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.

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Abstract

The Northwich Halite of the Cheshire Basin and the Preesall Halite of NW England and the East Irish Sea (EIS) are time and lateral equivalent (Anisian: 237-245 Ma), massively bedded halite deposits, with occasional intervals characterised by mudstone. The interbedded mudstone units, three of which attain significant thicknesses, are recognised from Cheshire northwards through Lancashire into the EIS. Onshore, these halite beds have been dry-mined for rocksalt and solution-mined during brine production. They are now also the target for the creation of gas storage caverns, with two sites operational and a number at varying stages of planning or development. Also planned is the Gateway project, offshore in the East Irish Sea.

We describe how detailed sedimentological descriptions of borehole core, geophysical log correlations and measurements on the thickness of halite beds and the interbedded mudstones provide information on the depositional environment of the halite and development of interbedded mudstones. This is important to assessing and predicting the lateral continuity of the halite beds across not just sedimentary basins, but also any particular site for the design and construction of gas storage caverns. Geophysical logs demonstrate that individual halite and interbedded mudstone sequences can be correlated over 150 kms north to south. The interbedded mudstones represent in the main, windblown (loessic) deposits, with the halites deposited in single, perennial, typically very shallow brinepool subject to occasional subaerial exposure. The depositional processes, systems and environments remained very stable for long periods of time over an area of at least 4700 km^2 and possibly pre-erosion, up to 46900 km^2.

Sequences thicken to the NW and offshore and this appears to be mainly as a result of increases in the thickness of halite beds. Preliminary assessments of the main interbedded mudstones are attempted to provide numerical data on the lateral continuity of the mudstones and possible lateral variations in the percentage insolubles of the Preesall Halite. Initial results indicate that subsidence was a major control on the thickness of the mudstones: where greatest, the halite beds are thicker and the interbedded mudstones show splitting. This suggests that increased subsidence rates created accommodation space that permitted increased halite precipitation, which was able to keep pace with subsidence rates, ‘drowning’ the siliciclastic input. During periods of slowed subsidence or increased sediment supply, deposition of beds of fine-grained siliciclastics (mudstones and fine siltstones) took place.

One potentially important feature is that thick mudstones with only minor halite interbeds seen in the Cheshire Basin and encountered at the Byley site, thicken to the NW by the incoming of number of thin halite beds (up to c. 3 m thick). These split the main mudstones into a number of thinner mudstone beds. They are thus likely to have differing impact on the leaching and cavern development processes.

Key words: Gas Storage, Preesall Halite, Northwich Halite, geophysical logs, sedimentary environments, United Kingdom

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1 Introduction

Developers of underground gas storage facilities are subject to increasing pressure to minimise subsurface risk in order to reduce construction cost uncertainties. For salt cavern gas storage, such uncertainties include cavern spatial volumes, the quantity of gas that can be safely contained within each cavern, and construction schedule delays.

When selecting and appraising sites for salt cavern gas storage development, a key role for the geologist is to advise on the continuity of the geology across the site area as a means of assessing the expected consistency of solution-mining performance.

Typically the geologist has available both seismic reflection and borehole data to assist such assessments. Thorough examination of recovered borehole cores may provide details on the salt crystal fabrics and sedimentary structures to (a) identify the depositional and sedimentary environments e.g. whether shallow or deep water, source of clastics etc. and (b) identify post-depositional deformations due to differential loading and diagenesis. Downhole geophysical logs provide further information on the nature and type of the rock penetrated by the borehole plus log correlations to estimate differential subsidence rates, all of which may impact the certainty of solution-mining performance across a development area.

This paper 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, 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.

2 UK background

Storage of natural gas and related products in salt caverns has been undertaken in a number of areas onshore UK for many decades now. Some of the first storage facilities were in former brine caverns in Permian salt deposits on Teesside (since the 1950s), with the first purposed designed and constructed facility in the same Permian salts at Hornsea (Atwick) in East Yorkshire (1979; Dean, 1978, 1985; Knott & Cross, 1992). Gas storage caverns are now operational in the Cheshire Basin at Holford (cavern H165 operational since 1999) and at Hole House.

Currently, a number of additional salt cavern gas storage projects are under construction or in the planning stages, both in the Permian salts of eastern England (Aldbrough, Whitecliffe) and the Triassic salt basins of Dorset, Cheshire, Lancashire and offshore in the East Irish Sea Basin (EISB). It is the Triassic salt basins of northern and northwestern England that are the focus of this paper.

Two important massively bedded halite formations of Triassic age crop out onshore England: the Northwich Halite in the Cheshire Basin and the Preesall Halite in NW England. The latter occurs on Walney Island (south Cumbria) and most importantly, around Preesall in NW England and is one of a number of halite units within the Mercia Mudstone Group (MMG) that extend and thicken offshore into the East Irish Sea Basin (EISB; refer Jackson et al., 1995; Jackson & Johnson, 1996). Penetrated in a series of hydrocarbon exploration wells the Preesall Halite is the most extensively geophysically-logged Triassic halite offshore, proving to be one of the thickest and cleanest halites in the Mercia Mudstone Group offshore (Jackson et al., 1997). The thick halites provide the main tool for subdividing the Mercia Mudstone Group across the EISB (Jackson & Johnson, 1996).

Although the lateral equivalency of the Northwich Halite of the Cheshire Basin and the Preesall Halite of NW England was at best half heartedly accepted (Raybould, 2005) and even questioned by the same author during the Public Inquiry for the Preesall gas storage application, correlations, aided by microfossils have established their Anisian age (Warrington et al., 1980; Earp & Taylor, 1986; Wilson, 1990, 1993; Jackson & Johnson, 1996), which in the Cheshire Basin, is confirmed by miospores recovered from the Thirty Foot Marl in ICI Borehole 192 at Holford in the Chester District (Warrington, 1970; Earp &Taylor, 1986). The Anisian is dated at around 237-245 Ma, representing a period of circa 8 Ma (Gradstein et al., 2004; BGS, 2010) during which the halite beds were deposited.

Thus the Preesall and Northwich halites were deposited in a single tract extending from the Cheshire Basin out into the EISB across the Llŷn-Rossendale Ridge, although evidence for the former continuity has been removed by erosion (Jackson & Johnson, 1996). The basin covered an area of at least 4700 km^2 and possibly pre-erosion up to 46900 km^2, within which, depositional processes, systems and environments remained very stable over long periods of geological time.

3 Geophysical log correlations of the Northwich and Preesall halites

The lateral equivalency of the halite beds is taken as proven (e.g. Warrington et al., 1980; Earp & Taylor, 1986; Wilson, 1990, 1993; Jackson & Johnson, 1996) and one purpose of this paper is, through a series of geophysical log correlations (gamma ray and sonic), to assess the lateral continuity of the halite beds. Previous work has shown the correlation of logs from the Preesall Halite sequences offshore, with one or two examples from onshore, which provide evidence of the internal stratigraphy of the Preesall and Northwich halites and demonstrate their consistency and lateral continuity over great distances. Mudstone beds ranging in thickness from generally less than 2-3 m thick but up to 10 m thick in the Cheshire Basin and exceptionally 15 m in the north of the EISB (well 113/27-1: Jackson & Johnson, 1996), can be traced laterally over many tens to hundreds of kilometres. Offshore within the EISB, around 20 individual mudstone partings can be correlated and traced widely across the basin, with thin red mudstone partings correlated individually over a distance of at least 15 km between wells 110/3-2 and 110/7-1 (Jackson et al., 1995; Jackson & Johnson, 1996; Smith et al., 2005).

This work provides correlations of a greater number of boreholes to those of the works cited above that further demonstrate the lateral continuity of the interbedded mudstones across individual sub-basins and more regionally, over distances of 150 kms or more, extending from the southern end of the Cheshire Basin, out into the East Irish Sea (Figs 2-4). The correlations are aided by cored material through the majority of the Northwich (Byley #1 borehole: Beutel & Black, 2005) and Preesall (Arm Hill #1 Borehole, Preesall: Ratigan, 2005; & Gateway 1-e Borehole, EISB: Eyermann, 2007) halites. Three mudstone dominated sequences in particular are recognised and are here informally termed mudstones 1-3. Mudstone 1 is proved to be the Thirty Foot Marl in the Byley #1 Borehole, drilled in 2003 by Scottish Power near Holford in the Cheshire Basin (Beutel & Black, 2005). The geophysical log character shows that many more, thinner mudstone dominated intervals can also be traced across the EISB and onshore into the Preesall Saltfield of NW England. When this is linked to detailed core descriptions, it provides important information on the environment of deposition and basin subsidence history.

3.1 Cheshire Basin log correlations

Seven boreholes with geophysical logs illustrate the lateral extent and nature of the Northwich Halite in the Cheshire Basin (Fig. 1). As described above, they are 'calibrated' by the Scottish Power Byley #1 Borehole (Beutel & Black, 2005), where the geophysical log response is proved by continuous core taken through the main part of the halite beds. The main halite beds give rise to sequences with low gamma ray and high sonic velocities, whilst interbedded mudstones have higher gamma and lower sonic log responses.

The geophysical logs reveal a remarkable lateral continuity of the halite beds with many high gamma peaks, and generally high overall responses indicative of thin mudstone interbeds and more mud-rich halite beds. Three main mudstone intervals are highlighted in the correlation lines: mudstones 1-3 (Fig. 1). The gamma ray logs reveal an obvious log break at the base of the lowest major halite, which equates to Earp & Taylor's (1986) Bottom Bed in the nearby Winsford mine.

Beneath the lowest section of massive halite beds lies a sequence with very characteristic alternations of high and low gamma ray responses, suggestive of a series of recognisably thicker alternating mudstones and halite beds, the base of which is here labeled '?Base Northwich Halite'. These beds were assigned to the underlying Bollin Mudstone Formation by Beutel & Black (2005). They represent the earliest halite sequences and precursors to the main Northwich Halite, deposited in the deepest and more remote parts of the Cheshire Basin. We would now suggest placement of the base of the Northwich (and Preesall) Halite at the base of the lowest significant bed of halite on top of the underlying mudstone sequence.

Above the Bottom Bed, a thick unit (up to 40 m thick) gives rise to a broad gamma peak and lower sonic velocities (mudstone 1). The interval is well developed across the Cheshire Basin (Fig. 1) and comprises the Thirty Foot Marl, either side of which are thick halites with low gamma ray responses (the Bottom and Top beds). Towards the base of this mudstone the incoming of a halite bed is indicated by a marked gamma low (and increased velocity) in the Elworth borehole. A salt of similar position is known in the Thirty Foot Marl of the Holford Brinefield and equates to the thin persistent bed of salt noted in many boreholes elsewhere in Cheshire by Earp & Taylor (1986). Gamma ray log signatures from the boreholes in Figure 2 show the alternation of gamma peaks and lows, indicating that the Thirty Foot Marl comprises a succession of mudstone and more halite-dominated strata. These halite interbeds are much diminished in the Thirty Foot Marl section of the Prees #1 Borehole.

The remaining Northwich Halite is characterised by thick units of low gamma response with at least 20 gamma ray peaks noted, producing rather ragged gamma ray profiles. Several broader intervals of high gamma peaks are obvious arising from sequences several metres thick representing a series of interbedded mudstone and halite beds. Two such higher gamma intervals (mudstones 2&3) are highlighted for the purposes of correlating the sequences. In general they are all traceable along the length of the Cheshire Basin from Prees #1 in the south to Byley #1 in the northern end near the Holford Brinefield, a distance of circa 40 kms. Between mudstones 1 and 2 is a prominent interval of alternating high and low gamma peaks that is traceable along the entire Cheshire Basin. This unit may be up to 35 m thick and is seen in e.g. Elworth (575 m and c. 605 m) and Burford (205 m and c. 240 m).

3.2 Cheshire Basin to Preesall Saltfield correlations

The Preesall Halite is an important sequence of massive bedded halites that occurs onshore in NW England in the Preesall Saltfield. It is also present to the north on Walney Island, where it is at shallow depths beneath wet rockhead (Jackson et al., 1987, 1996). In the Preesall Saltfield the halite was once dry mined at two different levels and has been extensively solution mined across the shallower eastern side of the saltfield (Wilson & Evans, 1990; Hough et al., 2011). At Preesall, the halite beds are preserved in a down faulted, westerly tilted asymmetric graben structure. It extends from outcrop in the east, where it is overlain by a zone of wet rockhead 500-600 m wide and comprising collapse breccias of the overlying Coat Walls Farm Mudstone, westwards to depth beneath the Wyre Estuary (Wilson & Evans, 1990; Evans et al., 2005). Its thickness is also shown by borehole and seismic reflection data to increase westwards across the saltfield. Some of the thickness change is across small faults affecting only the base of the halite beds and which were probably active during deposition of the halite, controlling its thickness and to some extent the occurrence of some early sequences.

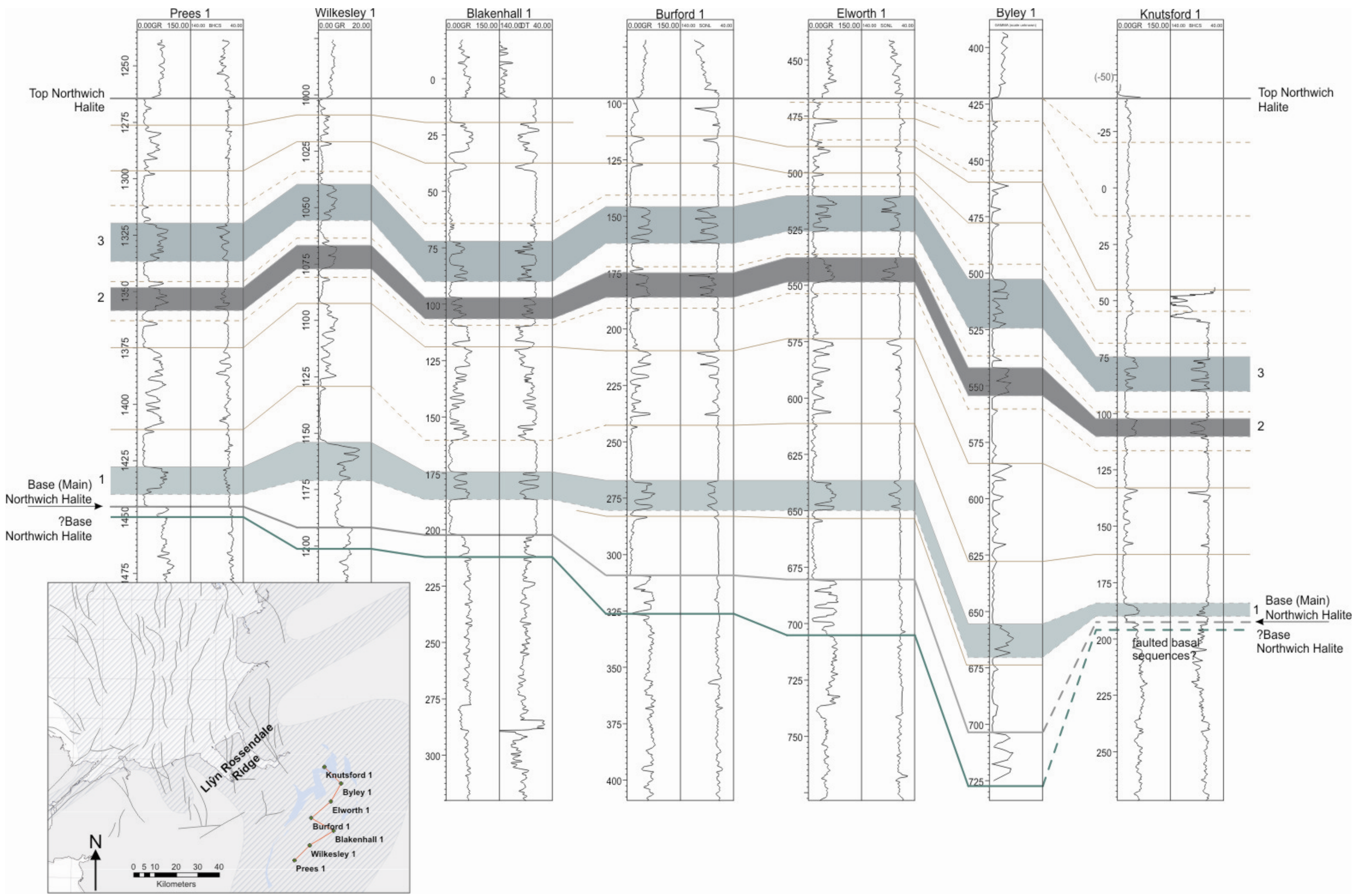
The Preesall Halite is proved in a BGS stratigraphic borehole (Coat Walls Farm), four recent salt exploration boreholes and numerous ICI brinewells. The recent salt exploration boreholes were drilled by Canatxx Gas Storage Limited (now Halite Energy Group) to assess the halite beds for gas storage purposes. In two of these boreholes drilled in 2004 (Arm Hill #1 and The Heads), a comprehensive suite of geophysical logs were run (refer Ratigan, 2005; Evans et al., 2005). The Preesall Halite sequence is described in detail by Wilson & Evans (1990) and geophysical log correlations of the succession published elsewhere (Evans & Holloway, 2009; Hough et al., 2011). The Arm Hill #1 Borehole cored the almost the entire thickness of the Preesall Halite, but was not deepened sufficiently into the underlying

Thornton Mudstones to permit geophysical logging of the entire range of the halite beds hence the geophysical signatures of the lowermost sequences of the Preesall Halite are not recorded (refer Fig. 2).

The geophysical logs illustrate a lateral and predictable internal stratigraphy across the Preesall Saltfield (Fig. 2 and see Evans & Holloway, 2009; Hough et al., 2011) that shows remarkable similarity to the Northwich Halite succession of the Cheshire Basin (Figs 1&2). The logs demonstrate that units can be readily correlated between the two sub-basins, as illustrated by the Prees #1, Elworth #1 and Byley #1 boreholes in Cheshire and The Heads, Brinewells BW114 and BW123 and the Arm Hill #1 Borehole at Preesall, Lancashire. The three mudstone intervals 1-3 with higher gamma ray responses described from the Cheshire Basin area are present, including the lateral equivalent of the Thirty Foot Marl (mudstone 1). It is also clear that other thinner units showing high gamma ray values can also be correlated between the two sub-basins over a distance of circa 75 km. However, in the Preesall area, the prominent zone of high and low gamma peaks described in the previous section between mudstones 1 and 2 in the Cheshire basin is not present in the Preesall logs, indicating a cleaner halite interval or non-preservation. It is however, albeit in a ‘cleaner facies’, present in the offshore boreholes, as illustrated below.

There is a general decrease in the overall higher background gamma log responses seen in the Northwich Halite succession in Cheshire to that of the Preesall Halite in NW Lancashire. This indicates a general change to cleaner halites and thinner sequences of more muddy aspect.

Figure 1 (next page). Correlations of the Northwich Halite in the Cheshire Basin based upon geophysical well logs. The Byley gamma ray log is from the exploration borehole at the gas storage site under development (Beutel & Black, 2005) and which cored the halite from 504m. For the logs, the left track is gamma ray, right track is sonic when both logs available, otherwise gamma ray only. Depths below mean sea level (msl).



Prees 1
Wilkesley 1
Blakenhall 1
Burford 1
Elworth 1
Byley 1
Knutsford 1
Top Northwich Halite
Base (Main) Northwich Halite
?Base Northwich Halite
faulted basal sequences?
1
2
3
Llŷn Rossendale Ridge
N
0 5 10 20 30 40
Kilometers

3.3 Preesall Saltfield to East Irish Sea correlations

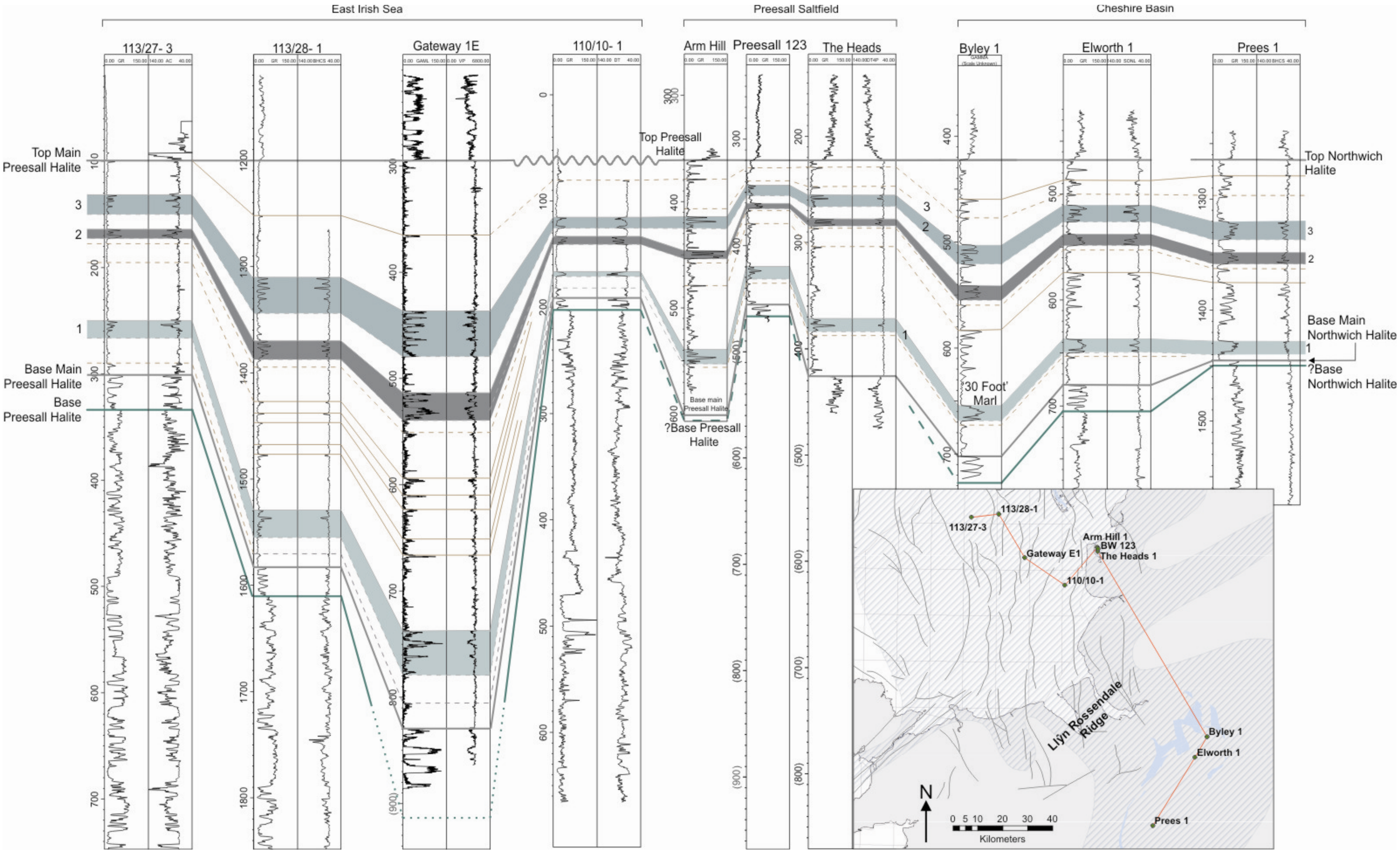
Offshore in the East Irish Sea Basin (EISB) the Preesall Halite is proved in many exploration wells and attains the greatest thicknesses in the centre and north of the EISB, lying within a number of narrow grabenal areas (Jackson & Johnson, 1996). The Gateway 1-e borehole drilled in 2007 lies within one such graben (the Crosh Vusta Graben). It was cored from above the top of the Preesall Halite into the basal members of the salt (Eyermann, 2007) and provides the calibration for the offshore Preesall Halite (Fig. 2).

The general continuity of the Preesall Halite succession from onshore at Preesall is shown in Figure 1 detailing the correlation of the Preesall Halite from onshore at Preesall offshore into the EISB. In the offshore areas, the Preesall Halite clearly thickens, but the overall log character is remarkably consistent with the main mudstone 1-3 units clearly developed, including the lateral equivalent of the Thirty Foot Marl (mudstone 1). Mudstones 1-3 show a thickening with the incoming of low gamma ray units 2-5 m thick, which are related to the development of thin interbedded halite beds. The correlations can be taken across the EISB into wells of the northwestern areas of the basin. Together with the Cheshire Basin to Preesall correlations, this illustrates that the correlations can be extended for the southern end of the Cheshire Basin, north and northwestwards for over 150 kms.

In addition to the regional correlations (Figs 1&2), there is clear evidence of the thickening of the Preesall Halite across fault zones into sub-basins indicating that they were active during deposition. This is illustrated well by a short correlation line across the Crosh Vusta Fault Zone (Fig. 3; see also Jackson & Johnson, 1996). Within the fault zone the thick sequences of the Gateway 1-e and 110/03-2 boreholes contrast with abnormally thin, condensed sequences encountered in boreholes drilled on the up-thrown western (110/03b-4) and eastern (110/10-1) footwall blocks. Borehole 110/3b-4 proved very thin Preesall Halite overlain by mudstones of the succeeding formation. In particular there is a notable absence of the high gamma peaks associated with mudstones represented in other borehole logs, with mudstones 1-3 not recognised. Borehole 110/10-1, although showing Quaternary deposits resting on the Preesall Halite and indicating some of the upper beds were lost to dissolution (Jackson & Johnson, 1996), proved a significantly thinner Preesall Halite but still showing similar character and through-going mudstones equating to mudstones 1-3. These thickness changes are related to syndepositional faulting, indicating that condensed sequences developed over areas of the basin that underwent less subsidence than adjacent areas over which continued fault controlled subsidence rates. In these areas subsidence rates were higher and thicker sequences of halite developed in addition to the interbedded mudstones that show the incoming of thin halite beds. It illustrates that the rate of precipitation was able to keep pace with the subsidence rates in the faster subsiding basin areas.

The geophysical logs through the Preesall Halite offshore show the internal stratigraphy of the Preesall Halite is remarkably constant and laterally very persistent. As described in the Preesall area, the lateral equivalent of Mudstone 1 unit which includes the Thirty Foot Marl in the Cheshire Basin appears present in most offshore boreholes, as do mudstone intervals 2&3. The geophysical logs reveal that in the offshore areas the mudstones are expanded and contain more and thicker interbedded halites, which within the EISB appear to remain remarkably consistent in their thicknesses and geophysical log responses.

Figure 2 (next page). Geophysical log correlation of the Pressall and Northwich halites to illustrate the lateral continuity of the halite beds over a distance of 150 kms from onshore in the Cheshire Basin (tied to partly cored Byley #1 Borehole; Beutel & Black, 2005) to the Preesall Saltfield (tied to the fully cored Arm Hill #1 Borehole; Ratigan, 2005) and extending offshore to Q110 and Q113, tied to the fully cored Gateway 1-e Borehole (Eyermann, 2007). Logs are shown with the top Preesall/Northwich halite as datum. For the logs, the left track is gamma ray, right track is sonic when both logs available, otherwise gamma ray only. Depths below mean sea level (msl).



East Irish Sea
Preesall Saltfield
Cheshire Basin
113/27- 3
113/28- 1
Gateway 1E
110/10- 1
Arm Hill
Preesall 123
The Heads
Byley 1
Elworth 1
Prees 1
Top Main Preesall Halite
Top Preesall Halite
Top Northwich Halite
Base Main Preesall Halite
Base Preesall Halite
?Base Preesall Halite
Base main Preesall Halite
Base Main Northwich Halite
?Base Northwich Halite
'30 Foot' Marl
113/27-3
113/28-1
Gateway E1
Arm Hill 1
BW 123
The Heads 1
110/10-1
Llŷn Rossendale Ridge
Byley 1
Elworth 1
Prees 1
N
0 5 10 20 30 40
Kilometers

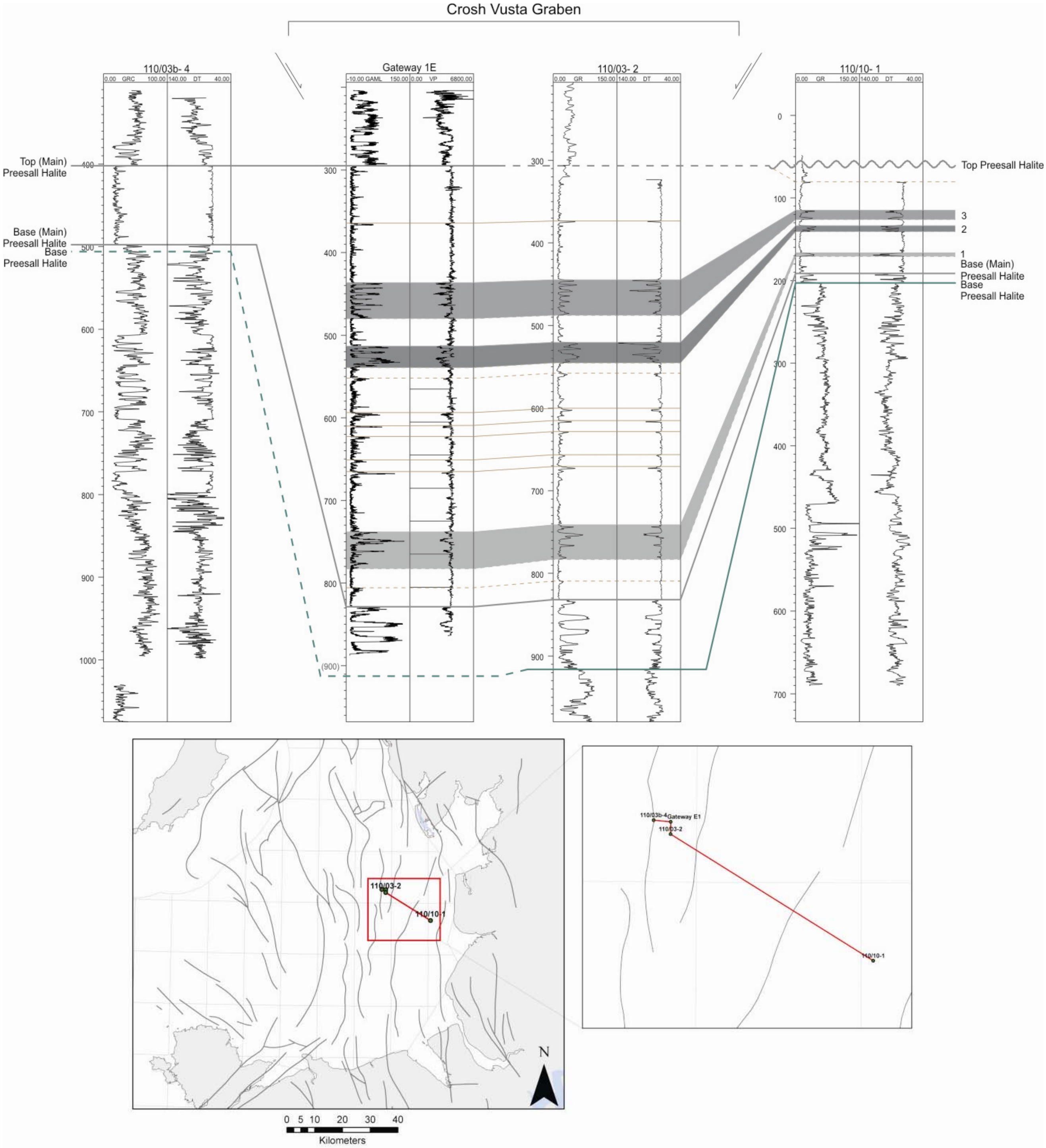


Figure 3. Geophysical log correlation showing detail of the Pressall Halite from thin sequences roved over relative highs during deposition (110/03b-4 & 110.10-1) into the thicker sequences of the Crosh Vusta Fault Zone in which Gateway 1-e and 110/03-2 boreholes were drilled. Also basal sequence of interbedded halite, muddy halite and mudstone beds beneath the main halite beds. Logs are shown with the top Preesall Halite as datum. For the logs, the left track is gamma ray, right track is sonic when both logs available, otherwise gamma ray only. Depths below mean sea level (msl).

3.4 Summary of overall correlations

A number of interbedded mudstones are present within the Northwich and Preesall halites of the Cheshire, Preesall and East Irish Sea basins. They can be reliably correlated over distances in excess of 150 kms, extending from the southern end of the Cheshire Basin, out into the East Irish Sea (Fig. 2).

Offshore, the lateral continuity of the mudstones is supported by seismic reflection data, which reveal a number of laterally continuous good continuity reflections are associated with the main interbedded mudstones (Fig. 4; refer Buckley, 2010).

Across the basin, beneath the lowermost main halite unit a sequence of characteristically alternating high and low gamma ray units is noted, representing mudstone and halite interbeds respectively (refer Fig. 2). These sequences are well developed in the Cheshire and EISB areas, but are also noted in the Preesall Saltfield, notably in BW123. In the EISB this lower interbedded succession is up to 75 m thick, compared to the 25-30 m in Cheshire or 10-15 m at Preesall. Offshore the sequence of interbedded mudstones and halites are not always assigned to the same formations. They may be represented as part of the underlying Cleverleys Mudstone Member of the Leyland Formation or the Preesall Halite (e.g. Jackson & Johnson, 1996).

Although Jackson & Johnson (1996) and Jackson et al. (1997) have included on these gamma log correlations interbedded mudstones and halites within the Preesall Halite, further south in the Cheshire Basin, lithologically based stratigraphic classifications place the alternating 20 m or so succession of mudstones with beds of halite up to 2 m thick (in e.g. the Plumley No.3 Borehole and in a borehole 5 km south of Middlewich) in the top levels of the underlying Bollin Mudstones (e.g. Earp & Taylor, 1986; Wilson, 1993; refer also Beutel & Black, 2005).

Perhaps more of an academic exercise, it suggests that as a result of detailed correlation, a better understanding of the depositional environment and facies development is demonstrated. The appearance of the basal log unit, its lateral continuity and thickening into central areas of the basins appears related to an incoming of thicker halite beds. It seems likely that these sequences are the same and represent the initiation of the period in which halite deposition assumed dominance and presumably reflects the difference in terms of relative location to the more central and deepest parts of the basins where halite was being deposited whilst more marginal basin areas received muddier salt (haselgebirge) facies and mudstones.

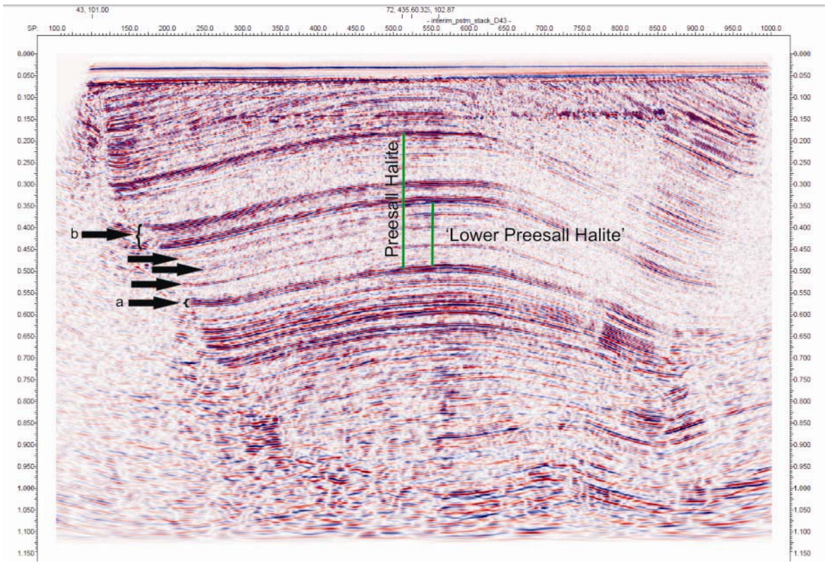


Figure 4. Example of a W-E seismic reflection line across the 'Gateway' site in Q110/03 of the East Irish Sea. Seismic line shows good internal reflectivity from the Preesall Halite, including from laterally continuous interbedded mudstones (both arrowed and labelled a&b) proved by the fully cored Gateway 1-e Borehole.

4 Detailed core descriptions and sedimentary fabrics of the Northwich and Preesall halites

Detailed core descriptions have been undertaken on borehole core material from the three Triassic halite basins:

1. Northwich Victoria Infirmary Borehole (Cheshire Basin)
2. Arm Hill 1 Borehole (Preesall Saltfield)
3. Gateway 1-e Borehole (EISB)

4.1 Core from the Cheshire Basin, England – Northwich Victoria Infirmary Borehole

The Northwich Victoria Infirmary Borehole (SJ67SE/137) is located 250 m to the west of the Weaver Navigation at Northwich (approximately [365400 373400]), in the northern part of the Cheshire Basin. The borehole is important as it is one of the few that proves the Thirty Foot Marl within the Northwich Halite succession; it is currently the only core held by BGS through this unit and shows many interesting crystal and sedimentary features suggestive of shallow water deposition (Fig. 5).

Halite-dominated units above and below the Thirty Foot Marl are characterised by primary laminated and recrystallised halite. Where recrystallised, the halite may retain 'ghosts' of primary crystals. Primary laminated units include elongate halite crystals up to 18 mm long, oriented with long axes normal to lamination (Fig. 5a); a thin film of mudstone is preserved between crystals at some horizons. Cracks and discontinuities are preserved disrupting primary laminated halite in a steeply-dipping zone of halite at 55.2 m (Fig. 5b). Of note at 54.8 m is a high angle unit, with dips up to 65 degrees, which is cut by a unit of gently dipping laminated halite, with anhydrite/gypsum and mudstone developed at the interface (Fig. 5c). The interface is likely to be a dissolution/erosion surface, and one further solution seam within the halite has been identified in the overlying flat lying unit. Mud-filled cracks/pipes cutting primary halite lamination are preserved below a thin mudstone lamina immediately below the base of a probable dissolution surface between 60.83-61.04 m (Fig. 5d). There is a distinct muddying of the halite immediately above the Thirty Foot Marl, with mudstone blocks and fragments brecciated but retaining a gross orientation broadly parallel to primary bedding. Many examples of flat-lying solution seams are noted, often closely spaced (Fig. 5i).

Cryptic colour banding parallel to dip is retained in some intervals and individual flat-lying solution seams within the halite are common. Where present, the mudstone component within the halite is typically brecciated, probably by repeated penecontemporaneous halite solution and crystallisation. Displacive halite growth occurring after mud deposition is indicated by mud films of varying thickness in pockets and between halite crystal boundaries in certain instances giving rise to a 'chicken-wire' fabric. There is evidence of banded halite, up to 0.7 m thick, separated by halite with primary crystallisation features, up to 1.16 m thick. The junction between these two types of halite is sharp and undulose, immediately overlying a solution seam. The banded halite units are very distinct from the primary crystallised halite, and are thought to be possible cumulate halite, deposited as a 'shower' of crystals from supersaturated, stratified brine. Interestingly, however, solution seams are present within the banded halite, suggesting the periodic emergence of the halite. Internally, the mudstone blocks are commonly structureless, although remnant lamination exhibiting soft sediment deformation was observed between 86.76-87.59 m, and parallel lamination between 87.9-88.06 m.

Lithologically, the siliciclastic component of the Thirty Foot Marl comprises interlaminated clay- and silt-grade material, and rare occurrences of very fine-grained sandstone. Sedimentary facies are dominated by wavy continuous and discontinuous parallel and non-parallel lamination; thick and thin laminae that are internally structureless are common. Small-scale soft sediment deformation structures related to loading and dewatering of an unconsolidated sediment pile are ubiquitous. These include flame structures and clastic dykes and small-scale slumping and load structures. The sediments include rare ripple-laminated, very fine-grained sandstones with silt or clay drapes, indicating deposition from a current that periodically waned and asymmetrical ripple-laminated siltstone. It is likely that the wavy non-parallel laminated facies represents sediment that was originally ripple-laminated and has been subject to soft sediment deformation. Overall, erosive bases to interlaminated units are rare.

Figure 5. Photographs of the Northwich Victoria Infirmary borehole core. (a) Steepened and radially developed primary lamination of elongate halite crystals, 53.68 m, (b) Steeply dipping primary laminated halite with minor cracks and discontinuities, 55.2 m, (c) Likely dissolution/erosion surface with development of anhydrite/gypsum, 54.8 m (d) Pipes/cracks infilled by mudstone, descending from a mudstone laminae immediately below a probable solution surface. Note pipe/crack feature cuts primary halite lamination, 60.83-61.04 m, (e) Small-scale flame structures developed at a single horizon of pale siltstone beneath thin laminae of dark grey claystone, 61.48-61.61 m, (f) Load structures preserved on the base of laminae, exposed on a drill-break, 64.13 m, (g) Thin laminae of very fine grained ripple-laminated sandstone with possible finer-grained drape, 63.76-64.13 m, (h) Asymmetrical ripple-laminated siltstone overlying structureless unit of mudstone, 64.55 m, (i) Series of stacked flat-lying solution surfaces within halite. 86.5-86.7 m, (j) Basal contact of Thirty Foot Marl on halite. Mud-filled pipes and caves extend downward from the basal contact, up to 125 mm into the underlying halite.

There is evidence of silt-filled desiccation cracks (at 64.1 m), however, other structures such as rootlets/rhizoliths, anhydrite nodules or multi-coloured mudstones that may indicate pedogenesis and emergence of the sediment pile were not apparent.

The basal contact of the Thirty Foot Marl comprises an indurated contact that is distorted by possibly displacive halite development. A pipe or crevasse fill 25 mm wide, composed of mudstone, extends down 125 mm from the basal mudstone into the underlying laminated halite (Fig. 5j), indicating emergence immediately prior to mudstone deposition.

In mudstones in the lower part of the Northwich Halite (106.1-106.4 m), an elongate, upward oriented mudstone filled fissure overlying a thin mudstone bed indicates emergence of the sediment pile. The basal junction of this bed is uneven, with a possible small-scale ‘cave’ fill, similar to features described by Hovorka et al. (1987). Evidence of desiccation is not observed in the interbedded units in the lower part of the succession, suggesting either complete reworking of desiccated horizons, or the lack of aerial desiccation of the mudstone units.

4.2 Core from Preesall Saltfield, Lancashire, NW England - Arm Hill 1 Borehole

The Arm Hill borehole at Preesall, drilled in 2004 by Canatxx Gas Storage Limited, was cored from 349.6 m to TD at 610.6 m. It proved a thick (241 m) sequence of layered halite from 366 m to 607 m. The core is now curated by BGS and a detailed core description including crystal textures and sedimentary fabrics has been undertaken and is briefly summarized here.

The Arm Hill 1 Borehole cored the entire Preesall Halite and a number of primary sedimentary fabrics and halite crystal textures are found throughout the entire length of the Arm Hill core (Fig. 6). Lithologically, the siliciclastic component of the mudstone dominated units comprises interlaminated clay- and silt-grade material.
The Arm Hill core also shows exceptional examples of infilled fractures of several generations in both the interbedded mudstones and halite beds with primary crystal textures. Those in the mudstones illustrate that the mudstones are cut by an interconnected network of halite filled fractures that are likely to allow brine access to the interior of the mudstone during leaching and facilitate the breakdown of the mudstones into small blocks.

The Arm Hill 1 Borehole cored the entire Preesall Halite and a number of primary sedimentary fabrics and halite crystal textures are found throughout the entire length of the core. There are a number of zones of Haselgebirge facies – typically 20-40% insolubles with a chaotic fabric (Fig. 6a). Primary lamination and crystal fabrics are found all the way down the borehole (Fig. 6b), with distinct thin beds of primary halite and mudstone present. Halite layers are present with elongate halite crystals normal to bedding evident throughout the borehole (Fig. 6b-e) and are often seen associated with solution surfaces or bands/seams, indicating penecontemporaneous solution (Fig. 6d-e). Beds or clasts of nodular anhydrite are present. One sequence between 518.5 and 523.5 m depth comprises rather chaotic clasts, veinlets and disrupted beds in which halite with primary lamination and crystals is preserved. These strata represent shallow water or emergent conditions where crusts of muddy evaporites probably formed in broad coastal salt flat (sabkha-like) environments.

A ‘chickenwire’ fabric (Fig. 6j), formed by films and smears of mudstone/clay along boundaries of large halite crystals, produces an interlocking (and sometimes discontinuous) meshwork of mudstone within some halite rich layers. This is suggestive of displacive growth and recrystallisation of halite at shallow depths of burial shortly after deposition, with deposition having been in very shallow water- with input of mud. Restricted to the lower part of Preesall Halite examples of a mudstone to chickenwire fabric transition are present. Hopper crystals, often of considerable size, are present in a variety of forms (e.g. Fig. 6f-h):

- at the base of thin mudstone interbeds, penetrating upwards into the mudstones indicating continued growth and disruption of the mudstone
- as large hopper crystals with classic fractures at crystal tips
- as thin beds within some mudstones
- zonation within crystals

o with inclusions of mudstones – indicating very slow crystallisation

One fabric found reveals clasts or pellets of red mudstone cemented by greener mudstone and evaporite minerals (Fig. 6k). This indicates disruption of at least a partially lithified blocky red mudstone.

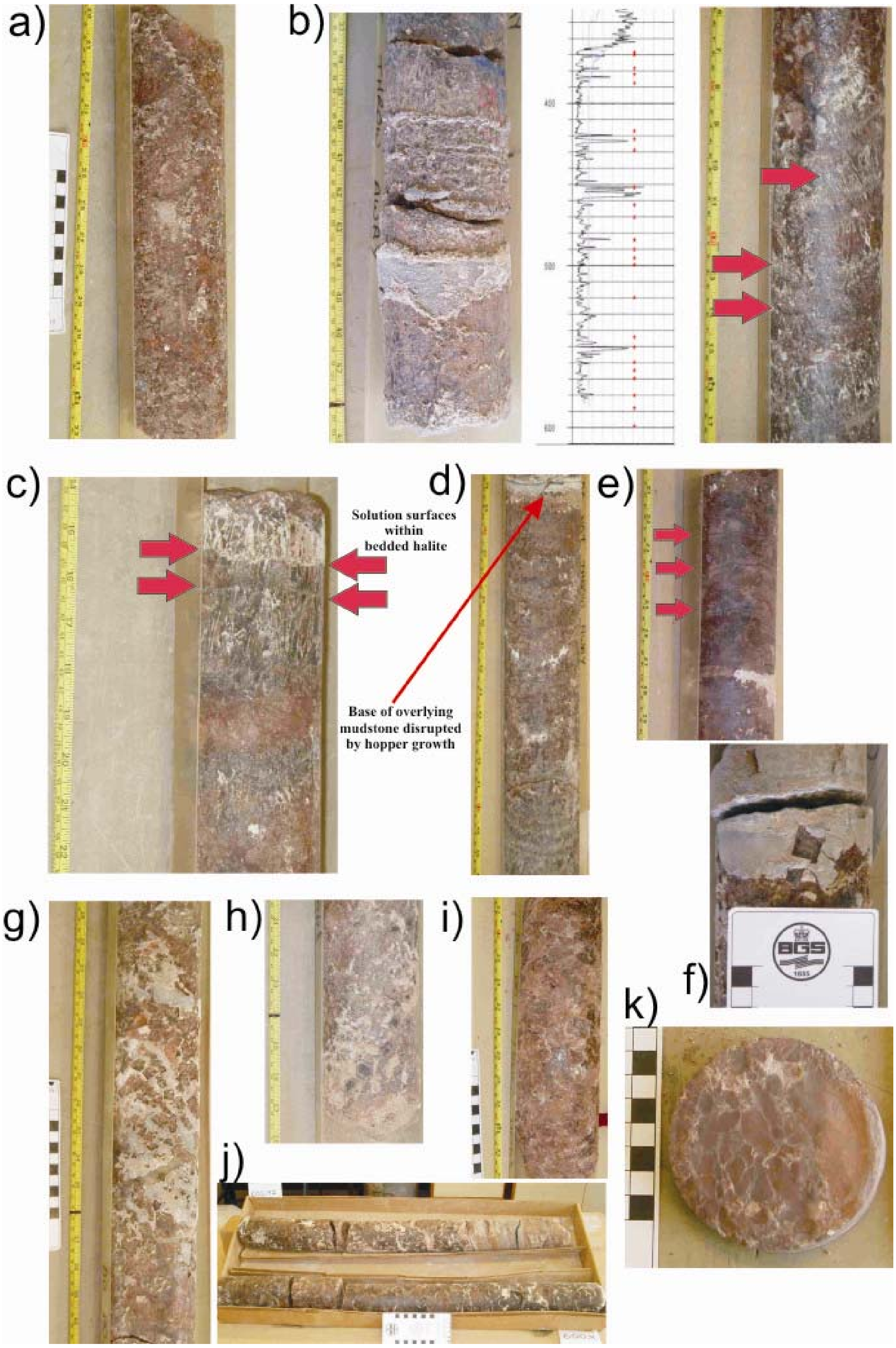


Figure 6 (previous page). Primary depositional features and crystal textures from the Preesall Halite cored in the Arm Hill #1 Borehole, Preesall, NW Lancashire. (a) haselgebirge facies – typically 20-40% insolubles and chaotic fabric, (b) primary lamination and crystal fabrics (elongate halite crystals normal to bedding & solution surfaces or bands/seams), observed all the way down the borehole, (c-e) primary halite crystal textures including elongate halite crystals normal to bedding and solution surfaces or bands/seams (d&f) hopper crystals often large at the base of thin mudstone interbeds, penetrating upwards into the mudstones indicating continued growth and disruption of the mudstone and with mudstone along crystal faces showing classic fractures at crystal tips (g) thin strings of hopper crystals within thin mudstone beds indicating synsedimentary gowth (h) zonation within hopper crystals indicating subaqueous growth in wet mudstones (i&j) 'chickenwire structure' with films and smears of mudstone/clay along boundaries of large halite crystals, forming an interlocking (and sometimes discontinuous) meshwork of mudstone within halite rich layers. This is suggestive of displacive growth and recrystallisation of halite at shallow depths of burial shortly after deposition (k) mudstone containing cemented clasts or pellets of mudstone which are suggestive of disruption of partially lithified mudstone during subaerial exposure.

4.3 Core from the Gateway site, offshore East Irish Sea – Gateway 1-e Borehole

The Gateway 1-e Borehole was drilled in mid 2007 and was cored from above the top of the Preesall Halite into the basal members of the salt and general lithological core descriptions were undertaken by Eyermann (2007). The core logging provided the required information on salt thickness and insolubles content, but as yet, no detailed lithological core description, or fracture logging has been undertaken.

In the absence of detailed core examination, photographs of the core sticks (taken shortly after recovery), are briefly described (Fig. 7). There is much evidence of primary halite crystal structures and bedding features, including laminated and wavy laminated grey-green mudstone beds, and sedimentary features suggestive of emergent conditions such as blocky reddish brown mudstones and pipes infilled with mudstone material.

Primary laminated halite on the cm scale is observed throughout the halite beds, with thin clear horizontal halite suggestive of solution seams. Signs of primary halite crystals elongate normal to bedding are found and in slabbed core are clearly developed (Fig. 8). These crystal fabrics are identical to the elongate primary crystals observed in the halite beds of the Cheshire Basin and Preesall Saltfield (Figs 5&6). Sequences of coarsely crystalline halite with faint banding probably represent recrystallised bedded halite (Fig. 7 left, a). Sequences of coarsely crystalline halite show a sort of white and brown speckled ('salt and pepper') texture or appearance. Whilst it could be a recrystallisation fabric it might also be indicative of deeper water cumulate crystals that settled on the brinepool floor.

Grey-green and brown finely laminated mudstones display parallel laminations (Fig. 7 left, g&h) and wavy non-parallel laminated facies. The latter represents sediment that was originally laminated and has been subject to soft sediment deformation (Fig. 7 left, i). Also present are blocky, structureless grey-green and brown mudstones, with apparent mudstone clasts in mudstone matrix indicating very shallow water or subaeriel deposition (Fig. 7 right, a). Sequences of laminated grey green mudstones passing up into red-brown, blocky structureless mudstones with little halite are observed. There are also examples where sequences become more halite rich and very chaotic mudstone in haselgebirge facies indicating increasing displacive coarsely crystalline halite producing 'chickenwire fabrics' – blebs and stringers of mudstone along crystal faces (Fig. 7 right, b&c). Anhydrite blebs within mudstones and seams in halite indicate shallow to emergent conditions (Figs 7 left, b, 7 right, c&d). There are also sequences of finely bedded material of alternating grey-green and browner mudstones, with possibly slightly coarser silty units.

Laminated and wavy lamination is apparent in mudstones, with very irregular bases to one or two units that may represent soft sediment deformation, with possible loading/flame structures into overlying halite beds also noted (Fig. 7 right, e). The tops and bases to some mudstones appear very undulose, interfingering with underlying halite and indicative of either deeper dissolution of underlying halite beds prior to deposition of mudstones or emergence and minor karstification (Fig. 7 right, e&f). There are also signs of small and large pipes or crevasses extending down into underlying bedded halite and mudstones indicating either desiccation cracks or karstification during emergence, with infill of the overlying mudstones, sometimes containing apparent brecciated clasts (Fig. 7 right, g&h).

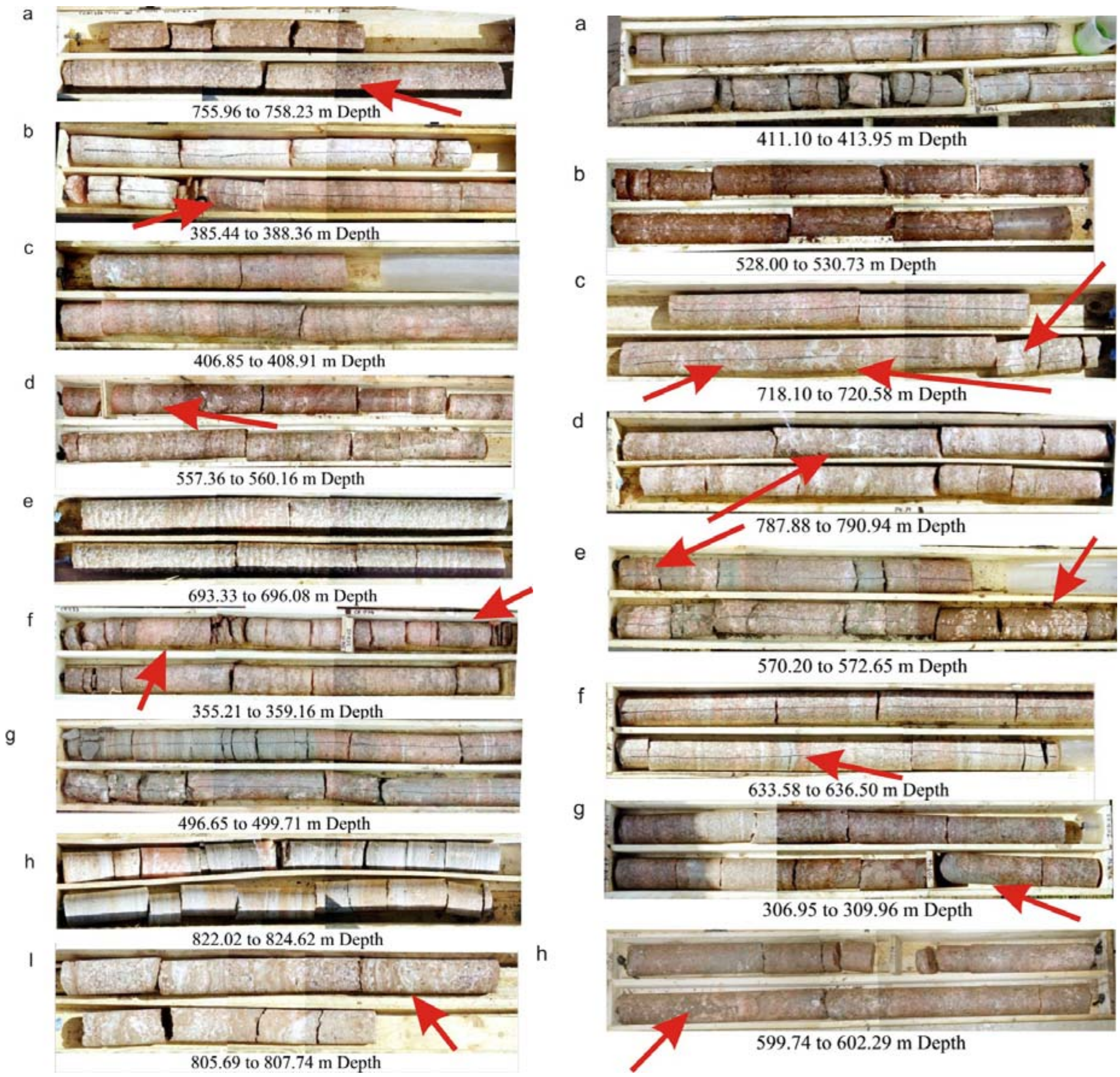


Figure 7 left & right. Core photographs from the Gateway 1-e Borehole (from Eyermann, 2007) illustrating primary crystal textures and sedimentary fabrics described in the text.

Photographs of slabbed core samples selected for laboratory testing (taken by DEEP) are also available. These show evidence of primary depositional features including lamination, elongate halite crystals, solution seams, hopper crystals with mudstone inclusions along crystal faces and sedimentary structures in some of the mudstones (Fig. 8). Based upon Arthurton (1973), the structures and features seen in the core photographs and slabbed core samples are indicative of hypersaline, shallow water conditions with periodic lowering of salinity and occasional emergence.

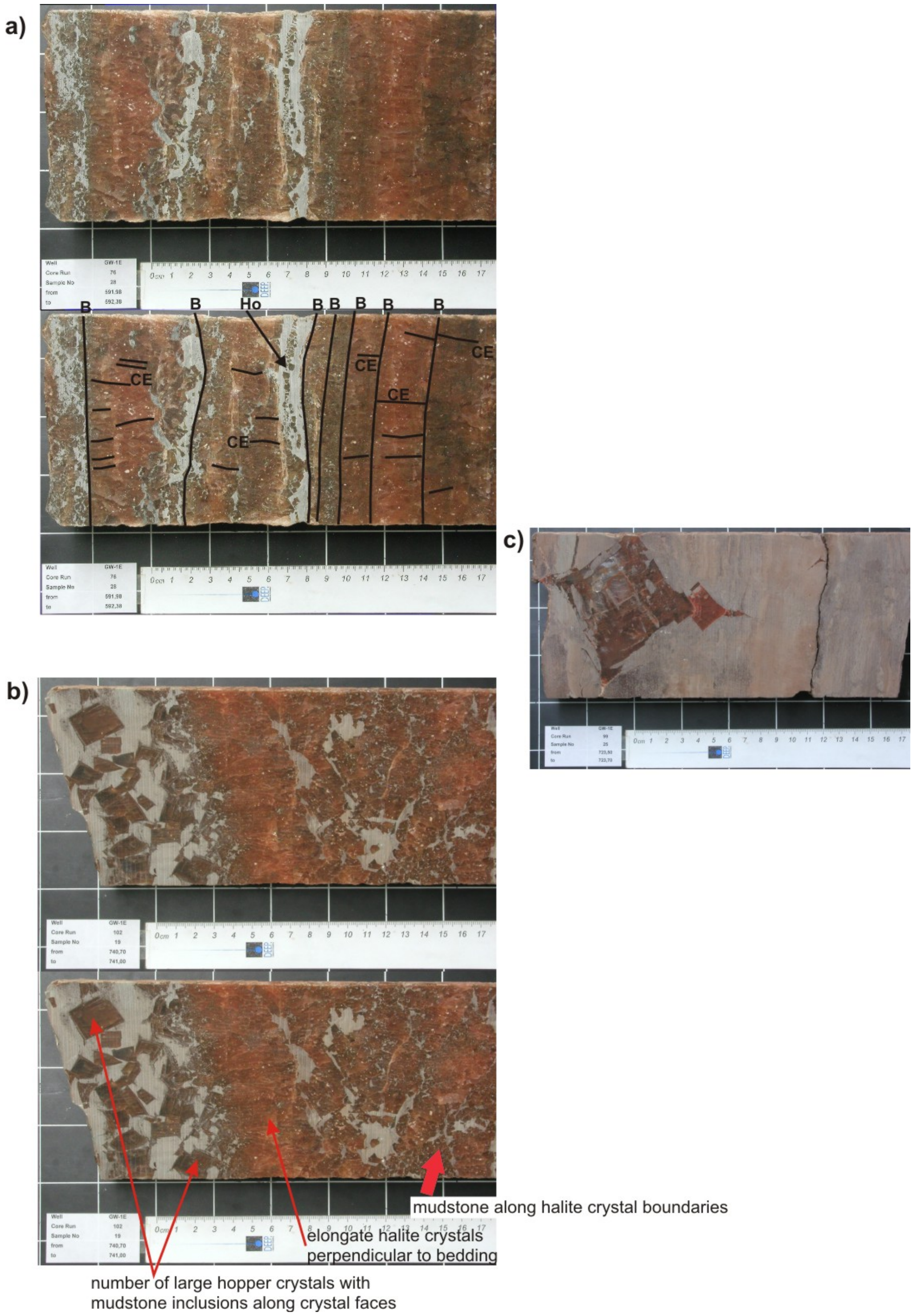


Figure 8. Primary depositional features and crystal textures from the Preesall Halite cored in the Gateway 1-e Borehole. Parts a & b show un-annotated and annotated images, see text for explanation. (c) large hopper crystal in mudstone/siltstone, with mudstone inclusions along crystal faces and pagoda type habit. Hopper crystals indicate growth of halite in sediment beneath water level. Top of core sections in direction of the zero on the ruler. Abbreviations: CE = crystal elongation; b = bedding; Ho = hopper crystals. Photographs courtesy of Lars Dittert and Fritz Wilke, DEEP Underground Engineering GmbH.

5 Interbedded mudstones and subsidence rates versus halite deposition

Geophysical log correlations provide both enhanced visual representations of, and an immediate method for, assessing the relative thicknesses and variation of the three main mudstone groups (1-3), individual halite or mudstone dominated units across the basin(s). Three main mudstone groups (1-3) are shown to split when traced from onshore to offshore areas. Visual examination of the geophysical logs indicates that this is due to incoming halite interbeds and this is now assessed further.

In addition to the regional correlations (Figs 1&2), clear evidence of the thickening of the Preesall Halite across fault zones into sub-basins, has been described across the margins of the Crosh Vusta Fault Zone (Fig. 3). The thickness changes are related to syndepositional faulting, with condensed sequences developed over areas of the basin that underwent less subsidence and thicker sequences of halite (with interbedded mudstones that show the incoming of thin halite beds) developed in downfaulted areas in which subsidence rates remained high. It illustrates that the rate of halite precipitation was able to keep pace with the subsidence rates in the faster subsiding basin areas.

In an attempt to determine what were the main processes behind mudstone deposition and provide a means to beginning to better understand the distribution of insolubles and the variation in insoluble content around the Northwich-Preesall halite basin a quantification of the variations of mudstone content in the main interbedded mudstone units 1-3 is attempted. Preliminary results are presented on the variations in the three main mudstone intervals (1-3) between boreholes, based upon examination of the gamma logs for boreholes used in the log correlations from the onshore to offshore areas. The term 'individual mudstones' refers to the entire mudstone interval, whereas 'clastic only' refers to the thickness of individual thin mudstones within each of mudstones 1-3, estimated from the gamma log. It should be noted that at this stage, the boundaries between the main mudstones and the halite and the thin mudstones and interbedded halites within the main mudstones 1-3 intervals, are estimated from the gamma curves, which is subject to vertical errors depending on the resolution of the logging tools used to acquire data.

The analysis of the data for mudstones 1-3 has focused on data from the Byley #1, Arm Hill #1 boreholes, and offshore wells 110/08a-5, 110/07-2, Gateway 1-e, 113/28-1 and 113/27-2, which provide a representative suite of logs through the Northwich and Preesall halites from onshore to offshore. The main categories are relative to the halite and other mudstones as per Figure 9:

1. the percentage individual mudstones 1-3 relative to overall Preesall/Northwich halite in a borehole (Fig. 9a: e.g. Tot M1:Tot PH/NH in bh %).
2. the percentage mudstone (clastic only) in individual mudstones 1-3 relative to overall Preesall/Northwich halite in a borehole (Fig. 9a: e.g. Tot M1 clastic:Tot PH/NH in bh %).
3. the percentage mudstones 1-3 combined in borehole to overall Preesall/Northwich halite in borehole (Fig. 9b: e.g. All M1-3:PH/NH in bh %)
4. the percentage mudstone (clastic only) combined in mudstones 1-3 to overall Preesall/Northwich halite in borehole (Fig. 9b: e.g. All M1-3 clastics only:PH/NH in bh %)
5. the percentage individual mudstones 1-3 relative to individual mudstones 1-3 in a borehole (Fig. 9b: e.g. mdst only (clastic) M1:Tot M1 in bh %)
6. the percentage total individual mudstone (total clastics) relative to total individual mudstone in a borehole (Fig. 9b: Tot clastic M1-3:Tot M1-3 in bh %)

The main points can be summarized as follows:

a) The data for individual mudstone intervals relative to the overall halite succession in the borehole (e.g. e.g. Tot M1:Tot PH/NH in bh %) reveal remarkably similar values across all boreholes (Fig. 9a). The variation in thickness of Mudstones 1- 3 from onshore to offshore and the comparison with the thickness of the Preesall/Northwich halite plots show a fairly constant decrease towards the onshore boreholes, with figures of between 7.5% and 9.5%, but falling slightly onshore, where the intervals are thicker, as seen in the log correlations (Fig. 9a). Thus where individual halite/mudstone beds in Mudstones 1-3 are recognisable in the gamma logs of Byely 1 and Gateway 1-e boreholes, then the thickness ratios are comparable.

b) When the percentage clastic in the mudstone interval is compared to the overall halite succession in the borehole (e.g. Tot M1 clastic:Tot PH/NH in bh %), the percentages are less that the percentages for the mudstone intervals (Fig. 9a). This a function of the thin halite beds introduced) but drop more in the offshore boreholes, demonstrating what is seen visually that more halite is present in those units, with more halite being introduced to the system
c) Trendlines show the total thickness data for mudstones 1-3 plotted against the thickness of the halite in the borehole show a consistent rise from onshore wells to offshore wells (Fig. 9a), including the overall combined data for the three mudstone intervals (Fig. 9b).
d) The big changes are seen in the mudstone only (clastic content) to mudstone unit comparisons per borehole (Fig. 9b), again supporting the conclusions drawn from the log correlations. Percentages are high in the Cheshire Basin falling northwestwards into the EISB to reach the lowest values in Gateway 1-e, before climbing again to the north in Q113. This reflects the greater subsidence offshore maintaining a brine column and halite precipitation in the offshore areas. In general Figure 9 shows a drop in the percentages mudstone in more basin central boreholes, with Gateway 1-e having the lowest percentage and support the observations that the thickening of the mudstone interval is due largely to incoming of halite beds. This suggests the percentage volume insolubles are lower in the thicker Preesall/Northwich halite sequences, effectively representing a ‘dilution’ of the insolubles content. This indicates the effect that slower basin subsidence is likely to result in the deposition of a less pure halite (e.g. Byley #1, 580-625m vs Gateway 1-e, 600-680m approx.), and also makes the insoluble content in the mudstone beds much higher.

Clearly much can be extracted from these plots (and others) and this paper only picks out some of the more immediate and pertinent detail. Further work on other boreholes to compare the percentage insoluble content in these boreholes with the equivalent mudstone sequences in the boreholes here is required to establish regional variations and trends. However, initial results are promising.

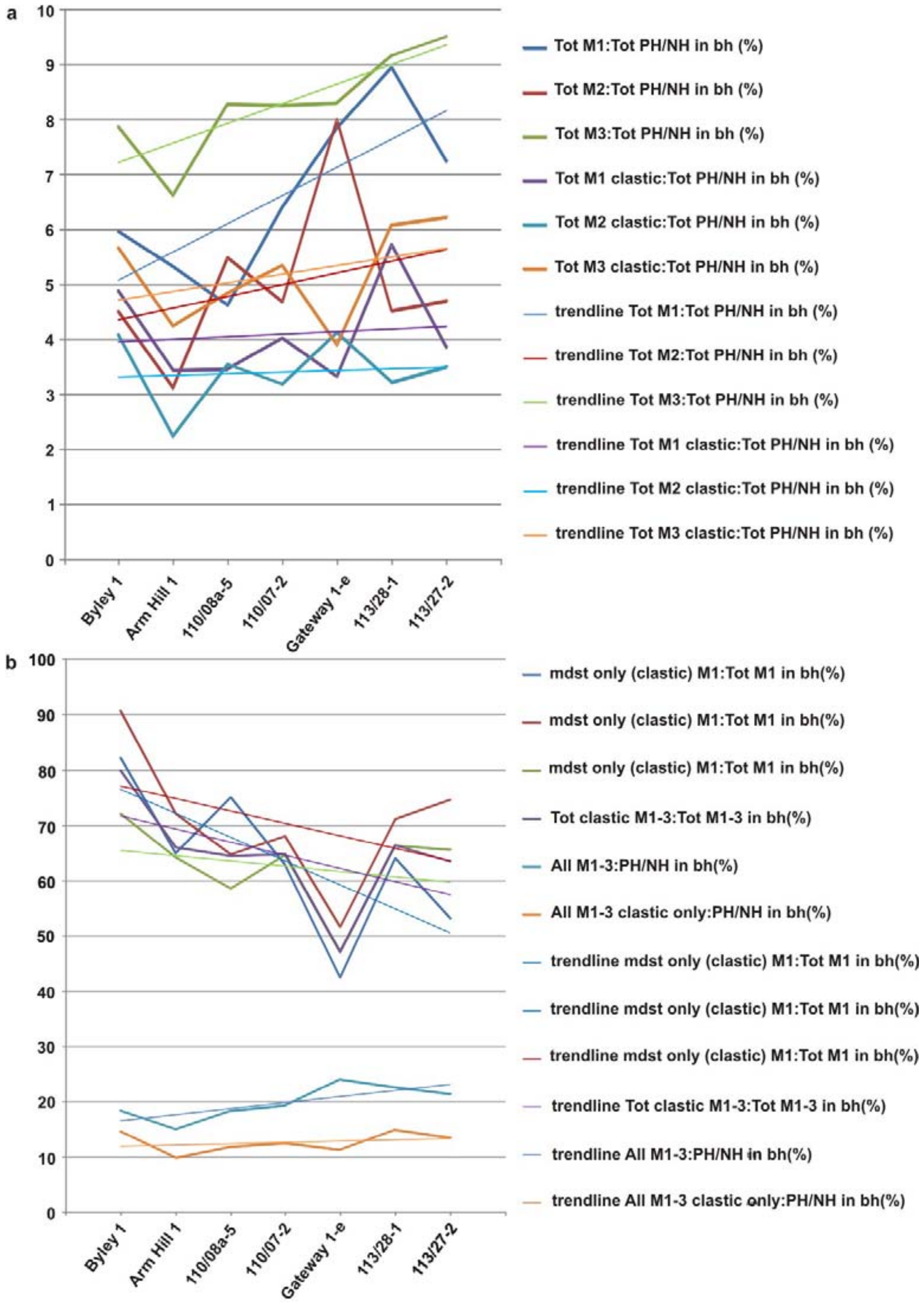


Figure 9. Various plots of Mudstone 1-3 thicknesses and clastic only content relative to thicknesses of mudstones or halite beds in seven boreholes across the Cheshire to East Irish Sea region. Vertical axes are percentages.

6 Discussion

This section discusses some of the observations on the Northwich, Arm Hill and Gateway 1-e cores and how through lithological core logging and description, important sedimentological detail of bedded halites is obtained. When coupled with analyses of wireline logs, from both regional and on-site well data, these data are of great relevance to the assessment and development of gas storage facilities in bedded halites. An understanding and improved confidence can be developed of the depositional environment of the salt deposits and associated clastics and the controlling factors during deposition. Defining basins, sub basins and intrabasinal highs, together with the processes behind halite accumulation and the development of mudstone interbeds provides greater confidence in the nature and regional distribution of lithologies across basins and importantly, across individual sites within sub basins. In bedded salts, therefore, a means is available to provide an improved assessment of both cavern construction and construction schedule uncertainty for each cavern with a greater understanding of (a) the likely distribution of clastics within the site area which affect the insoluble content, and hence sump volume uncertainty for each cavern, and (b) the likely variations, both regionally and more locally at site, in mudstone bed thicknesses and development of thin interbedded halites that may for example, enhance their solution-mining characteristics.

The laterally equivalent Preesall and Northwich halites contain thick sequences of clean bedded salt with thin partings of mudstone. They are typical of deposits traditionally assigned to desert lake or continental playa which dried out periodically and which was constantly replenished by, or supplied with, meteoric water (refer reviews in Arthurton, 1980; Taylor 1983; Wilson & Evans, 1990; Wilson, 1993). The persistence within the halites beds of mudstone beds and partings over 150 kms from the Cheshire Basin out into the East Irish Sea, indicates very uniform conditions of sedimentation over very wide areas of extremely low relief in a semi arid environment. As Wilson & Evans (1990) observed, it is unusual for such desert lakes or continental playa to deposit practically nothing but halite. The following therefore assess the evidence for the environment of deposition to provide an understanding of the nature and continuity of the main lithologies across not just the basin in general, but also within sub basin and individual project areas.

A growing body of published work describing the sedimentology and formation of bedded halite successions is emerging (e.g. Arthurton, 1973; Lowenstein & Hardie, 1985; Hovorka, 1987; Hovorka et al., 2007), although these typically give little detail on the interbedded mudstone units. Useful accounts describing the general sedimentology and origin of the Mercia Mudstone succession in the Cheshire Basin, Blackpool and East Irish Sea areas are given by Taylor et al. (1963), Arthurton (1980) and Wilson (1990, 1993), but we address in some detail some of the questions relating to the development of interbedded mudstones within the halite beds.

Primary halite crystal fabrics described from the Northwich Victoria Embankment, Arm Hill # and Gateway 1-e boreholes representing sub basins across the brine lake, comprising upward-oriented, elongate crystals of halite, indicate upward, competitive crystal growth from crystals present on the brine pan floor, in a similar manner to that described by Arthurton (1973) in the Cheshire Basin and Wilson (1990) from the Blackpool district. Crystals nucleate both at the brine/air interface and also directly on the basal substrate of the brine pan (Arthurton, 1973). Those formed at the surface form suspended mats of crystals which eventually founder and sink to the floor of the brine pan and from which elongate crystals grow upwards in competition with their near neighbours. Those nucleating on the brine pan floor also grow upwards in a similar fashion to the foundered crystal mats. Depths of brine less than a metre were suggested for the formation of elongate halite crystals by Arthurton (1973) and a shallow water origin for the formation of these types of halite crystals is supported by Handford (1981).

Further evidence for a shallow water origin (possibly even occasional emergent conditions) is present in the thin bands of flat-lying clearer halite representing solution seams. In shallow waters, brine mixing occurs and prevents stratified brines developing, allowing undersaturated brines to dissolve the upper surface of halite. Deeper waters lead to the stratification of the brine column with a dense, saturated brine forming a protective ‘blanket’ to the halite surface, preventing dissolution and the development of solution surfaces.

Arthurton (1973) also commented on the fact that a minor input of terriginous material need not halt halite crystallisation, resulting in a mix of elongate halite crystals with a thin veneer of mudstone, as seen in the cores from all three boreholes. This is also represented by accumulations of hopper crystals in which mudstone occurs along crystal faces, often forming complexly 'zoned' crystals and seen in all three borehole cores of this study.

In both the Northwich and Arm hill cores intraformational high-angle salt bedding truncated by flatter-lying salt beds, is seen, often with a thin anhydrite layer along the boundary (e.g. Figs 5b&c). Similar features are noted in the photographs of the Gateway 1-e core (Fig.7, left f), although these have not as yet been described directly. These sections of core show upheaved and truncated salt, perhaps representing sections through the margins of salt polygons. Such features up to several metres across have been described from the Northwich Halite in Cheshire (Tucker, 1981; Tucker & Tucker, 1981) and are also representative of extremely shallow-water to emergent conditions, developing in response to changes in the hydration of the halite.

The sequence of Northwich core between 91.49-94.6 m is of potential significance as it suggests an interplay between halite crystallisation at the base of a brine pan from unstratified brine, with that of cumulate-type deposition from supersaturated, stratified brines. Water depths are not suggested by presence of cumulate-type fabrics alone; the significance of these is that they indicate stratification of depositional brines. Indeed, within the banded possible cumulates, the presence of several solution seams suggests water depths were shallow enough to allow the periodic contact of unsaturated brines to the interface of the substrate. Similar crystal fabrics and textures have been described from the Arm Hill #1 core and photographs of the Gateway 1-e core sticks (Eyermann, 2007) show similar banding which may be related to the accumulation of cumulate-type salt, although this has not yet been tested in the latter by detailed core examination and logging.

Zones of recrystallised halite are not completely devoid of structures that are probably related to primary sedimentation of the halite body. Ghosts of elongate crystals can be identified imprinted within units of recrystallised halite with typically larger 'cornflake' shaped crystal form. There is also cryptic colour banding of coarser looking halite, which may relate to recrstallised original sedimentary laminations as they are parallel to dipping mudstone interbeds. These two pieces of information indicate that recrystallisation is likely to be a process that grades from partial to complete destruction of original sedimentary structure, in a similar process to increasing metamorphic grade.

The mudstone within the sequence can be divided between grey-green well-laminated and reddy-brown structureless facies. Where present, the well-laminated banded facies represent material carried in dust storms and blown into laterally uniform shallow water environments (Arthurton, 1980; Earp & Taylor, 1986). Rarely, examples of a possible erosional surface are present e.g. at 107.24m in the Northwich core. This and evidence elsewhere (Arthurton, 1980), indicates that occasional storm or flood-generated currents were sufficiently strong to produce cut and fill structures. Current activity is supported by examples of rippling, cross lamination and some asymmetric (current) ripple-lamination with an absence of lower scour/erosional surfaces in the Northwich core (Fig. 5h). These latter structures indicate low flows with little or no erosion at their bases. However, the rarity of such features, combined with the very fine grain size of the siliciclastic units (in some cases up to very fine-grained sand) and an absence of reworked/rip-up clasts suggests an overall low energy, which apart from the basin margin areas is likely to have had little, or only local fluvial influence.

The banded mudstones represent material carried in dust storms and blown into water (Arthurton, 1980; Earp & Taylor, 1986). The scarcity of desiccation features and other features associated with emergence suggests that the sediment pile rarely dried out enough aerial desiccation of the mudstone units. However, the lack of evidence for desiccation cracks could also result from the complete reworking of exposed and desiccated horizons by wind action. The abundance of small-scale soft sediment deformation structures indicate the mudstone sediments were deposited at a rapid rate relative to compaction.

Some evidence is, however, found in the cored material both in Cheshire and the East Irish Sea of dissolution/erosion surfaces and emergent conditions (Figs 5j & 6, right e, f, g&h). Mud-filled cracks/pipes/crevasses cut primary halite lamination and the mud-prone haselgebirge facies. There are also examples of deep fissures in red mudstones and halites infilled by red mudstone and angular clasts derived from the incised material (Fig. 7, right h). Some may represent karstification of more halite rich sediment whilst others are desiccation cracks in the blocky and laminated mudstones. The pipes develop in halite and muddy halite beds above the water table as a result of dissolution and corrosion of the halite by the downward flow of undersaturated brine/water and/or the drying out and polygonal cracking that can form conduits for water flow (e.g. Tucker, 1981; Hovorka et al., 2007). Elsewhere, Arthurton (1980) described how desiccation cracks are found to be most abundant in the upper parts of such units, directly under units of the blocky facies, material of which plugs the fissures, with each change from laminated to blocky lithology reflecting a change from subaqueous to emergent conditions.

The origin of the blocky structureless mudstones seen in the cores is, however, somewhat enigmatic. The blocky unstratified mudstone units in the halite beds represents dust deposition on drying or nearly dry ground, and may show signs of brecciation with small clasts or pellets of mudstone cemented by later mudstone and evaporite material (Fig. 6k). The absence of structure can be explained by a variety of processes, including autobrecciation due to haloturbation, pedogenesis, or complete desiccation and redistribution aerially. However, a purely aeolian origin for the mudstones seen is not supported due to the general absence of desiccation features in overlying and underlying laminae and the presence of rare structures in the mudstones indicating flow, such as current ripples. It is thought that the brecciated examples represent products of a process linked to haloturbation as the mudstones in question are closely associated with halite deposition. In this process the growth of evaporite minerals close to or just above the water table breaks up the surface of the ground, destroying any previous sedimentary structure (Earp & Taylor, 1986), which may then be subject to wind action and redistribution. They probably represent what is called the ‘ploughed ground’ or ‘zardeh’, which forms extensive flats around contemporary salt lakes in central Iran and the Ranns of Kutch (e.g. Glennie & Evans, 1976; Arthurton, 1980).

The evidence is now for the Preesall and Northwich halites having accumulated in an extensive flat lying, shallow water, hypersaline, brine pan covering perhaps 46,900 km^2 (Jackson & Mulholland, 1993; Wilson & Evans, 1990; Wilson, 1990, 1993; Warrington & Ivimey Cook, 1992; Jackson & Johnson, 1996). This may have been within an occasionally inundated coastal salina environment or perhaps, more realistically, on a wide subsiding coastal plain repeatedly inundated by the sea but across which periodic, probably short-term periods of drying-out occurred. The latter is supported by the association with acritarch-bearing mudstones above and below (the halite beds), indicating close proximity to the sea (Wilson & Evans, 1990). Studies on the geochemistry of the Northwich Halite and enclosing strata in the Cheshire Basin and into the Needwood Basin in Staffordshire, including Br, Sr, K and Mg isotope contents, confirm a dominantly marine brine regime with little continental input for the grabens and areas marginal to these depocentres (Halsam et al., 1950; Taylor 1983; Tucker in Thompson, 1990). More upland areas to the east in, for example Nottinghamshire (East Leake), were strongly influenced by continental brines, which derived sulphate from the exposed Carboniferous strata (Taylor, 1983). Further evidence of a marine origin for the Northwich Halite is the presence of small amounts of K and Mg salts at the top of individual depositional cycles in the halite (Wilson, 1993).

The geophysical logs illustrate how the interbedded mudstones vary across the brine pan region (Figs 1-3). In the areas of greatest halite thickness, the main mudstones (e.g. mudstones 1-3 discussed in the text) thicken, with the incoming of thin halite beds. This suggests that halite accumulation was able to keep pace with subsidence, which is demonstrably fault controlled in places (Fig. 3) and which at times overwhelmed the clastic input. The process of thickening is supported by initial analyses of the halite and clastic contents (Fig. 9), showing the latter remains essentially the same for the mudstones across the basin, but that thickening is associated with the incoming of the (thin) halite beds.

The environment of deposition would be similar to that proposed for the massive bedded San Andres Halite of Texas, which display near identical shallow water crystal textures and sedimentary fabrics. These are interpreted to have been deposited in shallow perennial brinepool conditions that extended over more than 10,000 kms^2 (Hovorka, 1987; Hovorka et al., 2007).

The climate and conditions of deposition for these features in the Northwich Halite have been likened to the present-day semi-arid region of the Ranns of Kutch in western India lying within a high-pressure zone north of the trade-wind belt. The Ranns are inundated by up to 2 m of sea water during monsoon flood tides. Aided by wind and high tides, the floods bring in fine clays with marine microplankton (foraminifera) being swept inland a distance of over 150 kms (Glennie & Evans, 1976). However, the area then largely dries out, something for which, as noted above, evidence is lacking in the Preesall and Northwich halite successions, unless it has been removed during periods of emergence. Horizontal dissolution seams are common, truncating primary halite crystals and given the lack of evidence of flooding and freshwater input via streams, this seems likely to be the result of the influx of fresher sea waters that lowered salinities in the brinepool and caused dissolution of the halite on the brinepool floor. The questions remain as to where the barrier to the EISB brinepool was located and what was its form. It is possible that the brinepool in which the Preesall-Northwich halite developed had an intermittent connection with Tethys to the south, perhaps via the linked rifts forming the Celtic seas and the Aquitaine Basin (e.g. Ziegler, 1982, 1990). Halites in the St George's and Bristol Channel basins (Barr et al., 1981; Kammerling, 1979; Penn, 1987) are proved although biostratigraphic evidence is minimal. Carbonates and a coastal microfauna in the North Celtic Sea and Fastnet basins also suggest marine-sourced environments (Warrington & Ivimey-Cook, 1992). It may be, therefore, that some of the mud was brought in by flooding via the series of Celtic Sea rifts from Tethys during monsoonal seasons, similar to that seen in the Ranns of Kutch area. The rifts themselves would have collected wind-blown fine mud and silt that could have been swept into the more isolated Preesall-Cheshire brinepool/seaway by high tides of the monsoonal seasons, or stormy periods.

Questions perhaps remain over the origin of the mudstones within the halite beds, which can be traced over the 4,700 km^2 of preserved Preesall Halite, and the depositional process that would explain the wide spatial extent of the correlatable mudstone units. As discussed by Hounslow & Ruffell (2006); both fluvial and aeolian origins for the mudstone units within the Mercia Mudstone as a whole having been suggested by many authors. A lack of structures in the interbedded mudstones that would indicate emergence suggests deposition in a water column that did not dry out, with rare examples of ripple-lamination and mud-drapes suggesting deposition from flowing water of varying, but typically low, velocities, although due to the interplay between halite and mudstone, many diagnostic sedimentary features within the mudstone will have been destroyed by autobrecciation and haloturbation.

A water-lain origin for the interbedded mudstones in general, presumably by a repeated sheetflood-type delivery process is not supported by the lack of erosion/scour surfaces at the bases of silt/very fine-grained sand units and the fact that the mudstones are developed across the entire basin. Most authors conclude that aeolian processes supplied significant volumes of silt and clay sized material to the basin and brinepool area. However, the processes and environments needed for the sustained delivery of enough fine clastic input, for example, account for the complete Thirty Foot Marl succession in Cheshire by exclusively aeolian transport into a water body is unclear.

The capability of winds to transport large volumes of clay and silt-sized material is well known (Young & Evans, 1986), but has generally been neglected as a factor in the origin of marine silts and sands (Fischer & Sarnthein, 1988). Siltstones of the Permian of the Delaware Basin, Texas, represent separation of sands and silts during aeolian transport across deserts: dust was supplied directly to the basin by fallout, resulting in bottom topography mantling laminated siltstones. Similar wind transported but water-lain fine silty and muddy sediments are known from the Atlantic margin to the west of the Sahara (Sarnthein & Diester-Haass, 1977; Koopman et al., 1979; Sarnthein & Koopman, 1980).

A wind-blown origin for the mud into a standing body of shallow water would seem most plausible and it may be that mud was introduced into the depositional basin by a complex association of aeolian and water-borne processes. Much of the clastic material in the halite beds is of likely distant origin. Palaeogeographical reconstructions (see Ziegler, 1990) indicate that the basins within which the MMG facies accumulated were favourably located with respect to potential major dust sources. MMG basins in England lay at the margin of a subtropical dry zone and within the southwesterly blowing trade winds (Parrish & Curtis, 1982; Parrish et al., 1982, 1986). To the NE and upwind were the arid interior basin of the southern-central North Sea region, a vast saline lake-sabkha complex, beyond which lay a belt of mixed fluvial and aeolian sediments sourced from the Scandinavian uplands (Ziegler, 1990). It is suggested that deflation of surface deposits in this basin could have produced large quantities of wind-blown dust for transport out of the basin by the southwest trade winds, which were subsequently deposited as loess over Britain (e.g. Talbot et al., 1994). However, local sources in drying out lakes and mudflats around the basin margins are likely to have provided additional sources of wind-blown material. Regional correlations of onshore successions (Arthurton, 1980) indicate that massive halite beds pass laterally into more muddy halite (*haselgebirge* facies) then dolomitic mudstones and eventually dolomitic siltstones (locally termed skerries in the UK midlands). The Mercia Mudstone Group (MMG) in Somerset and North Devon is representative of hot desert like continental, fluvio-lacustrine, subaqueous playa lake and sabkha and subaeriel environments to the south of the main brinepool (e.g. Talbot et al., 1994; Porter & Gallois, 2008). Desiccation of wide saline mud flats and playa surfaces provides a prolific source of wind-blown dust and silt (Dare-Edwards, 1984; Young & Evans, 1986; McTainsh, 1989) and more marginal basinal areas probably received and then supplied wind-blown material to the main brinepool.

It should be emphasised that the sustained delivery of fine-grained clastic material must have taken place over a few hundreds of thousands of years: it is envisaged that each mudstone represents the cumulative input of a number of windy periods. It is possible that the length of such periods of increased wind transport was influenced by Milankovitch cycles that may have had periodicities similar to those recognised during glacial and interglacial periods. To illustrate, the climate for the last 500,000 years has been characterised by strong 100,000 year cyclicity, with interglacial periods lasting between 12,000 and 28,000 years. Cold periods in Antarctica are characterised by much greater dust fallout than is found during warmer interglacials, due to a combination of increased aridity and wind strength (Augustin et al., 2004).

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