SOLUTION MINING RESEARCH INSTITUTE
105 Apple Valley Circle
Clarks Summit, Pennsylvania 18411, USA

Telephone: 570-585-8092 ◆ Fax: 570-585-8091
www.solutionmining.org ◆ smri@solutionmining.org

Technical Conference Paper

Salt deposits and gas cavern storage in the UK with a case study of salt exploration from Cheshire

Beutel, Thomas[1]
Black, Stuart[2]

KBB GmbH, Hannover, Germany[1]
Scottish Power, Glasgow, UK[2]

Fall 2004 Conference
3 – 6 October
Berlin, Germany

Solution Mining Research Institute; Fall 2004 Technical Meeting
Berlin, Germany, October 3 - 6, 2004

Salt Deposits and Gas Cavern Storage in the UK with a Case Study of Salt Exploration from Cheshire

Thomas Beutel, KBB GmbH Hanover/Germany
Stuart Black, ScottishPower, Glasgow/United Kingdom

Abstract

The use of salt caverns for gas storage is well proven and has been in use for over 40 years worldwide. As the UK moves to become a net importer of natural gas in the next few years the opportunities in developing more gas storage particularly in salt caverns has arisen.

The United Kingdom has a number of salt deposits. Mining for salt production is one of the oldest industries in the country. The technology for solution mining of salt caverns has developed rapidly during the last century including the introduction and use of salt caverns for the storage of gas and wastes.

Nevertheless, not all of the salt deposits in the UK are suitable for gas cavern construction. The first part of this paper gives a geological overview of the major salt deposits in the UK and an outline of the individual gas cavern storage projects from the geo-technical standpoint. The paper describes the distinctive features of the existing and planned gas cavern storage projects.

The final part of the paper is a case study of a recent salt exploration for the ScottishPower gas cavern storage project in Cheshire, which is located near Byley, south of Northwich, on the IneosChlor Enterprises Limited (ICEL) Holford Brinefield.

The results of the fieldwork are based on a seismic survey and an exploration well. The interpretation of seismic data proved the depth and integrity of the proposed storage area.

To calibrate the existing seismic data and allow pre-stack depth migration and final seismic interpretation, a Vertical Seismic Profile (VSP) was recorded in the exploration well, drilled in 2003 to TD 731.5 m. Geological investigations, measurements and tests were carried out in the exploratory well.

A geo-technical novelty for the Triassic salt beds used for gas storage in the UK, was the successful proof of gas integrity of the insoluble marl beds at the planned storage depth zone by packer tests. The permeability identified in the formation integrity tests is being regarded as tight.

Key words: Gas storage, salt caverns, UK, Cheshire,

1 Salt occurrence and exploitation in the UK

1.1 General setting, development and outlook

The United Kingdom has a number of known salt fields of Triassic and Permian age. Triassic salt occurs mainly within the bedded strata of the Cheshire Basin, and to a lesser extent also in Northern Ireland, Lancashire, the Isles of Man and Walney, Staffordshire, Worcestershire and Somerset. Permian salt is present in the NE of England (Yorkshire) and Northern Ireland (Figure 1).

The Triassic salt deposits in the United Kingdom were deposited in a semi-arid environment within mainly fault-controlled, land-locked basins linked to the major depositional centres of the North Sea and Irish Sea. The general Triassic sequence comprises thick sandstones and conglomerates overlain by red-brown siltstone and mudstone with interbedded halite and gypsum sequences.

The Permian salt deposits form part of the Zechstein Group sequence, which extends eastwards from the United Kingdom to Germany and Poland. Only the edge of the Zechstein Basin is present onshore in the United Kingdom, and is restricted to the coastal parts of northeast England. Here, the Permian salt is interbedded with thick dolomite, mudstone and anhydrite formations [1].

Fig. 1: Salt fields in the UK

The mining and subsequent production of salt is one of the oldest industries in England. Early interest at the time focused on Triassic salt, mainly because its shallow depth made abstraction easier and more cost effective. The earliest known Cheshire salt mine, sunk in 1682. Other mines were sunk and in 1781 a purer series of salt beds was identified in Northwich and salt mining activities increased during the 19th century [14].

Industrial solution mining for salt production began in the early 20th century. The solution mining of salt caverns was developed during the last century. The first use of caverns for storage purpose in the UK dates back to the early 60s, where the storage of manufactured gas at Teesside was reported.

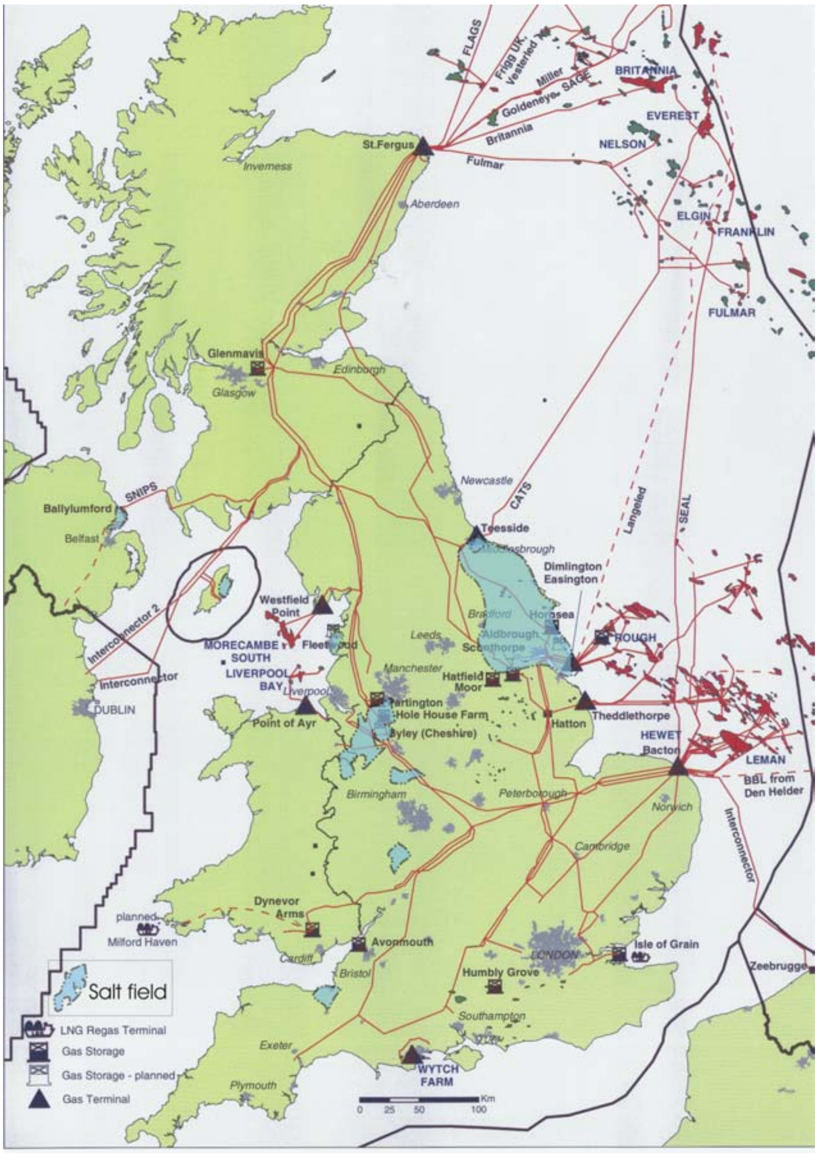

Fig. 2: Salt occurrences in the UK against the gas infrastructure [2]

The gap between UK demand and UKCS supply is forecast to widen due to a rapid decline in UKCS production and continued growth in gas demand [3]. Proposed gas imports via new pipelines and LNG terminals are anticipated to fill this gap. However, the high capital cost of this infrastructure means that gas supplies will have lower swing capability (circa 120%) compared with existing UKCS swing capacity (circa 167%). During this period of change we expect there to be a strong increase in the demand for gas storage and in particular flexible storage.

Salt cavern storage (and other forms of storage) however are less developed in the UK than in other European countries, reflecting the fact that the UK historically has relied on the flexibility of UKCS production. The UK has four underground gas storage (including depleted fields) and five LNG peak-shaving units with a working capacity of 3.8 Billion m^3, representing 4% of annual gas consumption. In Germany, France, Italy and Austria, this ratio is between 20 and 30%.

The need for additional gas storage in the UK is essential to maintain security of supply of the gas network and to improve competition in the gas market. Potential storage sites are limited due to unique geological requirements combined with the location of essential natural gas infrastructure. Figure 2 presents a plot of salt occurrence in the UK overlayd on the gas infrastructure. The location and characterisation of potential sites for natural gas storage can be compared to the existing gas infrastructure in the UK to demonstrate where industrial need meets geological potential.

The gas industry is called on to increase the investigation of potential sites for suitable salt deposits as well as porous rock formations suitable for gas storage i.e. depleted gas fields or aquifers. Depleted North Sea gas fields do offer a major potential storage resource but capital costs for such developments are significant compared to onshore storage operations.

1.2 Yorkshire and Teesside Salt field

In the northeast of England, salt is present in the Permian strata of the Zechstein Group. This evaporite and carbonate sequence extends from northern England eastwards beneath the North Sea to Germany and Poland. Only the marginal part of the Zechstein Basin reaches England onshore where it includes thick units of anhydrite, halite and potash.

The prospective salt deposits in Yorkshire can be divided into four cycles, which have been termed Zechstein I to IV from the base upwards. Each cycle starts with a carbonate rock unit (limestone or dolomite) passing up through anhydrite, polyhalite into halite. Included in these evaporites, and particularly in the halite section, may be a variety of less common evaporite minerals such as kieserite, carnallite and sylvite. Each of these cycles originally resulted from the drying out of a landlocked sea. Insoluble carbonates are the basal layer. As the water evaporated, soluble material was precipitated, the least soluble being precipitated first. In the Yorkshire area, the second or Zechstein II cycle (Fordon Evaporites) is the thickest overall and has the thickest salt sequence. It is this layer that has the best conditions for constructing caverns for gas storage.

Moving from the edge of the basin in central Yorkshire to the deeper parts, the sequence moves from carbonates and anhydrites to predominantly halite deposits. Wells drilled in

Yorkshire and the North Sea show that the eastern limit of the predominantly carbonate sequence lies along a more or less north-south line through central Yorkshire. Eastwards, the evaporites appear, and by the Yorkshire coast they predominate. This is seen in wells drilled along the coast from Robin Hood's Bay to the south of Aldbrough. [4; 10]

Between Robin Hood's Bay and Scarborough, the Zechstein II salt is about 1220 m deep at Robin Hood's Bay, deepening to about 1450 m at Scarborough. The thickness varies from about 75 to 90 m. At Fordon, the Zechstein II salt is deeper (1850 m) but also thicker (120 m). Information from the wells south of Bridlington shows that the salt lies at 1700 m.

Two exploration wells were also drilled south of Hornsea: Great Hatfield 1 and Aldbrough 1. Some widely spaced seismic lines indicated a simple structure in the area between Great Hatfield and Aldbrough. Faulting appears to be absent apart from some minor features. Correlation between the Fordon No. 1 and Atwick No.1 well was found to be remarkably good, and the sub zones of the Fordon Evaporites (Zechstein II) on the basis of the relative proportions of the main minerals can be identified in Aldbrough No. 1. The evaluation of Aldbrough 1 also indicated its potential as a suitable location for gas caverns.

The Permian salt and potash deposits of Yorkshire are currently mined by pillar-and-room workings near the coast at Whitby. Here they are up to about 80 m thick and occur at depths of 1,000-1,250 m. Cleveland Potash operates two shafts which were established in the early 70's; The mine workings from these shafts stretches below the North sea.

Special conditions occur in the **Teesside Salt field** around the estuary area of the river Tees, where the Zechstein salt is due to tectonic faulting locally only about 340 m deep and varies in thickness between 30 and 45 m. Glacial Drift cover consists of 30 m sand and boulder clay. Triassic Sherwood Sandstone (approx. 220 m thick) overlying Upper Permian red beds comprising the Upper Permian Marls (approx. 70 m thick), the Upper Anhydrite (3 m), Rotten Marl (10 m), Upper Salt (30 m) Honeycomb salt (2 m), Lower Salt (5 m), the Main Anhydrite and the Upper Magnesian Limestones. Marl from 420 to 500 m.

The Rotten Marl, covering the Upper salt, is a typical local secondary porous bed. It is thought that circulating groundwater (wet rock head condition similar to that in parts of Northwich, Cheshire) dissolved the halite and potash salt. The resulting broken residues consist of clay marl. Collapse fractures have only partially been healed with halite.

There are a number of indications (well data) that the Zechstein Halite in Teesside is cut by numerous faults. These faults are clearly seen in fractures in the underlying Billingham Anhydrite, and are manifested in the salt as healed and open joints.

The halite was extracted by dissolution at Teeside in the early 20th century, and its presence was largely responsible for the development of the chemical industry in the area [1].

ICI produced brine from smaller caverns in the Teesside brine fields north (Saltholm) and south (Wilton) of the river Tees. Under the ICI land at Saltholm the salt strata is approximately 340 m below the surface, and varies in thickness between 27 m and 40 m. ICI extracted the salt from Saltholm for chemical manufacture. Over a hundred of these caverns have been formed, varying in final leached volumes from 10,000 m^3 to 100,000 m^3 capacity.

At Wilton the caverns were developed solely for storage purposes and used to store ethylene, butane and nitrogen. Here the salt is of about the same thickness as at Saltholm, but at a much greater depth, approximately 647 m below the surface. The rock formations overlying the salt here also include Keuper Marl from 109 m down to 312 m, and Bunter (Sherwood) sandstone from 312 m down to 574 m [5].

ICI converted smaller caverns in the Saltholm and Wilton brine fields into storages for light hydrocarbons, propane, propylene, crude oil, gas oil, naphtha, ethylene, nitrogen and hydrogen.

1.3 Larne Salt field (Northern Ireland)

Triassic saliferous rocks of the Mercia Mudstone Formation are present in the area around Carrickfergus and Larne, bordering Belfast Loch in Northern Ireland.

Rock salt at the Larne Salt field was discovered in 1850 while drilling for coal. Salt was first mined and brine production started in 1897. The Irish Salt Mining and Exploration Co. Ltd produce salt from the Kilroot Salt mine since 1965, operating drift and shafts.

The Triassic sequence includes up to 200 m thick salt, proved in the Larne boreholes, but in the Carrickfergus salt field only about 40 - 50 m has been proved [1]. Three saliferous beds, termed the Larne Halite (481 m), the Carnduff Halite (41 m) and the Ballyboley Halite (18 m) were identified in the Larne No. 1 borehole between 363 and 1027 m depth. The Larne Halite between 363 and 844 m is clearly the thickest salt unit. The geological situation is complicated by the presence of several more or less vertical tertiary intrusions of fractured dolerite dykes within the halite beds.

The Larne No 2 borehole also indicated a 113 m thick salt unit of the Upper Zechstein between 1688 m and 1801 m depth below surface [6].

1.4 Lancashire Salt field

The Lancashire salt field appears to be the northern margin of the Cheshire basin. The Lancashire coast beneath Blackpool and Preesall is underlain by the Triassic Mercia Mudstone Group, which includes several salt units with up to 180 m total thickness between 75 m and 385 m depth.

Salt was first discovered in the area in 1872. Halite was formerly worked in salt mines at Preesall on the east side of the River Wyre. By 1893, the first brine well had been drilled and extraction of the salt continued in this way until air blanket control was introduced in 1960.

The salt deposit is relatively small in extent, and is confined to an area between the River Wyre to the west and the Preesall Fault zone to the east. This fault throws down the Triassic Marls bearing the salt relative to the water bearing Bunter Sandstone to the east. On average the salt is about 110 m thick. Away from its eastern limit it dips down relatively steeply towards the west [7].

Two less persistent units, the Rossal Halite and the Mythop Halite occur low in the sequence and a third more persistent unit, the Preesall Halite, occurs high in the sequence. The Preesall Halite was formerly worked in salt mines at Preesall on the east side of the River Wyre.

ICI made numerous caverns in the Preesall brine field for brine production by controlled solution mining. The brine production caverns were typically developed between 130 and 240 m depth. The halite formation at the brine field consists of halite beds interbedded with several marl bands.

The brine has been used as feedstock for the ICI Hillhouse plant, which produces chlorine and caustic soda by electrolysis. In 1992, the process was closed down and the salt/brine field placed in care and maintenance.

Occurrence of the same salt strata (Triassic Mercia Mudstone Group) is reported from the Isles of Man and Walney.

1.5 Cheshire Salt field

The Cheshire salt field has a long history of exploitation, growing from its first pre-Roman development around the salt springs into a major industry.

Within the Cheshire Basin, the major Triassic salt beds fall into two formations termed the Wilkesley Halite Formation (Upper Saliferous Beds) and the Northwich Halite Formation (Lower Saliferous Beds).

The Wilkesley Halite Formation (up to 300 m thick) near the top, and the Northwich Halite Formation (up to 295 m thick, with mudstone partings) in the middle of the group. The sequence between and below the salt formations mainly consists of red-brown gypsiferous and dolomitic mudstones and siltstones [1]. The salt purity is approx. 90 to 95 % Halite. The Northwich Halite Formation in Cheshire does not contain any potassium salt but does contain a certain amount of insoluble rock (red and grey mudstone beds, partly silty, of varying thickness). The uniformity of halite sedimentation allows good correlation, not only between adjacent wells, but also across wide areas of the central Cheshire Basin [17; 18].

Imperial Chemical Industries Plc (ICI) was the largest salt producer in the United Kingdom. ICI operated the **Winsford** mine near Northwich, Cheshire, one of the largest rocksalt room -and-pillar mines in the United Kingdom. The mine has the capacity to produce circa 2 Million t/a, and is now operated by Salt Union mainly to produce de-icing salt [16].

The typical mix of halite and mudstone beds, as known throughout the Triassic Halite Formation is present at **Holford**. ICI first produced brine at the Holford Brinefield as early as the 1920's. The Brinefield is now owned and operated by IneosChlor Enterprises Ltd (ICEL) who supplies approx. 4 million t/a of salt (in the form of saturated brine) to the chemical industry in the northwest of England. Holford is located in the middle of the Cheshire Basin, where the salt bearing Triassic Northwich Halite Formation is approx. 250 m thick and located between 200 to 500 m below surface.

The southern end of the Holford Brinefield borders on the **Byley** area, where the thickest beds of salt and mudstone were deposited between Winsford and Byley.

At Byley below the rock head (top of the salt) lies the Northwich Halite Formation with up to 270 m thickness. Depth to top salt at Byley is approx. 440 m below ground level; base salt is at approx. 710 m below ground level.

Further south, at **Warmingham**, midway between Crewe and Middlewich, Cheshire, British Stasal (a sister company of British Salt) operates 12 caverns to produce brine by solution mining. Around 825,000 mt/a of undried vacuum and pure dried vacuum salt is produced at its Middlewich processing plant.

This Brinefield was established by ICI in the 1970's to replace wild brining operations supplying British Stasal's plant in Middlewich. The existing caverns have a very similar geometry to ICEL caverns at Holford. Typically top salt is about 180 to 250 metres below surface. The salt strata lie between 180 to 250 m (top) and 420 m (bottom) below surface.

1.6 Staffordshire Salt field

The salt deposits under the town of Stafford lie in a synclinal structure faulted along its eastern side. The Triassic salt (up to 21 m) occurs interbedded with mudstone in a sequence 50 – 65 m thick within the Mercia Mudstone Group. The shallow deposits have dissolved to a depth of around 50 m (wet rock head) and the salt has largely dissolved adjacent to the eastern fault zone [1]. Limited information is known about the feasibility of mineral development in this area.

1.7 Worcestershire Salt field

The Triassic saliferous rocks in Worcestershire occur in the Mercia Mudstone Group and include the upper and middle sequence of salt (~ 20 m) approximately equivalent to the Cheshire salt beds further north. The saliferous sequence is about 90 m thick, of which 40% consists of siltstone and mudstone units. The depth to top salt ranges from 90 m to 125 m below ground.

In the 17th century, shafts were sunk which increased the brine flow from the Droitwich springs. Some salt mining was undertaken in the district, but it encountered natural brine runs and the subsequent exploitation was by brine extraction up to 1972 [1].

1.8 Somerset Salt field

Salt was found in the Triassic saliferous rocks of the Mercia Mudstone Group in the Wessex Basin. The thickness varies and the salt is interbedded with claystone at depths of 190 to 220 m. Salt Union has extracted salt early in the 20th century. In the west of the basin at about 500 m depth, beds are of limited thickness up to a maximum of 23 m [1; 8].

2 Natural gas cavern storages developed or planned in the UK

2.1 The East

2.1.1 Teesside

ICI converted smaller brine production caverns in the Teesside brine fields north (Saltholm) and south (Wilton) of the River Tees into storages for light hydrocarbons, propane, propylene, crude oil, gas oil, naphtha, ethylene, nitrogen and hydrogen. At least 4 caverns at Saltholm, with cavern volumes between 10,000 m^3 to 30,000 m^3 were converted into natural gas storage caverns by Huntsman. Total net cavern volume is 80,000 m^3.

2.1.2 Hornsea - Atwick

Following the successful drilling of the Atwick 1 exploration well near Hornsea in 1972, British Gas Corporation [9] began construction of the first natural gas storage caverns in the deep salt beds of the Zechstein in Yorkshire. The facility was designed to provide peak shaving natural gas for the National Transmission System (NTS) for up to 20 days in a severe winter and became operational in 1979. Ten wells were drilled down to the Main Salt of the Fordon Evaporites (Zechstein II) and nine caverns were constructed for natural gas storage at depths between approx. 1730 and 1830 m below ground.

Variations in the salt formation are illustrated by the varying size of the completed caverns ranging between 140 and 420 million m^3. One well was abandoned, as a suitable mass of salt was not encountered. Hornsea - Atwick has a total working gas volume of around 325 Million m^3 with a deliverability rate of 18 Million m^3/day. Scottish and Southern Energy (SSE) acquired Hornsea - Atwick from DYNERGY in 2002 [4; 10; 11].

2.1.3 Hornsea - Aldbrough

A £225 million gas storage project is proposed by a joint venture involving Scottish and Southern Energy (SSE), and the Norwegian energy company STATOIL. The gas storage project at Hornsea - Aldbrough lies south of SSE's facility at Hornsea - Atwick. The project aims to create nine salt caverns at a depth of between 1800 and 1900 m below ground, with a total working gas capacity of approximately 420 million m^3. The Hornsea - Aldbrough project was the first example where a formal Public Inquiry was held which resulted in planning permission for the project (in 2000).

The original proposal for Aldbrough involved two separate proposals. British Gas at Aldbrough-North (6 caverns) and INTERGEN at Aldbrough-South (3 caverns). Planning applications were submitted in 1997 by both parties and were refused by the local authority following active campaigning by a local action group. A second application was also refused and both companies then instigated a Public Inquiry, which was held in 1999. The Government granted planning permission to both BG and INTERGEN.

DYNERGY acquired Rough (offshore depleted reservoir), Hornsea - Atwick and Hornsea - Aldbrough (North) from BG in 2001. DYNERGY then subsequently sold it in September 2002 to Scottish & Southern Energy (SSE). INTERGEN sold the Hornsea - Aldbrough (South) to

STATOIL in 2003. Both companies then combined the Hornsea - Aldbrough projects (North and South) in late 2003. Construction of the facility is now underway and the facility is likely to be operational late 2007 [12].

2.2 The West

2.2.1 Preesall

Canatxx Gas Storage Limited (CGS) is planning to construct and operate a salt cavern natural gas storage facility at Preesall Salt field in Lancashire.

The planned site is located on the western edge of the deposit in order to use the deepest accessible locations. The gas wellheads are to be located adjacent to the existing brine field, which was originally solution mined by ICI during the 1960/70's.

The roofs of the caverns are planned to be at around 365 m depth below ground. The thickness of the Halite Formation here is greater than 110 m. The development of a natural gas storage facility will include up to 20 wellheads concentrated in clusters of probably 4-7 S-shaped wells. Brine discharge is planned via a pipeline and associated outfall to the Irish Sea. The total working gas is planned to be about 566 Million m^3.

A planning application for the proposed development was submitted in 2003. The project has attracted significant opposition from a local action group and the local planning authority and some statutory undertakers due to the potential impact of the development on the local environment has also raised concerns. A decision on this proposed storage development might be passed to the Government.

2.2.2 Holford

In 1984, ICI converted a brine production cavern in Holford (H 165) with 175,000 m^3 net volume to natural gas storage and added a second borehole [13]. This cavern is leased to Transco who use the storage cavern for diurnal storage. Two ethylene storage caverns also exist in Holford, these are leased by Huntsman.

2.2.3 Byley

ScottishPower plans to construct a £100 million gas cavern storage facility at Byley in the Cheshire Basin south of Northwich, next to the ICEL (former ICI) Holford Brinefield. ICEL will provide the water for solution mining and utilise the brine produced during the construction of the caverns to supply its existing customers.

The facility will assist in providing flexible and secure gas supplies to businesses and residential customers throughout the UK. The proposed storage facility will store up to 160 million m^3 of working gas in 8 salt caverns. The caverns will have 300,000 m^3 net volume each, with a depth to cavern roof of approx. 630 m (Figure 3). The facility will be connected to the National Transmission System (NTS) via a 4 km gas pipeline.

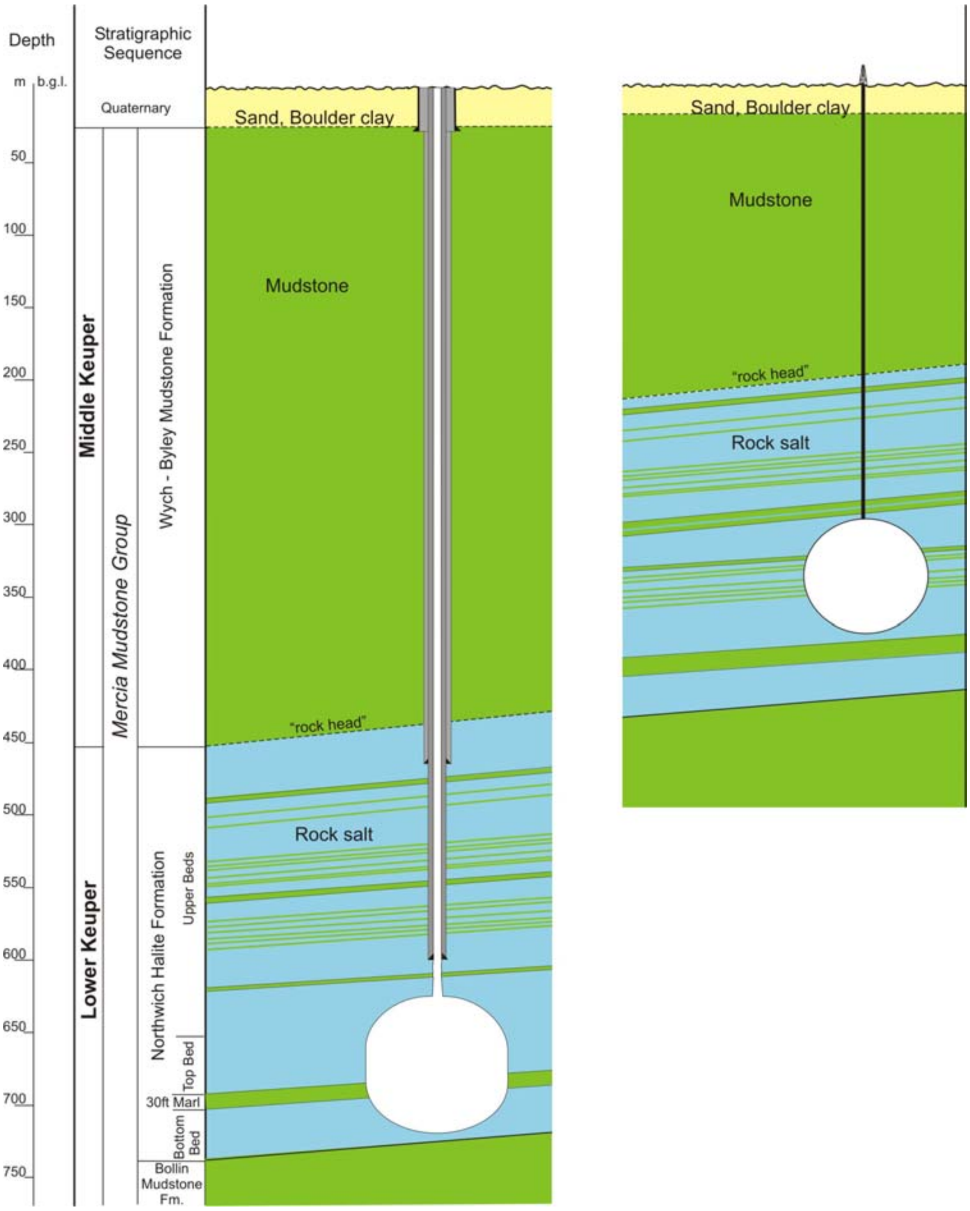

Figure 3: Schematic geological profile of the Triassic Mercia Mudstone Formation for Byley (left) and the area around Hole House (right), showing their geological comparability.

Following the completion of a conceptual design for the caverns and above ground infrastructure a planning application was made to Cheshire County Council (CCC). Significant local opposition to the proposal was encountered and following the narrow refusal by CCC of the planning application in May 2002, ScottishPower challenged the decision and instigated appeal proceedings, which led to a formal Public Inquiry. The Public Inquiry was held in November/December 2002. On 19th May 2004 (after 17 months), the First Secretary of State and the Secretary of State for Trade and Industry granted planning permission.

The principle consideration in this determination was the national need for security of supply along with the benefits to the market that gas storage will provide.

The opposition group filed a legal challenge in June 2004 challenging the Governments decision to grant planning permission for Byley. A court hearing date is expected in late 2004.

ScottishPower chose to develop the Byley project, within ICEL Holford brine field in Cheshire, due primarily to the site’s unique geological position and also because commercial arrangements with ICEL offers access to land and mineral rights, water for solution mining and beneficial use of the brine created from leaching the storage caverns. The caverns are ideally located with respect to the depth of the salt formation, and the close proximity to the NTS and a suitable site for the location of the gas processing plant.

2.2.4 Hole House

West of the village of Warmingham, at Hole House Farm a consortium called Brinefield Storage of which British Stasal was a part, obtained a planning permission to develop a storage facility including four gas storage caverns in October 1995. Later Aquila Energy Limited started the construction of the Hole House gas storage and British Salt use the brine produced during gas cavern construction. The storage has been designed as a high flexible facility to feed into the NTS with the intention of supplying the peak gas. The geometrical volume of the storage caverns amounts between 275,000 and 300,000 m^3 each.

EDF Trading acquired the storage site in 2002 from Aquila and proceeded to develop the facility, which is now owned and operated by its subsidiary Energy Merchant Gas Storage (UK) Ltd. Two caverns are currently in operation and another two are under construction.

Below the rock head (top of the salt) lays the Northwich Halite Formation with up to 230 m thickness. The depth to the cavern roof is approx. 300 m below ground. The sequences are very similar to the strata at Holford and Byley but occur at shallower depth (Figure 3). Its flat bedding with only minor dip to the south and southeast marks the salt deposit in the cavern section.

2.3 Conclusions

This first part of this paper gave a geological overview of the major salt deposits in the UK and highlighted their history and potential future use for gas cavern construction.

The ratio between gas demand and available storage capacity in the UK is relatively small compared with a number of European countries. A critical issue is the availability of suitable sites and planning/consent obstacles. Beside partially depleted onshore and offshore fields, not all of the bedded salt deposits in the UK (no diapiric salt occurs throughout) have appropriate conditions for gas cavern construction. Important are the depth, thickness, purity and structural integrity of the salt body.

A small coastal strip of East Yorkshire and central parts of the Cheshire Basin (Figure 2) between Hole House and Preesall fulfil these requirements at a few sites. Both areas have existing storage caverns in operation (Table 1 & 2).

The depth of the caverns in both occurrences is dictated by the site-specific geological conditions. While the construction of caverns in Hornsea (Atwick and Aldbrough) is only possible at relatively deep positions between approx. 1700 and 1900 m below surface, the caverns in Byley can be constructed between 630 and 730 m. The caverns at Holford, Hole House and Preesall are even shallower, between 300 and 365 m.

An important factor for cavern construction is the solubility of the salt rock. The salt rock is affected by various conditions during salt sedimentation and seldom consists of pure halite, but usually a mixture with a number of other minerals. The composition of the Zechstein in East Yorkshire is significantly different from the Triassic salt in Cheshire. At Hornsea - Atwick, all the caverns have been developed in the lower Zechstein Fordon Evaporite Formation. This formation contains a certain amount of insoluble rock like anhydrite and claystone, as well as highly soluble potassium salt.

Table 1: Overview on Salt Cavern Gas Storages in Great Britain

Area	Site	Owner / Operator	Approx. cavern depth top - bottom	No. of caverns	Planning permission granted
East Yorkshire (Permian salt)	Hornsea - Atwick	Scottish and Southern Energy	1730 m - 1830 m	9	1973
	Hornsea - Aldbrough (Under construction)	Scottish and Southern Energy & STATOIL	1800 m - 1900 m	9	2000
	Saltholm (Teesside)	IneosChlor / Huntsman	340 m - 370 m	4	?
Cheshire (Triassic salt)	Holford, H-165	IneosChlor / Transco	350 m - 420 m	1	1983
	Hole House Farm	Energy Merchant (EDF Trading)	300 m - 400 m	4	1995
	Byley (Planning granted)	ScottishPower	630 m - 730 m	8	2004
	Preesall (Planned)	Canatxx Gas Storage Limited	365 m - ?	20?	Not yet granted

The Cheshire Northwich Halite Formation does not contain any potassium salt but does contain a certain amount of insoluble rock. Because the insolubles in the Northwich Halite Formation consist of bedded marl bands only, they will soften and accumulate in the cavern sump during solution mining operations, but require special solution mining technique and modelling.

The Cheshire Basin is also not free of faulting. Therefore, ScottishPower carried out substantial structural analysis and structural modelling, followed up by a seismic investigation of the whole site and its vicinity (covering approx. 20 km^2). This investigation carefully identified faults to ensure that they were at a safe distance from the cavern installations.

Considering the two salt occurrences (Permian and Triassic) in the UK from a geo-technical standpoint, it is clear that in addition to the basic suitability with respect to salt thickness and quality, the conditions in each case for layout planning, construction and operation will be subject to very different concepts (Table 2). A high level of geo-engineering knowledge is required for such a challenge in cavern planning, construction (leaching) and maintenance.

Table 2: Gas cavern storage capacity [16]

Storage facility	Space (capacity) (Million m^3)	Deliverability (Million m^3/day)
Hornsea - Atwick (e)	325	18
Hornsea - Aldbrough (p)	420 SSE: 280 / STATOIL: 140	18
Byley (p)	160	16
Hole House (e)	75	5.5
Teesside (e)	80.000 m^3 (Total net volume)	n.a.
Holford H 165 (e)	175,000 m^3 (free space)	2
Preesall (p)	566	n.a.
Total UK storage capacity *(incl. gas fields & salt caverns)	3,321*	64.7*

(e) Existing
(p) Planned or under construction

3 Geological exploration for the Byley gas storage project - a case study

3.1 Overview

The final part of the paper will give an update on the exploration work carried out for ScottishPowers gas storage project, near Byley. Site-specific geological conditions have a major influence on the formation integrity, the rock mechanical layout of the caverns and the solution-mining concept. The scope of the exploration work was designed and adapted to the local structural setting and site-specific geological conditions of the salt deposit. This following will summarize the main results of the field exploration work.

The whole geological investigation included reviewing the regional data, the structural analysis, structural modelling of the area, seismic investigations in 2001 and an exploration well in 2003. The main objectives of the exploration well, drilled and cored in November 2003 down to 731.5 m, were geological investigations, measurements and tests to prove the suitability of the proposed field and to obtain site specific samples and data for detailed design. The salt formation was identified between 438.0 and 707.5 m below ground. Thickness is 269.5 m.

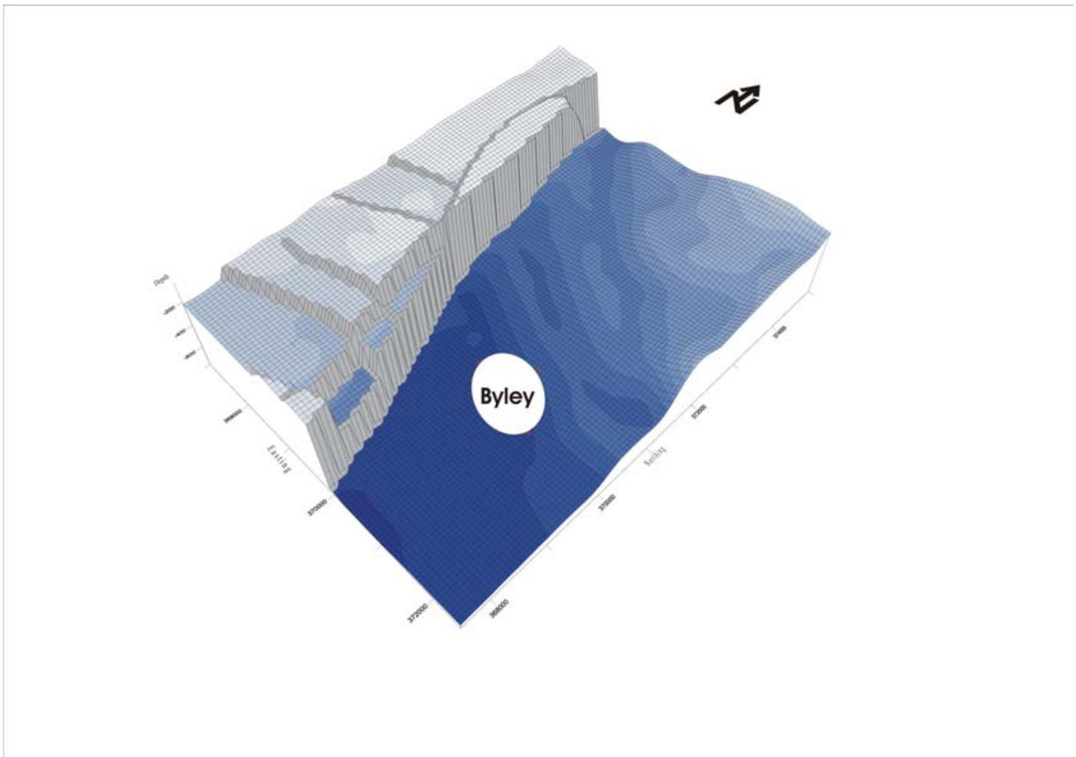

Figure 4: Structure model (base of salt) of Byley and adjacent areas

3.2 Evaluation and modelling

A thorough evaluation was made by KBB of all available geological and geophysical data. Evaluation of this geological data provided detailed information on the planned site and gave a fundamental platform for further planning and conceptual design activities. As a result of the assessment of geological data, a three dimensional structure model of the areas adjacent to the planned site was made (Figure 4) to establish a practical and comprehensive basis for planning the necessary site exploration (seismic and exploratory well).

3.3 Seismic survey

20 kilometres of 2D seismic was recorded by KBB/DMT on behalf of ScottishPower in 2001 on the basis of the above mentioned site interpretation. As major faults are often accompanied by minor sub-faults, one objective was to look for any accompanying sub-fault and determine the exact distance to the planned storage facility in order to establish minimum safety distances.

A VSP was recorded in the exploration well to calibrate the existing seismic data and allow prestack depth migration and finalise the seismic interpretation (Figure 5).

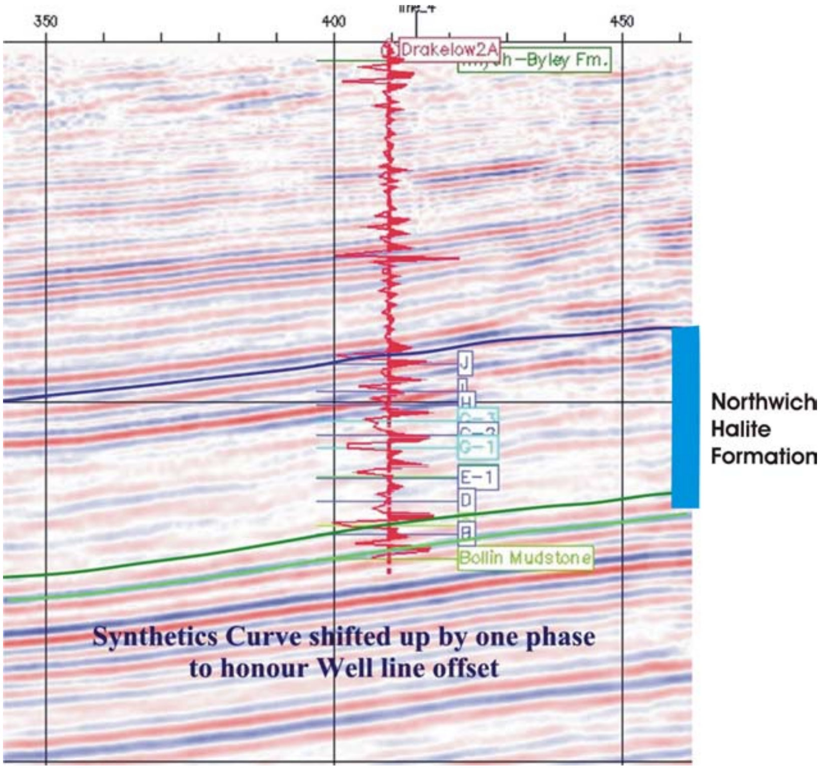

Figure 5: Clip of Seismic section, with the exploration well and synthetic seismogram from VSP log, showing the correlation with the zones of Northwich Halite Formation.

The following final conclusions were made concerning the structure of the area under exploration:

- The King Street Fault zone (younger system) comprises two major faults and one minor fault of which the western fault is already known from geological exploration of the Winsford mine. The King Street Fault zone is approx. 800 to 1100 m wide in the area under investigation.
- The WSW-ENE striking faults (older system) proven in the upper block in the area of the Winsford mine cross the King Street Fault zone and continue on the lower block.
- The total thickness of the Northwich Halite Formation estimated from the final seismic interpretation is approx. 270 m in the northern part and up to 280 m in the southern part of the planned cavern field. The salt beds in the planned cavern field show a weak SW-oriented dip of approx 5°.

As a result of the seismic investigation, an adequate safety margin between cavern wall and the nearest sub faults was unequivocally verified (Figure 6).

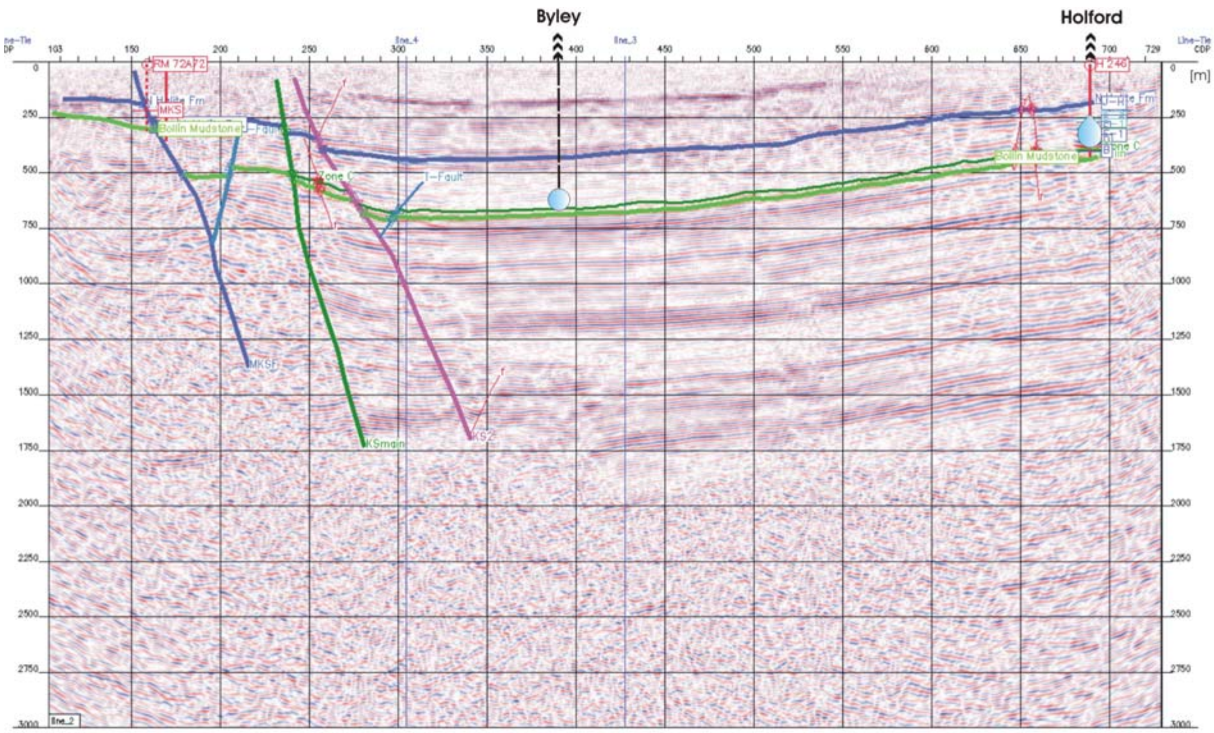

Figure 6: Interpreted PSD - migrated seismic section, with approx. location of the King-Street Fault zone (left) the Byley storage site, and a Holford brine cavern.

3.4 Exploration well

Prior to commencing construction of the main cavern storage development at Byley, it was decided that an exploration well should be drilled. The exploration well was drilled in November 2003 without any technical difficulties. British Drilling and Freezing (BDF) carried out the drilling operation on behalf of ScottishPower as follows:

- Rotary drilling vertically 12 1/4” hole into the Wych-Byley Mudstone to 54 m,
- Running and cementing 9 5/8” casing;
- Displacing well from bentonite based mud system to brine mud system;
- Rotary drill out with 8 1/2” through 266 m and with 6 3/4 “ through to the Upper Northwich Halite Formation;
- Coring wire line of 202 m Northwich Halite Formation and 24 m of underlying Bollin Mudstone Formation with 6 7/32“ core bit.

Geological investigations, measurements and tests were then carried out. The exploration well delivered the site-specific data and information required for detailed rock mechanical and solution mining design and technical planning of the main gas storage cavern project as:

- High-level delineation of salt development in the area by calibration (Vertical Seismic Profiling) of the 2D seismic survey;
- Information on the depth, thickness and bedding as well as on structural features of the salt layers at the cavern depth range;
- Sufficient salt rock material (cores) for investigating the lithological and structural characteristics as well as later solution mining and rock mechanical investigations, laboratory testing and calculations;
- A comprehensive logging campaign targeting the structural characterisation and fracture identification; supporting the seismic evaluation, lithological classification and determination of boundaries;
- Demonstration of the gas integrity of the storage formation, to verify lateral gas tightness of the contact zones between salt and gas tight mudstone.

After the well was drilled, REEVES Wireline Services performed the logging service:

- LCS - Long Spaced Compensated Sonic Log
- CNS - Compensated Neutron Log
- PDS - Photo Density Log
- SGS - Natural Gamma Ray Spectroscopy
- BGN - Borehole Geometry Navigation
- AST - Acoustic Scanning Tool

The geological depth determination of the well was undertaken using the REEVES log (Table 3). A non-oriented full core section of 226 m was recovered using wire line coring. The intention from the rock mechanical standpoint was to cover at least the formation between approx. 100 m above the planned cavern interval and 25 m below the planned cavern interval, including the lowermost 10 m of salt and 15 m of Bollin Mudstone below the Northwich Halite Formation (Figure 7).

The Vertical Seismic Profile (VSP) survey was carried out after open hole wire line logging by DMT with hydrophones run into the well and record at every 2 m depth. The small single vibrator truck, used for the seismic survey in 2001, was used again as source.

Table 3: Stratigraphical Summary of the exploration well near Byley

Depth (logger) b. Ground level (m)	Drilled thickness (m)	Stratigraphy
- 15.00	15.00	Quaternary
- 438.00	423.00	Wych-Byley Mudstone Formation (Triassic)
- 707.50	269.50	Northwich Halite Formation (Triassic)
- 731.50	24.00	Bollin Mudstone Formation (Triassic)

The integrity of the zones in the exploration well was proven by the formation integrity testing by GOLDER Associates:

The planned depth zone of interest for the storage caverns is partially occupied by insoluble marl beds. Experience with existing gas storage caverns in Cheshire with formations of this type indicate that adequate gas integrity will be present. Nevertheless it was decided to carry out integrity packer tests at selected depth intervals after drilling the exploration well, to verify lateral gas tightness of the contact zones between salt and gas tight mudstone.

For the design of the integrity test, the maximum pressure to be used at each test interval was determined, based on the average overburden formation pressure calculated from density log and the lateral pressure coefficient.

Two types of tests were performed. First a slug test with water, where the pressure was decreased rapidly. The permeability of the formation for water was calculated from the subsequent pressure build-up. In addition water was injected at a constant head pressure. These tests were performed to determine the permeability of the formation.

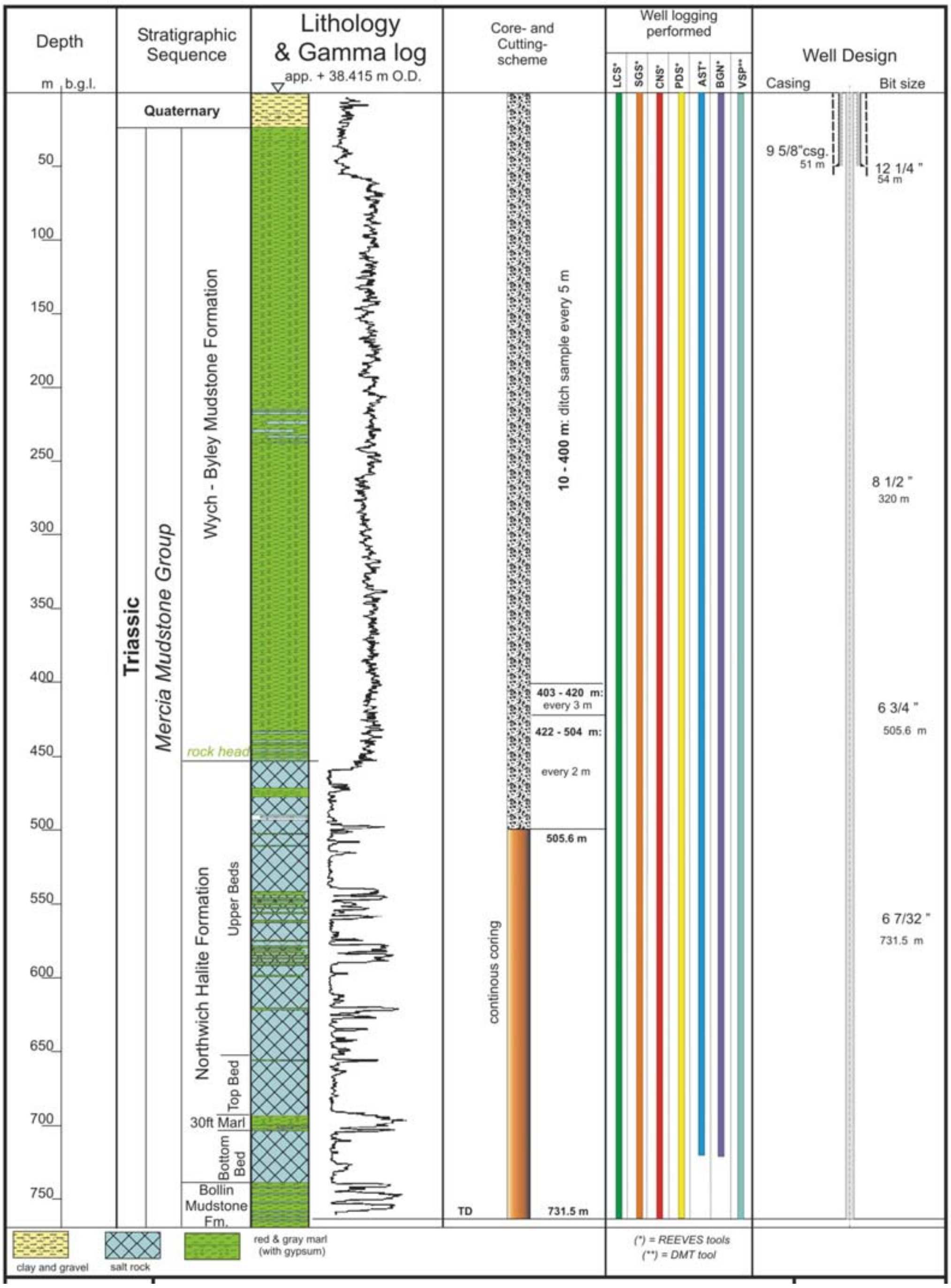

Figure 7: Litho-stratigraphic column with technical layout scheme of a Byley cavern

During the four hydrodynamic tests, using water as test fluid, the integrity of the non salt layers in the exploration well were verified in the depth range of interest and the pressure range as per the current basis of design. The mean value of the permeability identified in the formation integrity tests is being regarded as tight.

In addition to the evaluation of the hydraulic tests the determination of the capillary threshold pressure must be considered to assess the tightness of the 30-ft-marl and the adjacent clay layers towards gas flow.

As the pores in a claystone formation are filled with water, and the rock is water wet, the water is held in the pores by capillary forces. Before gas can flow through these pores, a threshold pressure has to be reached. This pressure can be detected by attempting to inject gas into the formation at increasing pressure and determine the point in pressure, where gas starts to flow.

During the constant rate gas injection performed in the test it was demonstrated that the gas capillary threshold pressure is at least the maximum achieved pressure in the test interval. This pressure exceeds the design value of the maximum operating pressure of the cavern facility, hence it can be concluded that the tightness of the formation towards gas flow has been verified at the exploration well in the depth range of interest and the pressure range as per the current basis of design.

3.5 Summary of exploration results

The salt layers encountered in the depth range of the planned cavern are assessed as being well suited to solution mining. The technical dissolution characteristics of the individual caverns will correspond with that of the neighbouring caverns in the IneosChlor Holford brine field. The dissolution behaviour of the 30-foot-marl requires a tailor-made technical solution-mining concept because of its special lithological composition. ScottishPower are in the process of carrying out the design activities for the solution mining infrastructure and the gas storage caverns, including preparation of rock mechanical and solution mining design studies based on location specific parameters. It is anticipated that construction could start as early as May 2005 with solution mining commencing early 2006 and completion late 2007 of the first phase of caverns.

4 References

[1] COOPER, A. H.: Halite karst geohazards (natural and man-made) in the United Kingdom, Environmental Geology (2002) 42:505-512.

[2] WOOD Mackenzie: UK Gas Infrastructure, 2004.

[3] Transco: Transportation Ten-Year Statement 2002.

[4] DEAN, F. & GAS, M.I: The Hornsea salt cavity storage installation, Yorkshire Gas Association.

[5] MULLALY, M.: Underground storage in thin salt layers on Teesside, ICI PLC, SMRI paper.

[6] DOWING, R.A. at al: Geothermal aspects of the Larne No 2 Borehole. Investigation of the geothermal potential of the UK, Institute of Geological Sciences, London, 1982.

[7] SMRI Research report: Relationship between Overbrining and subsidence, Report of Phase 1: Desktop study of existing data development of a preliminary model. Report by Sofregaz, France, 1998.

[8] LENFOND,S.J. (1969), Handbook of World salt recourses, Monographs in Geosciences, New York.

[9] Boardman, J. & Spicer, E.R., Construction and Operation of Salt Cavities for Storage of Natural Gas, European Petroleum Conference, EUR 328, London, 25-28, October 1982.

[10] COLTER, V.S. & REED, G.E: “Zechstein 2 Fordon Evaporites of the Atwick No. 1 borehole, surrounding areas of N.E. England and the adjacent southern North Sea” Contr. Sedimentology, 9, 1980.

[11] KNOTT, I. & CROSS, K.G.: Gas storage caverns in East Yorkshire Zechstein salt: Some geological and Engineering aspects of site selection, SPE 24923, 1992.

[12] OLIVER, J.: The role of gas storage in the UK Energy market, Gas processors Association, European Chapter, 22nd May 2003.

[13] CHALLINOR, D. & BRAY, M. (1994), Techniques for Cavity Revalidation under Gas Pressure, SMRI Fall Meeting, Hannover, Germany, pp. 88 -93, 95, 96.

[14] BELL, F.G. (1992), Salt mining and associated subsidence in Mid-Cheshire, England, and its influence on planning, Bull.Ass. Eng. Geol. 29, 4, pp. 371-386.

[15] International Energy Agency: “Security of Gas supply in open markets”, IEA, 2004.

[16] Winsford Rock salt mine (1980), Min. Mag.7, pp. 12-23.

[17] EARP, J. R. & TAYLOR, B. J. (1986), Geology of the country around Chester & Winsford, Memoir for 1:50 000 geological sheet 109, London, British Geol. Surv., pp. 39-61.

[18] EVANS et al (1968), Geology of the Country around Macclesfield, Congleton, Crew and Middlewich, Explanation of one-inch geological sheet 110, new series, London, Inst. Geol. Sci.

[19] TUCKER, R. M. & TUCKER, M. E. (1981), Evidence of synsedimentory tectonic movements in the Triassic halite of Cheshire, Nature 290, pp. 495-496.

[20] OFGEM Storage regulation post April 2004-08-09