults affecting the saltfield. This line was calibrated with a synthetic seismogram generated from The Heads #1 Borehole (also shown), allowing the horizon of the Preesall Halite to be confirmed.

3D model construction

A first stage to generation of the 3D model was to thoroughly check and validate all relevant data holdings relating to the Preesall area. For analogue data, this included verifying the brine well/borehole location and name, as these metadata are details that can become confused in areas, such as Preesall, where there has been a long and varied exploration activity under numerous owners. It is also essential to verify the spatial parameters including reference systems (National Grid/ Lat-Long and spheroid) for more recently acquired digital datasets and within modeling packages, as errors and inconsistencies with these parameters can cause spatial errors in excess of 50 m on the ground. Much useful data are part of BGS holdings, which importantly include over 1.1 million borehole records from onshore Great Britain. Section 23 of the Mining Industry Act 1926 (as amended by the Mines and Quarries Act 1954 and the Science and Technology Act 1965) requires that borehole logs relating to boreholes over 30 m deep from surface, and any boreholes drilled for mineral exploration or exploitation (including petroleum) are lodged with BGS; interpretations of these data contribute to BGS strategic survey activities. Legacy downhole geophysical log data, including down-hole geophysics and temperature changes with depth is also held by BGS, and included data from 25 boreholes within the saltfield. These included two BGS stratigraphic boreholes drilled in the 1970s to characterize the mudstone overburden to the Preesall Halite; additionally data of variable composition and quality from brine wells was also available. Data from 745 boreholes describing the superficial (Drift) deposits, and top and base of the halite unit were extracted and captured according to modern stratigraphic nomenclature (e.g., Howard *et al*., 2008). Where not otherwise recorded, the start height of borehole logs was assumed to be ground level, and assigned automatically from the Intermap Technologies/CEH NEXTMap™ 5 m 'bare earth' Digital Terrain Model (Intermap Technologies, 2007). Additional data, where present, describing factors such as the state of rockhead (wet or dry), location of mine levels, horizons of interbedded insoluble material (mudstone and anhydrite) and dates of brine well activity were also captured. Following reprocessing and reinterpretation (detailed by Evans *et al*., 2005), top and base halite depth data from over 15 line kilometers of depth-converted seismic lines relevant to the saltfield were also databased. These data form the core dataset used to describe the geology of the saltfield.

3D modeling has developed over the past 20 years to become the industry standard tool by which geological scenarios are communicated to users (Giles *et al*., 2010). Since the late 1980s, the BGS has developed in-house capability in 3D modeling, culminating with the co-development of the GSI3D modeling system, with Insight (Kessler, Mathers & Sobisch, 2009).

All data relating to subsurface geological horizons were initially imported into GSI3D, which holds attributed data points in their correct spatial position (geological interface; easting, northing and height data/depth below ground level). In GSI3D, a series of 44 cross-sections were manually constructed, which allowed for the accommodation of geological interpretation to be applied to the data (for example, to accommodate areas of wet rockhead to explain reduced provings of the thickness of halite). 'Loop-tying' allowed interpretations and trends of the geological surfaces to influence adjacent cross-section lines, and control points were used to constrain the model to take into account influences including the effect of dip in regions of sparse/absent data, based on projected intersections from adjacent cross-sections. Thus, a data cloud of attributed nodes represents the geological interpretation of the major geological horizons within the saltfield.

The data cloud generated in GSI3D was exported to the Gocad 3D modeling platform, where fault surfaces were inserted into the model. Their positions were based on the hanging and footwall cutoffs against the upper and lower surfaces of the halite body, as interpreted from seismic reflection lines, or from borehole interpretation; with the hade (dip) of the faults was estimated from the throw of the fault and the intersection of the fault with upper/lower halite surfaces.

Structure and thickness changes of the Preesall Halite across the Preesall Saltfield

The modelled surfaces (Figure 5) of the top and base of the Preesall Halite indicate that the halite is shallowest in the north-east, around Town Foot [333600 447000]. The halite generally deepens westwards, in response to a prevailing westerly dip. The halite thickens from 100 m or less in the south and west, to a maximum proved thickness of 320 m, proved by the Burrows Marsh Borehole (Evans *et al*., 2009). Seismic reflection data indicate that the halite reaches a maximum thickness of over 440 m in the basin depocentre, which is located in the area beneath Barnaby Sands, some 500 m north-west of The Heads, in the western part of the graben. For comparison, this is excess of the thickest development of the Northwich Halite of 283 m, proved by the Byley Borehole [372070 369420] in the Macclesfield district of Cheshire (Evans *et al*., 1968). The basin depocentre is bound to the south by a complex of west-north-west trending faults; south of this zone, the halite thins dramatically to interpreted thicknesses in the order of 150 m.

Thickness changes in the halite are apparent from the geophysical logs of ICI brine wells in the south-western part of the brinefield, and ICI exploration well P1 (located to the north of the brinefield), and gas storage exploration wells completed in 2003 - 4 (Arm Hill #1 & The Heads #1, Figure 6). Subsequent exploration boreholes, Burrows Marsh and Hay Nook, completed in 2009, have confirmed this trend (Dobbs et al., 2009 a&b; Evans et al, 2009 a&b). These geophysical data indicate that thickening is accommodated within the halite units, with intervening mudstone beds becoming vertically dispersed and more halite-rich.

Thickness differences in the halite body, typically in the region of 30 – 80 m, are apparent across faults in the saltfield. Tectonic thinning of the salt body is expected with normal faulting of this type, but does not fully account for the greater thickness variations apparent in the south-western part of the saltfield. In these areas, an element of synsedimentary faulting was likely to have been active during the deposition of the halite, allowing the central part of the graben to subside at a greater rate than the eastern and possibly the western margins.

Identification of wet rockhead in the Preesall Saltfield, the effect of human activity and potential for further migration

Natural wet rockhead conditions are present in the eastern part of the brinefield, adjacent to the eastern bounding Preesall Fault Zone, in a north-trending band up to 600 wide, from Town Foot in the north to Burrows Farm [335670 444280] in the south (Wilson & Evans, 1990). Wet rockhead

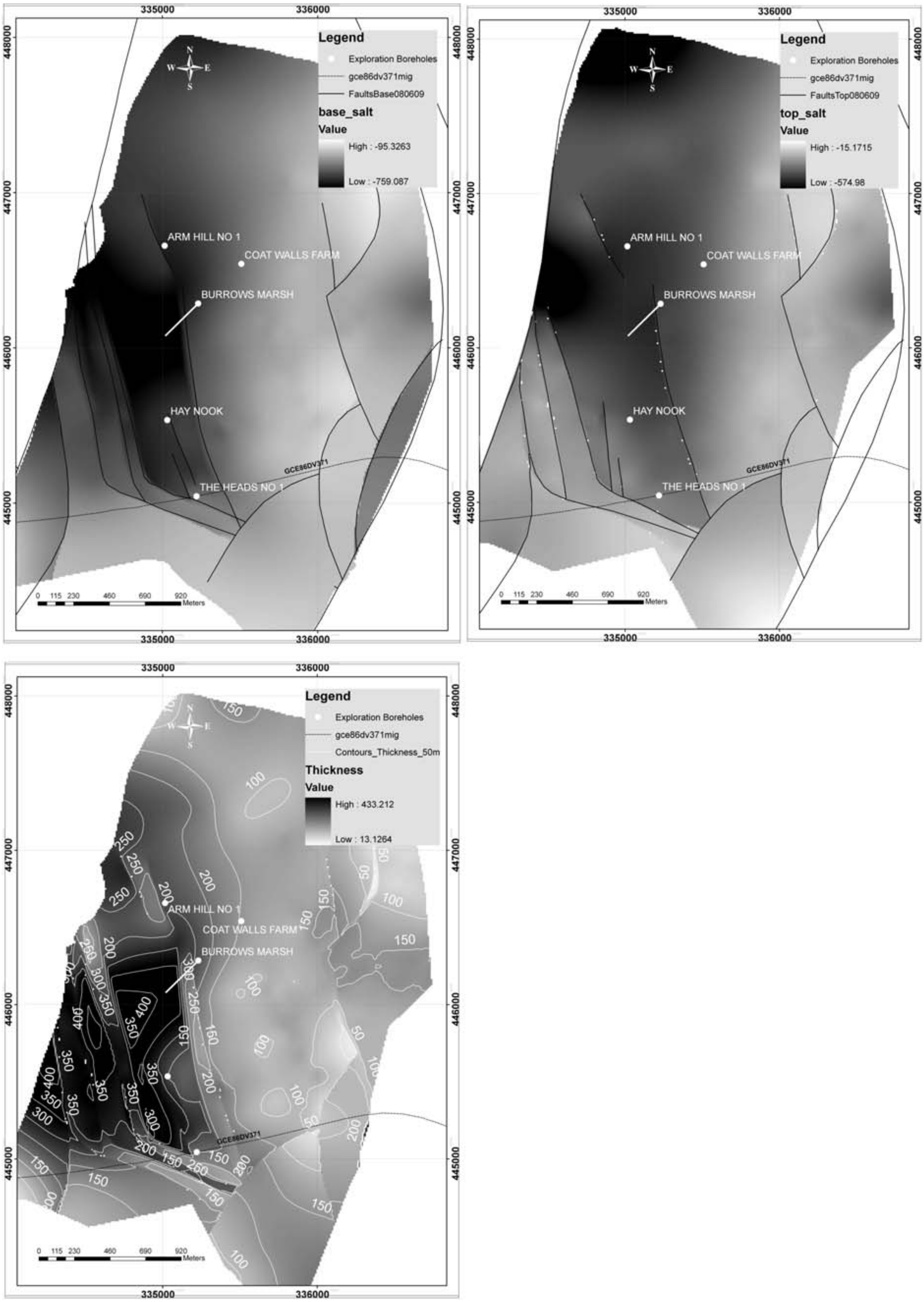


Figure 5. Modelled surfaces of the top and base of the Preesall Halite, along with an halite isopachyte map generated by subtracting the top surface from the base and synthetically filling in fault gaps to create a seamless model of the halite body. Data was initially input into the BGS GSI-3D modeling

package. Data were then exported to Gocad, where faults were inserted into the model. Resulting surfaces were exported to ESRI ArcGIS to enable smooth contouring for final output.

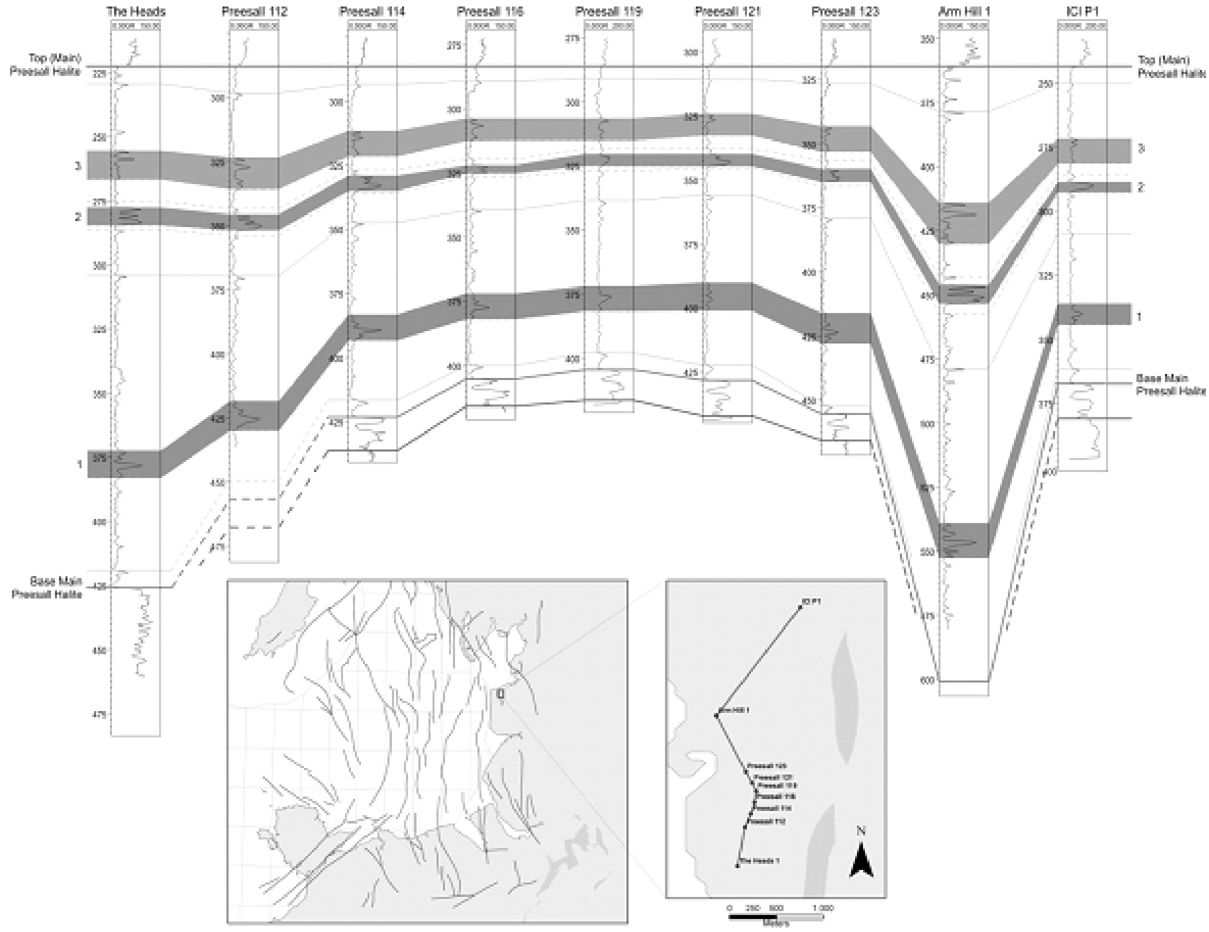


Figure 6. South to north geophysical log correlations between the gas exploration boreholes of The Heads #1 and Arm Hill #1 and ICI brine wells for the Preesall Halite of the Preesall Saltfield, Lancashire (based upon Evans & Holloway, 2009). Correlations show the variation in thickness of the halite beds and reveal the Preesall Halite has a well developed internal stratigraphy, with through-going mudstones, themselves containing thin interbedded halites. Indicated here are three main mudstones (numbered 1-3) that are also identified in the Cheshire Basin and East Irish Sea: mudstone 1 is the lateral equivalent of the Thirty Foot Marl in the Cheshire Basin (refer Evans et al., 2011).

conditions have been identified from lithological logs of archival borehole by rockhead descriptions including ‘soft marls’ (mudstone), brine or voids overlying halite, and poor borehole conditions. Rarely, remnant collapse breccias overlying halite have been described. Dry rockhead conditions are indicated by ‘hard marls’ overlying halite, and are also proved in several cored boreholes, including the BGS Cote Walls Farm stratigraphic borehole (BGS reference number SD34NE/130). The borehole, drilled in 1974 at Cote (formerly ‘Coat’) Walls Farm [335510 446540] to characterize the mudstone succession overlying the Preesall Halite, proved dry rockhead at a depth of 281.46 m (Figure 7). Mudstone immediately above the halite is well-laminated or was brecciated by natural penecontepmoraneous halite dissolution and recrystallisation. Halite in the upper part of the Preesall Halite shows well-preserved primary lamination, and crystal fabrics including thick laminae and thin beds of upward-oriented cornet shaped crystals.

An assessment of the depth variations of natural wet and dry rockhead below ground has been undertaken (Evans *et al*., 2008b; Evans & Hough, 2009b). This study identified the shallowest occurrence of halite from borehole logs, either as thin beds, fracture/fissure infills or isolated, individual crystals. This indicates that dry rockhead is present at depths between 85 – 205 m below ground level (although the latter depth is questionable for natural wet rockhead developed in interglacial times; see discussion below); this is similar to the ranges for the depth of wet rockhead in the Cheshire area, the deepest known documented occurrences being at 152 in the Stockport and Knutsford district (Taylor *et al*., 1963), although typically strata below 50 – 100 m below ground level are not affected (Cooper, 2001; Cooper; 2002; Genske, 2003).

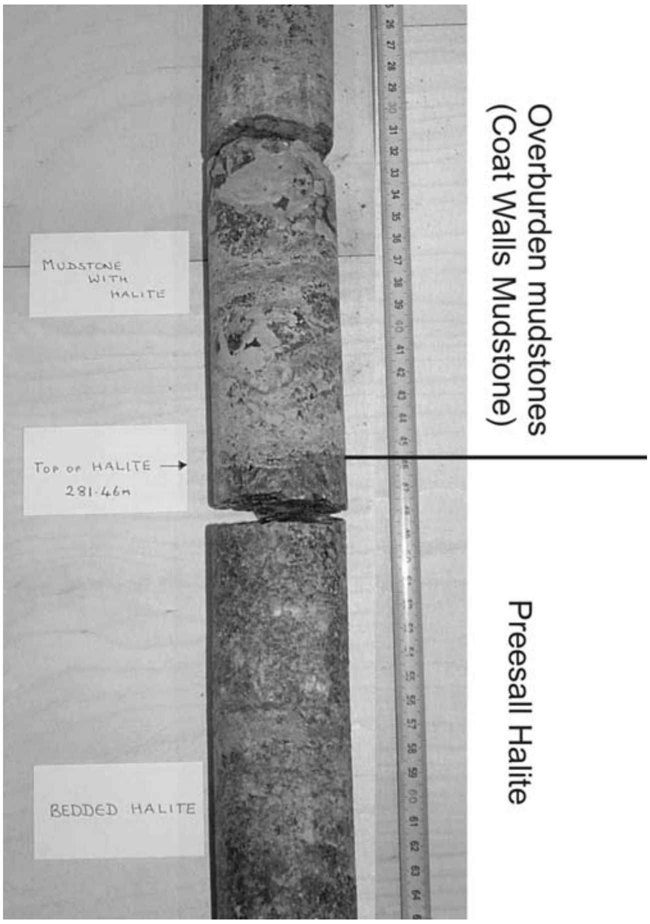


Figure 7. The upper surface of the Preesall Halite, cored by the BGS Coat Walls Farm Borehole, located at Cote Walls Farm [335510 446540]. The interface between halite and overlying mudstone is dry, with no evidence of any development of wet rockhead. This finding, at a depth of 281.46 m, is comparable with provings in the Cheshire district, where naturally developed wet rockhead is not known below depths of 152 m.

In the Cheshire Basin, halite and mudstone generally become impermeable with fissures and fractures closed at a depth of about 180 m below ground level (Howell, 1984). However, in glacial times, it is likely that fresh groundwaters were forced to much greater depths, possibly up to 300 m (Boulton *et al*., 1995; Cooper, 2001) with studies associated with a proposed deep nuclear repository in Cumbria (Heathcote & Michie, 2004) indicating the depth may be much greater than these estimates. Given the large time periods following the most recent glaciation during the Devensian, which ended in this area some 12,000 years BP (Wilson & Evans, 1990), it is considered that these systems are now stable. Further natural development of wet rockhead is prevented due the development of a dense layer of saturated brine (a protective ‘brine blanket’) that overlies exposed halite, protecting from further dissolution and migration of the wet rockhead front down-dip. Indeed, further dissolution of the halite would only be possible if there was a down-gradient sink or outlet for the saturated brine (Cooper, 2001), or if the system becomes disturbed through human intervention. In the case of the Preesall Saltfield, there is no evidence of offshore brine ‘seeps’ to indicate dense brine is moving from onshore to offshore creating a flow to drive wet rockhead development in the Preesall Saltfield.

The activities and processes of brine extraction and dry salt mining have had a major impact on the anthropogenic development of wet rockhead in the Preesall Brinefield. At least 12 early-developed brine wells have collapsed (Table 2), through upward migration of the cavity through the overburden mudstone via chimney collapse. There are a further 26 brine wells, all developed between 1905 – 1954, with known 'marl' roofs, and that are therefore susceptible to upward migration through the overburden to surface (Evans & Hough, 2008b).

Connectivity between some brine wells was intentionally developed to aid the brining process. At Preesall, unpublished ICI cavern maintenance records indicate that this was commonly between 3 adjacent wells, often between cavities at horizons within the salt body but sometimes at the salt/marl interface (rockhead). This connectivity, where fresher brines have come into contact with halite at rockhead has led to the development of 'anthropogenic' wet rockhead at depths far in excess of those expected in a natural system. Of particular note is ICI brine well No. 107 (Evans & Hough, 2009b), located some 250 m west of the area of present-day wet rockhead, which proved a void at the top of the halite at 205 m below ground level. The borehole record for the well states: 'Slight air blow (see 698 ft). A slightly pressurized air cavity encountered at rock head gave off bubbles of gas for several minutes. Similar gas discharges in Holford Brinefield have proved to be of nitrogen' (IGS, 1960). Development of natural wet rockhead at this depth is considered anomalous in the UK under interglacial hydrological conditions. Taylor (1937) states that gas is given off as halite dissolves, which is mostly from reactions with the water, but also the liberation of gas from fluid inclusions in the salt crystals. The development of deep salt karst features during glacial periods may be a factor in the development of the cavity noted at BW-107.

Conclusion and relevance to UGS in bedded halite

The current need for increased gas storage capacity in the UK will result in more solution cavity underground gas storage schemes being proposed. If the gas markets continue to evolve, resulting in more expensive gas sourced from areas outside the UK, the likelihood is that further gas storage schemes (including depleted aquifer sites as well as solution-mined salt cavity) will be developed, both on and offshore, to improve UK supply security. As part of this process, it is likely that all salt bodies of economic potential (principally those of suitable depth and thickness) in onshore UK will be further investigated as potential hosts. Thin bedded salts, although providing additional challenges to domal and massive bedded halites, already provide storage volumes for various hydrocarbons, including gas in the USA (e.g. Bruno et al., 2005).

The Preesall Saltfield provides an excellent opportunity to present a case-study of brine- and saltfield development in the UK. A full understanding of the stratigraphical and structural setting of the Preesall Halite allows some key geological parameters to be understood, including the sedimentology of the halite and the depositional history. By using GIS, all relevant spatial data can be held in an interoperable format, allowing for swift and simple interpolation of datasets, and allowing for data to be refreshed as more data is acquired and interpreted. Of particular importance is the ability to hold the surfaces of the halite body and faults digitally, allowing other relevant datasets (such as areas of wet rockhead, potential cavern locations, surface infrastructure and cultural data) to be viewed in the spatial context of the halite body.

The work also illustrates how core logging and description provides important sedimentological detail, which can help define the depositional environment for the salt deposits and associated clastics. When, coupled with analyses of wireline logs, from both regional and on-site well data, an understanding can be developed of (a) the likely distribution of clastics within the site area which affect the insoluble content, and hence sump volume uncertainty for each cavern (refer also Kingdon et al., 2011), and (b) the likely variations in mudstone bed thicknesses. In bedded salts, therefore, a means is available to provide an improved assessment of both cavern construction and construction schedule uncertainty for each cavern. These data together with a comprehensive set of non-geological information would provide the basis for a risk assessment, and could inform any appropriate follow-up monitoring programme after development has commenced.

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References

ARTHURTON, RS. 1973. Experimentally produced halite compared with Triassic layered halite-rock from Cheshire, England. *Sedimentology*, 20, 145-160.

INSTITUTE OF GEOLOGICAL SCIENCES. 1960. Record of ICI Preesall No. 107 *Brine well* (SD34NE/111). BGS/NGRC borehole record sheets pdf, 4pp.

BGS. 2006. *Mineral Planning Factsheet – Salt*. British Geological Survey, for the Office of the Deputy Prime Minister.

BOULTON, GS, CABAN, PE & VAN GIJSSEL, K. 1995. Groundwater flow beneath ice sheets: Part II – large scale patterns. *Quaternary Science Reviews*, 14, 545 – 562.

BRUNO, M., DORFMAN, L., HAN, G., LAO, K. & YOUNG, J. 2005. 3D Geomechanical Analysis of Multiple Caverns in Bedded Salt. Paper presented at the SMRI Fall 2005 Meeting, October 1-5, Nancy, France, 26pp.

BURDEN, WJ. 2009. Land at King Street (High House Farm) Lach Dennis, Northwich, CW9 7RX; route of pipeline from King Street, Northwich to Commercial Road, Bromborough. Report to the Secretary of State for Communities and Local Government. Report numbers APP/Z0645/A/08/2093471 and APP/Z0645/A/08/2093465.

COOPER, AH. 2001. Natural and induced halite karst geohazards in Great Britain. In BF Bech and JG Herring (eds). *Geotechnical and Environmental Applications of Karst Geology and Hydrology*. Swets & Zettlinger, Lisse.

COOPER, AH. 2002. Halite karst geohazards (natural and man-made) in the United Kingdom. *Environmental Geology,* 42, 505-512.

DECC, 2011A. *Gas Statistics: Digest of United Kingdom Energy Statistics (DUKES) Chapter 4: Natural gas*. World Wide Web address: http://www.decc.gov.uk/en/content/cms/statistics/ energy_stats/source/gas/gas.aspx.

DECC. 2011B.*Overarching National Policy Statement for Energy (EN-1)*. London: The Stationary Office.

DTI. 2006. *Digest of United Kingdom Energy Statistics (DUKES) 2006*. Department of Trade and Industry, URN No. 06/87.

DTI. 2007. *Meeting the Energy Challenge: A White Paper on Energy*. Department of Trade and Industry, May 2007. World Wide Web address: http://www.berr.gov.uk/files/file39387.pdf

DARAN PETROLEUM. 1996. Fleetwood Project – salt cavern gas storage for British Gas Hydrocarbon Resources Limited. Daran Petroleum Consultants Limited, Berkshire.

DE RANCE, CE. 1875. The geology of the country around Blackpool, Poulton and Fleetwood. *Memoir of the Geological Survey of Great Britain*.

DOBBS, M, HOUGH, E & EVANS, DJ. 2009A. Report on Burrows Marsh Borehole (Middle Deviated), Preesall, Lancashire. *British Geological Survey commissioned report* CR/09/015.

DOBBS, M, HOUGH, E & EVANS, DJ. 2009B. Report on Hay Nook Borehole, Preesall, Lancashire. *British Geological Survey commissioned report* CR/09/049.

EVANS, DJ, HOUGH, E, CROFTS, RG, TERRINGTON, RL & WILLIAMS, G. 2005. The geology of the Preesall Saltfield area. *British Geological Survey commissioned report* CR/05/183N.

EVANS, DJ. 2008. *An appraisal of underground gas storage techniques and incidents, for the development of risk assessment methodology*. Health & Safety Executive (HSE) Research Report RR605.

EVANS, DJ & HOUGH, E. 2008A. Reviews of BGS work for Canatxx in support of a revised planning application at Preesall. *British Geological Survey commissioned report* CR/08/149.

EVANS, DJ & HOUGH, E. 2008B. Review of Canatxx work relating to mining in the Preesall Saltfield and comments on wet rockhead conditions. *British Geological Survey commissioned report* CR/08/114.

EVANS, DJ & HOUGH, E. 2009A. Faulting at Preesall and other saltfields: information relevant to gas storage in the Preesall Halite. *British Geological Survey commissioned report* CR/09/038.

EVANS, DJ & HOUGH, E. 2009B. Rockhead conditions, salt extraction, subsidence and stability of the Preesall Saltfield with comparison to other saltfields: information relevant to gas storage in halite in the Preesall Saltfield. *British Geological Survey commissioned report* CR/09/037.

EVANS, DJ, HOUGH, E, KINGDON, A & DOBBS, M. 2009A. Preliminary geophysical log interpretation and correlation of the Canatxx Burrows Marsh (Middle Deviated) exploration borehole with previous exploration boreholes at Preesall. *British Geological Survey commissioned report* CR/09/040.

EVANS, DJ, HOUGH, E, KINGDON, A & DOBBS, M. 2009B. Preliminary geophysical log interpretation and correlation of the Canatxx Hay Nook exploration borehole with previous exploration boreholes at Preesall. *British Geological Survey commissioned report* CR/09/048.

EVANS, DJ & HOLLOWAY, S. 2009. A review of onshore UK salt deposits and their potential for underground gas storage. In Evans, DJ & Chadwick RA (eds). *Underground Gas Storage: Worldwide Experiences and Future Development in the UK and Europe*. The Geological Society, London Special Publications 313, 39 – 80.

EVANS, DJ, WILLIAMS, JDO, HOUGH, E & STACEY, A. 2011. The stratigraphy and lateral correlations of the Northwich and Preesall halites from the Cheshire Basin – East irish Sea areas: implications for sedimentary environments, rates of deposition and the solution mining of gas storage caverns. *SMRI Fall 2011 Technical Conference, 3-4 October 2011, York, UK*.

EVANS, WB, WILSON, AA, TAYLOR, BJ & PROCE, D. 1968. Geology of the country around Macclesfield. *Memoirs of the Geological Survey of Great Britain, England and Wales, Sheet 110.*

GENSKE, DD. 2003. *Urban Land: Degradation, Investigation, Remediation*. Springer.

GEOLOGICAL SURVEY. 1939. Unpublished assessment of the Preesall Halite, dated September 1939.

GEOLOGICAL SURVEY. 1948. Unpublished field map of the Preesall Mine boreholes, dated September 1948.

GILES, JRA, HUGHES, A, KESSLER, H, WATSON, C & PEACH, D. 2010. Data and research for environmental applications and models (DREAM): scoping study report. *British Geological Survey Open Report* OR/10/020.

HOWARD, AS, WARRINGTON, G, AMBROSE, K & REES, J. 2008. A formational framework for the Mercia Mudstone Group (Triassic) of England and Wales. *British Geological Survey Research Report* RR/08/04.

HOWELL, FT. 1984. Salt karst of the Cheshire Basin, England. In: Castany G, Groba E, Romijn E (eds) Hydrogeology of karstic terranes. *International Association Hydrogeologists, International Contributions to Hydrogeology*, 1, 252–254.

ICI VARIOUS DATES Cavern Maintenance Records: Unpublished borehole logs including data regarding 'hooking and dipping' surveys, and brine well connectivity.

ICI, 1997. Unpublished map of Preesall Brinefield with information regarding cavern conditions.

IGS (INSTITUTE OF GEOLOGICAL SCIENCES). 1960. Record of ICI Preesall No. 107 *Brine well* (SD34NE/111). BGS/NGRC borehole record sheets pdf, 4pp.

IGS (INSTITUTE OF GEOLOGICAL SCIENCES). 1968. Unpublished field map for SD34NE, compiled 1968.

INTERMAP TECHNOLOGIES. 2007. NEXTMap Britain: Digital terrain mapping of the UK, [Internet]. NERC Earth Observation Data Centre, 2007, 2011. Available from http://badc.nerc.ac.uk/view/neodc.nerc.ac.uk__ATOM__dataent_11658383444211836

JACKSON, D. I. & JOHNSON, H. 1996. Lithostratigraphic nomenclature of the Triassic, Permian and Carboniferous of the UK offshore East Irish Sea Basin. *British Geological Survey*, Keyworth, Nottingham.

JENYON, MK. 1997. The Preesall Salt Basin: a provisional report for Canatxx Energy Ventures.

KESSLER, H, MATHERS, SJ & SOBISCH, H-J. 2009. The capture and dissemination of integrated 3D geospatial knowledge at the British Geological Survey using GSI3D software and methodology. *Computers & Geosciences*, 35, 1311-1321.

KINGDON, A, EVANS, DJ, HOUGH, E, HEITMANN, N & REYNOLDS, W. 2011. Use of resistivity borehole imaging to assess the structure, sedimentiology and insoluble content of the massively bedded Preesall Halite NW England. *SMRI Fall 2011 Technical Conference, 3-4 October 2011, York, UK*.

LANDLESS, V. 1979. Preesall salt mines. *Memoirs of the Northern Mine Research Society, British Mining*, 11, 38-43.

PLANT, JA, JONES, DG & HASLAM, HW (EDS). 1999. *The Cheshire Basin: Basin evolution, fluid movement and mineral resources in a Permo-Triassic rift setting*. (Keyworth, Nottinghamshire: the British Geological Survey).

SIMPSON, EA. 2007. Land at Preesall Saltfield, Stalmine, Wyre Estuary, and Fleetwood, Lancashire. Report to the Secretary of State for Communities and Local Government. Report numbers APP/Q2371/A/05/1183799 & APP/HSC/05/07. includes APPENDIX A Report by the Technical Assessor.

SMITH, D.B. 1996. Deformation in late late Permian Boulby Halite (EZ3Na) in Teesside, NE England. In: ALSOP, G.I., BLUNDELL, D.J. & DAVISON, I. (eds), *Salt Tectonics*, Geological Society Special Publication, 100, 77-87.

TALBOT, C. J., TULLY, C.P. & WOODS, P.J.E. 1982. The structural geology of the Boulby (Potash) Mine, Cleveland, United Kingdom. *Tectonophysics*, 85, 167-204.

TAYLOR, BJ, PRICE, RH & TROTTER, FM. 1963. Geology of the country around Stockport and Knutsford. *Memoirs of the Geological Survey of Great Britain, England and Wales, Sheet 98*.

TAYLOR, RE. 1937. Water insoluble residues from the rock salt of Louisiana salt plugs. *Bulletin American Association Petroleum Geology*, 21(10), 1268-1310.

THOMPSON, FJ. 1908. The rocksalt deposits at Preesall, Fleetwood and the mining operations therein. *Transactions of the Manchester Geological and Mining Society*, 30, 105-116.

WILSON, AA. & EVANS, WB. 1990. Geology of the country around Blackpool. *Memoir of the British Geological Survey, Sheet 66 (England and Wales)*, HMSO, London.