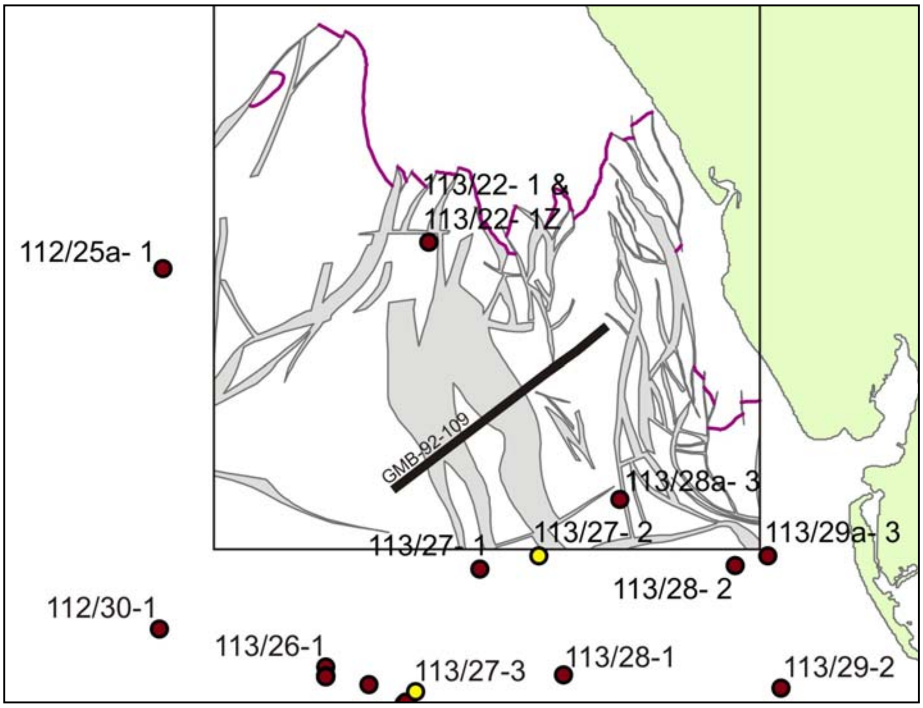
# Contribution to Nirex review of a Deep Brine Repository Concept

Chemical and Biological Hazards Programme

Commissioned Report CR/05/230N



BRITISH GEOLOGICAL SURVEY

CHEMICAL AND BIOLOGICAL HAZARDS PROGRAMME

COMMISSIONED REPORT CR/05/230N

# Contribution to Nirex review of a Deep Brine Repository Concept

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Map of part of the East Irish Sea Basin showing the study area with exploration wells.

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# Foreword

Nirex has developed a multi-barrier concept for a deep repository for the phased disposal of intermediate level (ILW) and certain low level (LLW) solid radioactive wastes, making use of both engineered and natural barriers to form a containment system.

As part of the generic studies being carried out by Nirex, a concept is being examined in which a repository is constructed within rocks containing dense brines in which, on the basis of currently available data, groundwater flow rates are expected to be low and travel times for transport of repository derived radionuclides are expected to be long. If a repository could be constructed within an area containing dense brines it could potentially offer significant benefits in terms of enhanced long-term radiological performance. This report provides collated and cartographic information in a form suitable for use in the preparation of the feasibility report. The use by Nirex of Sellafield as an illustration of the dense brine concept is based solely on the fact that there is existing information on which to base the studies and does not indicate or imply that the site has been selected for detailed consideration as a potential site for an actual repository.

# Contents

**Enclosures**

# 1 Introduction

Nirex has developed a multi-barrier concept for a deep repository for the phased disposal of intermediate level (ILW) and certain low level (LLW) solid radioactive wastes, making use of both engineered and natural barriers to form a containment system.

As part of the generic studies being carried out by Nirex, a concept is being examined in which a repository is constructed within rocks containing dense brines in which, on the basis of currently available data, groundwater flow rates are expected to be low and travel times for transport of repository derived radionuclides are expected to be long. If a repository could be constructed within an area containing dense brines it could potentially offer significant benefits in terms of enhanced long-term radiological performance.

Currently, a feasibility report is being prepared by Nirex to further examine the dense brines concept. As part of this exercise, to illustrate the way such a concept could be delivered, the potential of creating a repository in the dense brines known to exist close to Sellafield in west Cumbria is being used as an illustration based solely on the fact that there is some existing information on which to base the study. It does not indicate or imply that the site has been selected for detailed consideration as a potential site for an actual repository.

Although there is a substantial amount of existing geological information from the Sellafield area that is relevant to the dense brines study, the information is not currently in a suitable form for direct incorporation in the study. Furthermore, there has not been an assessment to evaluate the degree of confidence that is associated with such information.

The objectives of the work package are to:

- Prepare a series of maps and plans to present the geological structure of areas adjacent to Sellafield in a form suitable for use in the feasibility report currently under preparation by Nirex;
- Provide an assessment of the levels of confidence that can be assigned to the various items of geological information presented in the plans, such as the range of uncertainty that is associated with the positions of subsurface boundaries between geological units, the locations of faults and the location of contours on salinity;
- Provide an assessment of the likely geological succession, including the presence of halite bands, within the Mercia Mudstone Group in the area extending approximately 30 km offshore from the coast near Sellafield and to provide an evaluation of the level of confidence that can be assigned to the estimated geological succession. The basis on which the succession has been assessed is to be explained.
- Provide an evaluation of whether additional information is available that could be used for improving the levels of knowledge or understanding regarding the above aspects of the Sellafield dense brines, geological structure or geological

succession, e.g. by reprocessing and reinterpretation of existing geophysical data.

- Provide an assessment of locations of dense brine bodies present in onshore UK and offshore within 40 km of the coast. The evidence on which knowledge of the locations of these dense brine bodies is based is to be explained and levels of confidence assigned to this knowledge is to be evaluated.

This report provides collated and cartographic information in a form suitable for use in the preparation of the feasibility report. The four main sections of this report provide information on a specific aspects of the feasibility study. Chapter 2 describes the methodology used in preparing four 'available thickness' maps for the main geological units in the off-shore Sellafield area and the production of a 'level plan' at a depth of 1600 m below OD for the Sellafield area. The resulting maps are provided as enclosures to this report. Chapter 3 provides an assessment of the geological succession present within the Mercia Mudstone Group within the area covered by the above plans showing the position and thickness of any identified halite and mudstone horizons present within the sequence. Availability of new information that has been acquired since the work undertaken in the Sellafield area by Nirex during their Sellafield investigations is identified at the end of the chapter. Chapters 4 and 5 provide an assessment of locations of dense brine bodies present in onshore UK and offshore UK territorial waters within a buffer 40 km from the coast to depths of up to about 2 km, respectively. Chapter 6 identifies additional data that may be available or data processing that could be undertaken to improve information provided in this report.

An indication of the confidence levels associated with the assessments is provided.

It is stressed that this report is not a premature initiation of a new site selection exercise for a radioactive waste disposal facility, but a conceptual study to provide general information and guidance to help those charged with designing any future site selection process. The decision on how to select individual sites and which sites to investigate will rest with Government.

# 2 Sellafield area maps

RP Barnes

## 2.1 SOURCE DOCUMENTS

Plans were prepared using the base formation elevation maps in the Nirex Reference Drawing set (Nirex; 1995), plan scale 1:200,000 and 1:100,000) and in the subsequent revision to the Site and its vicinity (Nirex; 1997a), 1:20,000 scale) (Figure 2.1). Sea bed elevation was taken from bathymetric contours at 5 m intervals shown on BGS offshore maps at 1:250,000 scale.

## 2.2 SERIAL SECTION

Drawing NR3062/12-1 provides a horizontal geological section at –1600 m OD for the area 300,000 to 307,000 E and 500,000 to 507,000 N (Figure 2.1). It was prepared from the District Reference Drawings and Site revision (Nirex; 1997a) structure contour plans at base Calder Sandstone, base St. Bees Sandstone, base Permo-Triassic and base Carboniferous. It includes the trace of isochlors corresponding to 60,000 mg/l chloride based on high and low salinity models (Nirex; 1997b). The –1,400 m OD contour on the top of the Borrowdale Volcanic Group is projected vertically onto the plan and the area between it and the low salinity isochlor is shaded as a 'potential repository zone'

### 2.2.1 Stratigraphy

In the south-west of the plan area the Permian (Brockram and/or St Bees Shale) and Carboniferous (probably the lower part of the Dinantian Chief Limestone Group) rocks are intersected at the depth of the section.

Most of the section lies within the Lower Palaeozoic basement (Figure 2.2). This has been proved to be the Borrowdale Volcanic Group in boreholes at several locations in the onshore area to depths in excess of 1000 m. However, only two boreholes near the coast (BH3 & BH13A) prove volcanic rocks to depths greater than –1600 m. Therefore, at the depth of the section over most of the plan area, the nature of the Lower Palaeozoic basement remains uncertain. It is likely to be volcanic rocks of the Borrowdale Volcanic Group. However, the possibility of mudrocks of the Skiddaw Group cannot be excluded, especially in the west of the plan area.

### 2.2.2 Faults

Faults are mapped at –1600 m or deeper at base Permo-Triassic and base Carboniferous in the south-western part of the plan area and are drawn with solid lines. Elsewhere faults have been extrapolated from the intercepts at the mapped surfaces to –1600 m assuming approximately constant dip. In the south-west of the plan area relatively steeply dipping faults mapped at two or three stratigraphical surfaces are extrapolated over depths of 500 m or less are shown as pecked lines. However, over a large part of the plan area the faults have been extrapolated over depths of more than 500 m (up to 1300 m in the north-east of the plan area) and are shown as dotted lines on the plan. In this part of the plan area a number of relatively small faults are omitted from the plan.

### 2.2.3 Uncertainty

Most of the plan area lies within an area subjected to several iterations of geological interpretation related to the acquisition of seismic and borehole data and culminating in the 1997 Site interpretation (Nirex; 1997a). The structural interpretation is therefore likely to be relatively robust.

Significant uncertainty exists in the location of the stratigraphical intercepts at the plan depth deriving from the availability and quality of the seismic and borehole data, the accuracy of the interpretation of the seismic data and the conversion of the two way travel time (TWTT) from the seismic data to depth. These factors are considered to comprise an uncertainty of ±5%. On the plan this equates to a positional uncertainty on the stratigraphical intercepts that varies from ±250 m to ±900 m depending on the dip.

Similar factors affect the interpretation of the faults but, where mapped at or near the plan depth, their positional uncertainty is relatively small owing to their steeper dip. Of far greater significance is the uncertainty involved in extrapolation of the faults to the –1600 m plan depth, this involves several factors as follows:

- The continuity of faults to the plan depth is unknown, especially where faults are mapped only in the relatively shallow sedimentary cover sequence.
- The dip of a fault is relatively well constrained when it is mapped at several widely separated surfaces. However, over much of the plan area the fault mapping relies on the interpretation of offsets only at the relatively closely spaced base St Bees Sandstone and base Permian surfaces.
- Faults are extrapolated to the plan depth assuming a constant dip, but they may be curved or listric in profile. This is illustrated by F2 which is mapped as having a relatively low dip in the shallow part of the section and may have a curved profile (Figure 2.2).
- The inter-relationships of the faults at depth is unknown; F3 and F10 and F113 and F114 are sub-parallel and closely spaced and are therefore shown as single faults at the plan depth; the nature of intersections between faults of opposed dip is not known (see below)
- It is likely that faults exist within the basement that have little or no expression within the sedimentary cover sequence and therefore have not been recognised and/or mapped (e.g. shaft predictions report on structural dip in the Borrowdale Volcanic Group).

The fault pattern as drawn is based on the assumption that a group of SW-dipping faults in the north-east of the plan area, including F9, F31 and F32, die out at depth or terminate at their intersection with the NE-dipping faults (F3/F10 and F2). This seems likely as the SW-dipping faults, mapped in the Permo-Triassic rocks at shallow depth (100-300 m), have relatively small displacement and are laterally discontinuous within the Site. It is, however, possible that these structures develop downwards into a more significant SW-dipping strand of the Lake District Boundary Fault Zone (possibly continuing F118) with F2, F3 and F10 restricted to its hanging wall-block (Figure 2.2). In this case 'F9' will appear on the level plan in the vicinity of F1/F202/F22 or a short distance to the east, truncating F2 and removing F3/F10.

### 2.2.4 Isochlors

Two salinity models are presented as horizontal and vertical sections and isochlor depth maps in Nirex (1997b). The precise combination of parameters required, i.e. 60,000 mg/l chloride at –1,600 m OD in the low and high salinity models, is not present within these drawings therefore some interpolation was necessary.

Uncertainty in the isochlor models is dealt with in Nirex (1997b).

## 2.3 ISOPACHYTES OF AVAILABLE THICKNESS UNITS

The scope of work required plans of the area 270,000 to 310,000 east and 470,000 to 510,000 N (Figure 2.1) showing isopachytes of the 'available thickness' of the Mercia Mudstone Group (in two versions) Ormskirk Sandstone, Calder Sandstone and St. Bees Sandstone. The definition of available thickness and deliverable plans were varied in agreement with Nirex as described below.

### 2.3.1 Definition of available thickness

Specifications for the computation of available thickness given in the scope of work were as follows:

- The top of the available thickness is the deeper of 100 m below the stratigraphical top of the formation or at a cut-off depth of 300 m below sea bed or 100 m below the base of the Quaternary deposits.
- The base of the available thickness is the shallower of 100 m above the stratigraphical base of the formation or a base cut-off depth set at –1000 m OD for the St. Bees Sandstone and -800 m OD for the Ormskirk Sandstone, Calder Sandstone and Mercia Mudstone Group; a second version of the Mercia Mudstone Group plan was also to be prepared with a base cut-off depth of –500 m OD.

Variations to these specifications were discussed and agreed with Nirex as follows:

- The top cut-off offshore would be taken as 300 m below sea bed. The Quaternary deposits is mapped only in that part of the study area which lies within the former Nirex 'District' (Figure 2.1), but does not exceed 160 m below Ordnance Datum (OD). It is therefore assumed that 100 m below the base of these deposits would not exceed 300 m below sea bed anywhere in the study area.
- The top cut-off depth onshore would be taken at 300 m below OD
- The Ormskirk Sandstone and Calder Sandstone would be treated as a single unit for three reasons:
    i. the boundary is a subtle facies change within the mixed aeolian and fluviatile sandstone succession;
    ii. the base of the Ormskirk Sandstone had not previously been mapped;

iii. the thickness of the Ormskirk Sandstone in the east Irish Sea Basin is about 250 m (Jackson et al; 1987 and 1995, Jackson & Johnson; 1996), a maximum available thickness of 150 m taking the top 100 m below the base of the Mercia Mudstone Group.

- The top of the available St. Bees Sandstone and the base of the available Calder Sandstone within the depth cut-offs would be taken at the formation boundary. This boundary is a facies change from predominantly fluviatile to predominantly aeolian facies within the sandstone succession. The 200 m gap that would result from taking the boundaries of the available thickness St. Bees Sandstone and Calder Sandstone 100 m below and above this boundary respectively were not considered necessary.
- Fault locations would be illustrated as a 'zone of fault influence' defined by the fault trace at outcrop or the footwall cut-off at the top of the formation and the hanging wall cutoff at the base of the formation. This defines a zone within which the available thickness may be reduced (Figure 2.3). The width of this zone depends primarily upon the dip of the fault and the thickness of the formation and to a lesser extent on the amount of displacement; a zone of influence may be particularly wide where a number of faults occur close together.

### 2.3.2 Derivation of available thickness and fault intercepts

In cross-section the available thickness of the St. Bees Sandstone and Calder Sandstone/Ormskirk Sandstone is a prism defined by sub-horizontal and horizontal surfaces at the top and base cut-offs respectively and two sloping surfaces at or parallel to the stratigraphical boundaries (Figure 2.3). The stratigraphical top of the Mercia Mudstone Group is not preserved within the study area, hence one side of the available thickness prism is non-limited. The available thickness unit is therefore laterally extensive and largely tabular, its top lying at 300-350 m depth.

For each available thickness unit the defining surfaces were prepared as contour maps by integration of information from the source documents. Vertical thickness was derived by subtraction of pairs of surfaces as appropriate to different segments of the prism as illustrated in figures 2.3 to 2.5.

Zones of fault influence were derived by shading the area between fault traces at outcrop or the footwall cut-off at the top of the formation and the hanging wall cutoff at the base of the formation as mapped on sub-surface structure contour maps. Adjoining or overlapping zones of fault influence are amalgamated on the plans.

### 2.3.3 Uncertainty in the determination of available thickness

The geological model for the Sellafield region is available as outcrop maps and sub-surface structure contour maps in the Nirex Reference Drawings (Nirex; 1995) updated in 1996-97 in the vicinity of Sellafield (Nirex; 1997a). Offshore the model was derived primarily from the interpretation of seismic data. A single phase of interpretation of a grid of commercial and Nirex seismic data was constrained by a limited number of existing exploration boreholes (Nirex; 1993) (see Figure 3.1 for borehole locations). Onshore, the geological model evolved through three iterations related to phases of Nirex seismic and borehole data acquisition and incorporated data from outcrop and a large number of boreholes drilled mainly north of Sellafield for exploration for hematite and coal resources.

Significant uncertainty exists in the depth of the stratigraphical surfaces mapped deriving from the availability and quality of the seismic and supporting data, the accuracy of the interpretation of the seismic data and the conversion of the TWTT to depth. It is considered that these factors may amount to a cumulative uncertainty of ±5% on each surface.

This error affects two of the four surfaces bounding the available thickness units. However, other than in small areas of the St Bees Sandstone (zone 3 in Figure 2.4c) only one of these surfaces is used in definition of the available thickness at any given location. Hence the vertical error on the thickness may be taken as ±5%. This translates to errors in vertical thickness and in the horizontal position of the isopachytes that vary according to the dip (ranging from 2-10°) and depth (ranging from 300-1000 m) as follows:

| Dip | Depth | Vertical error | Horizontal error |
|---|---|---|---|
| 2° | 300 m | ± 15 m | ± 430 m |
| 2° | 800 m | ± 40 m | ± 1145 m |
| 2° | 1000 m | ± 50 m | ± 1430 m |
| 5° | 300 m | ± 15 m | ± 171 m |
| 5° | 800 m | ± 40 m | ± 457 m |
| 5° | 1000 m | ± 50 m | ± 572 m |
| 10° | 300 m | ± 15 m | ± 85 m |
| 10° | 800 m | ± 40 m | ± 227 m |
| 10° | 1000 m | ± 50 m | ± 284 m |

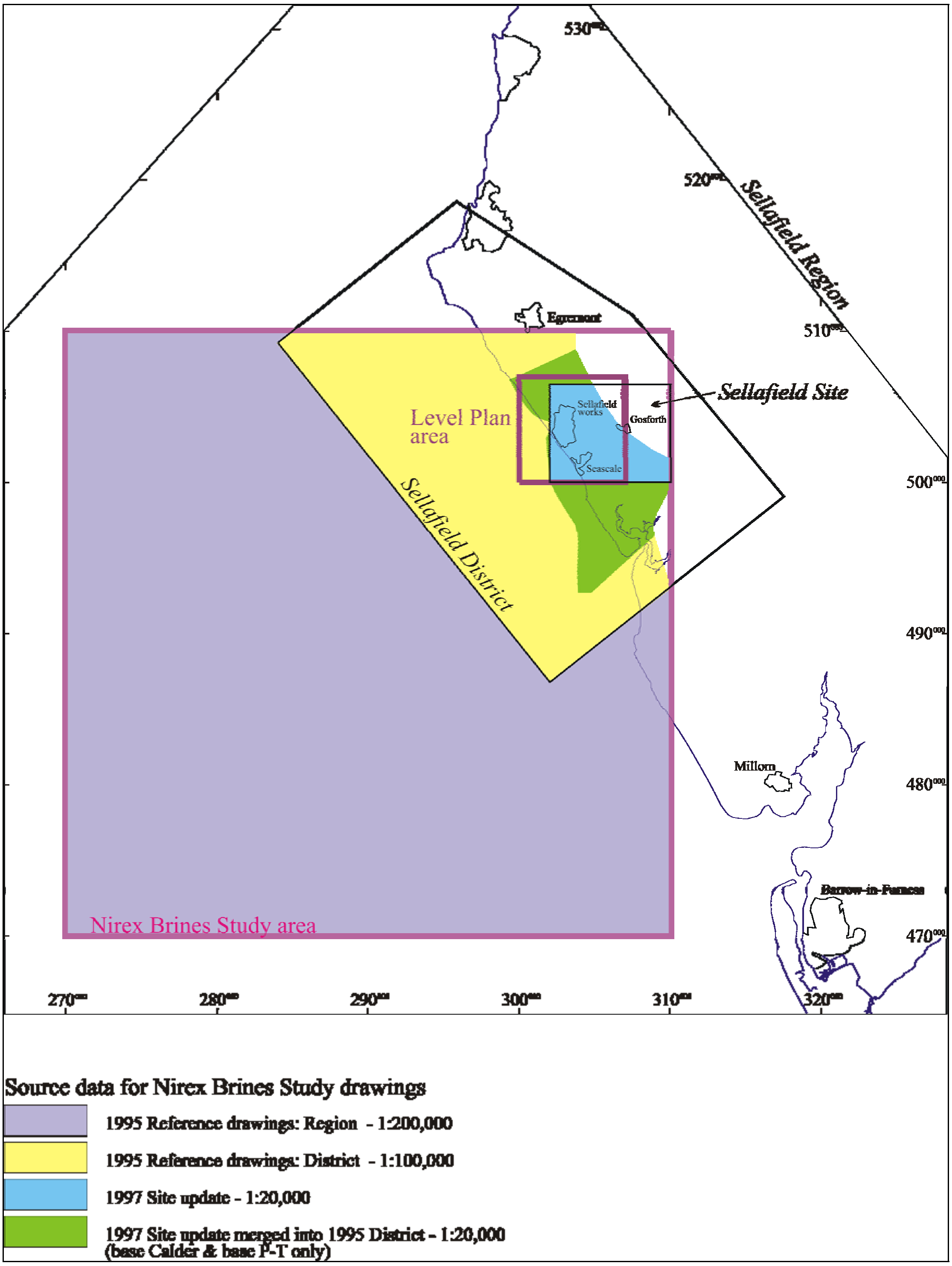


Figure 2.1 Location map showing 1990 Nirex Region, District and Site area and Nirex Brines Study area

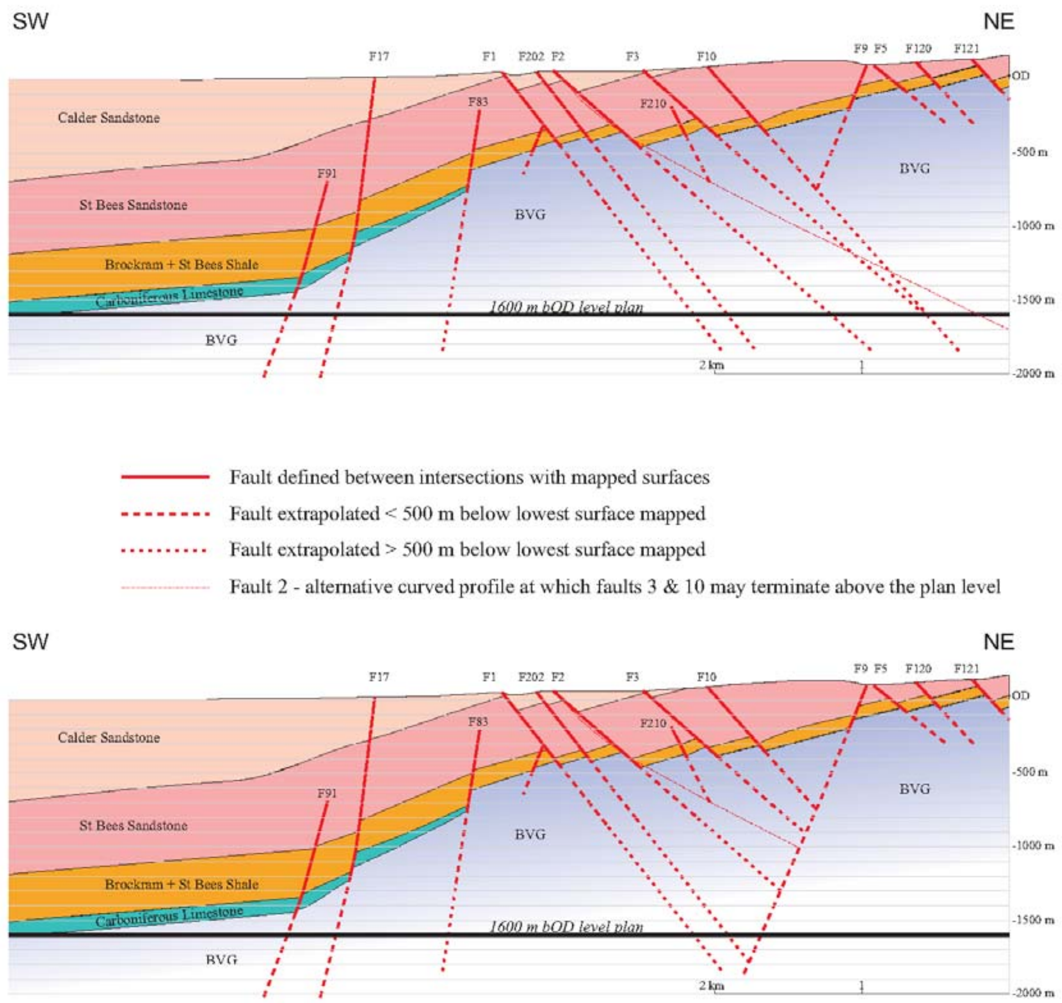


Figure 2.2 Alternative interpretations of the dip of Fault 2 and relationships between the NE- and SW-dipping faults on the line of section drawn on the plan

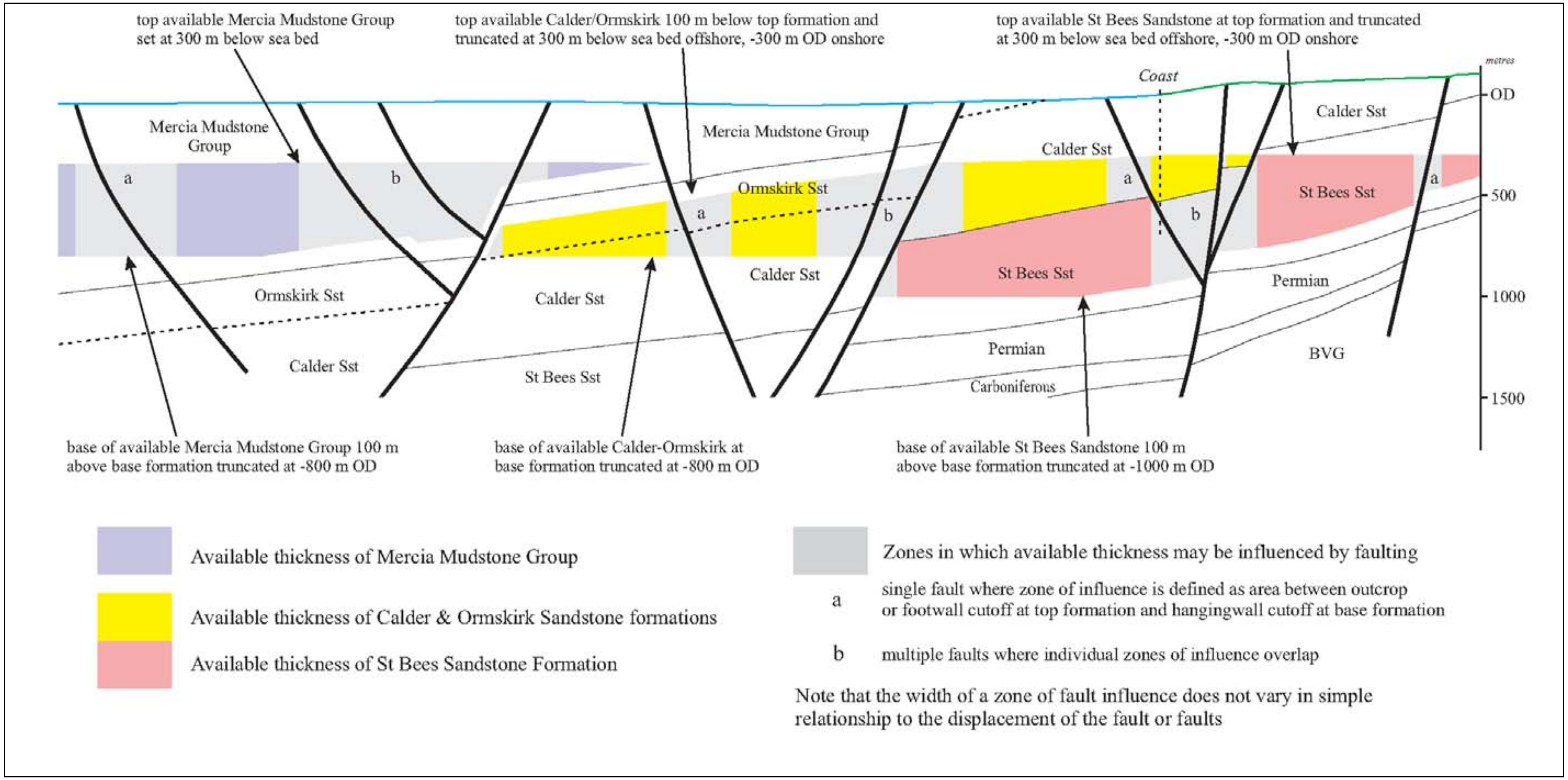


Figure 2.3 Conceptual illustration of parameters defining available thickness units

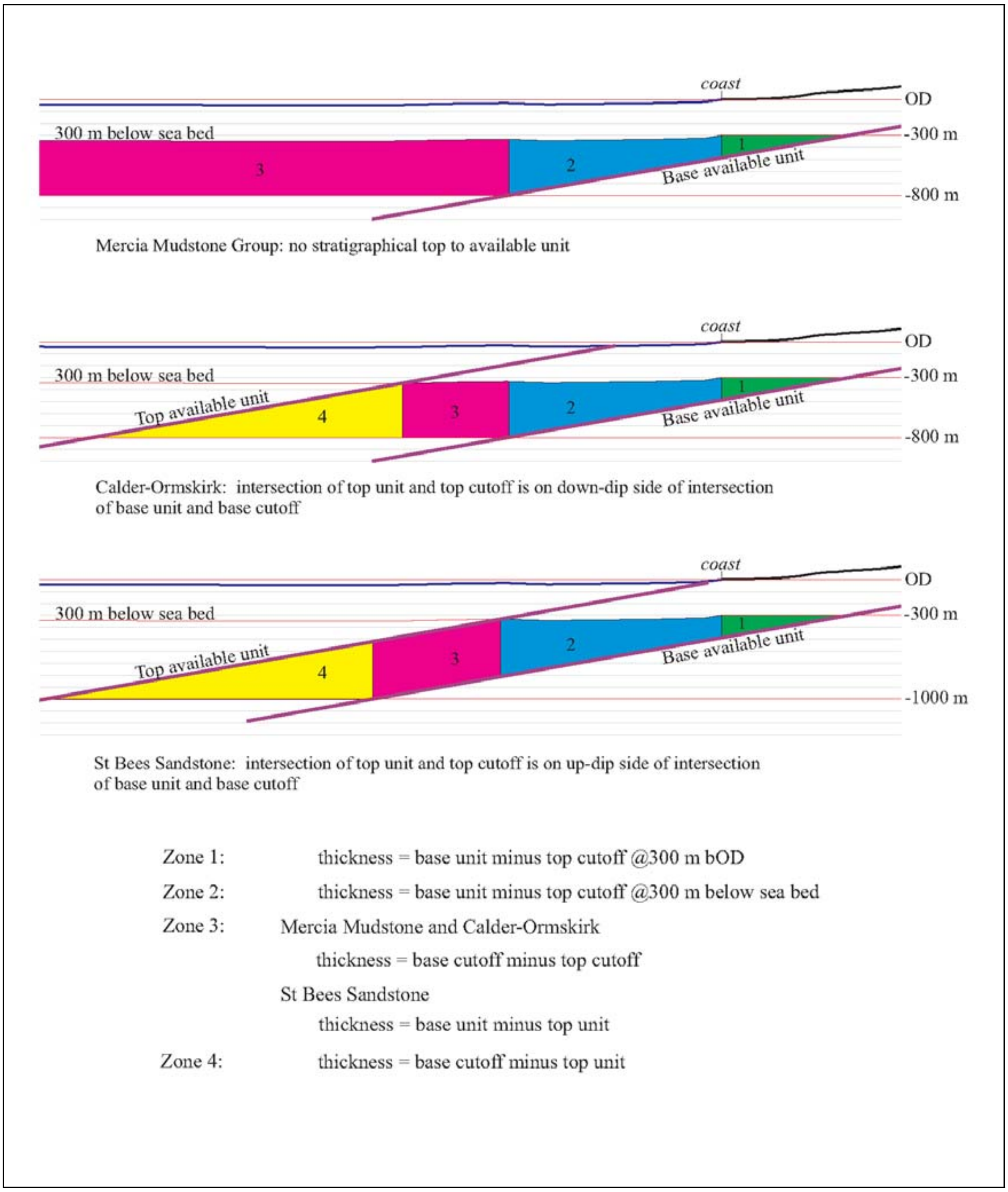


Figure 2.4 Isopach zone models

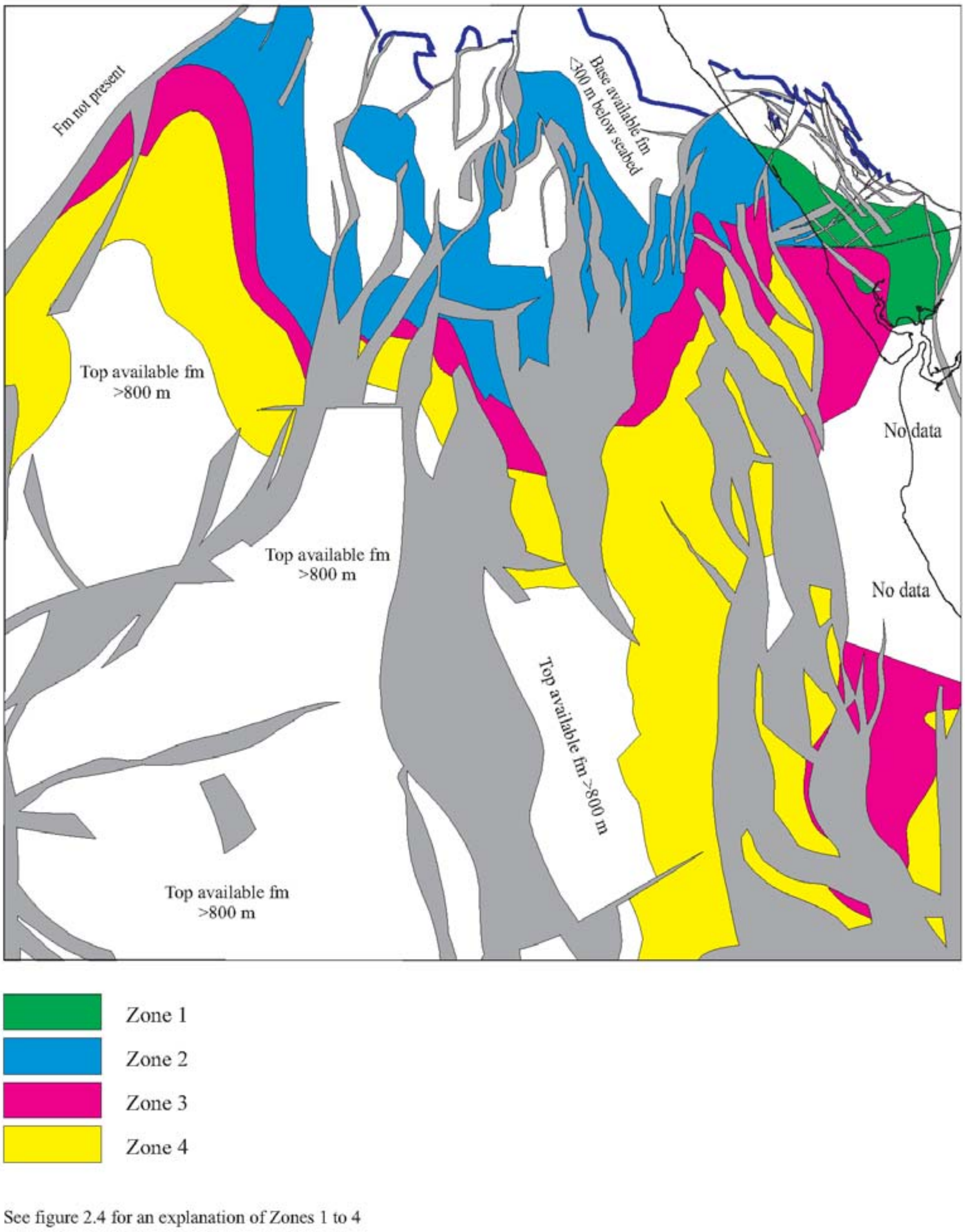


Figure 2.5 Map of model isopach zones: Calder-Ormskirk Sandstone formation

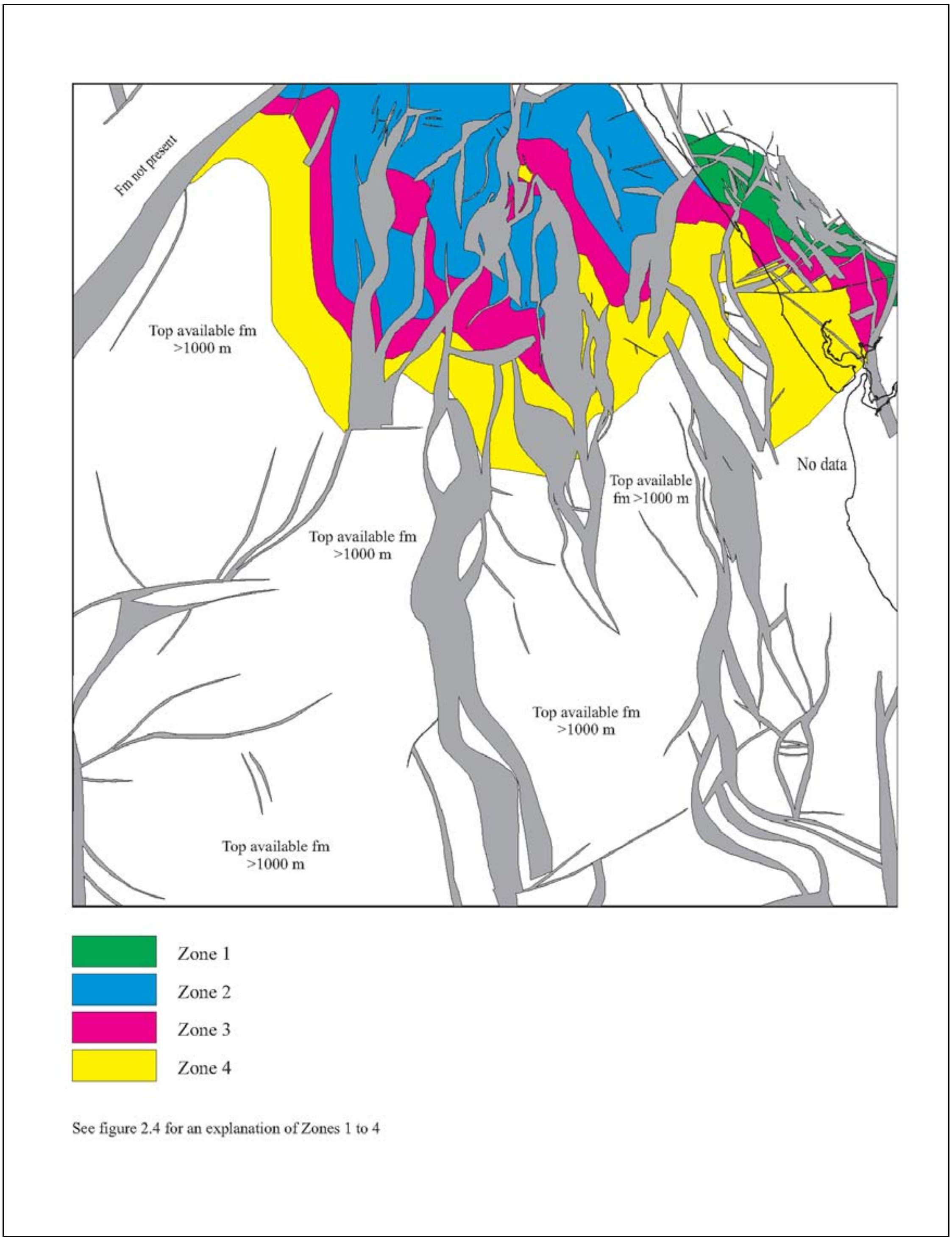


Figure 2.6 Map of model isopach zones: St Bees Sandstone Formation

# 3 East Irish Sea Basin Mercia Mudstone Group

KL Kirk and RA Chadwick

The Mercia Mudstone Group (MMG) is present over much of the study area in the northern part of the East Irish Sea Basin. Knowledge of the distribution and stratigraphy of the MMG is based on scattered well information, mostly outwith the study area (Figure 3.1), and interpretation of 2D seismic datasets (e.g. Jackson & Johnson 1996).

The full MMG succession is locally preserved in the southwest of the study area, where it is overlain by Jurassic strata (Jackson et al. 1995), but over much of the study area it is stratigraphically incomplete. In particular its upper parts have been removed by erosion, which cuts progressively more deeply northeastwards towards the basal outcrop offshore of Sellafield.

In Section 3.1 we describe the general nature of the full MMG succession in the northern part of the East Irish Sea Basin, and the characteristics of the main halite units. In Section 3.2 we go on to discuss the likely nature of the much thinner MMG succession to be found in the target zone of interest (within ~25 km of Sellafield). In Section 3.3 we identify additional work or datasets that could reduce uncertainty.

## 3.1 MAIN HALITE UNITS

Because of the dearth of core material from the Mercia Mudstone Group offshore, direct lithological and textural identification is generally lacking. However, on the basis of cuttings descriptions and wireline log signatures, the MMG can be divided into three main lithological categories, following Jackson & Johnson (1996):

1. Clean halite with mudstone partings, in which the gamma values of the halite range from ~7 to 15 API units (e.g. much of the Preesall and Warton halite formations).
2. Argillaceous, generally thinner-bedded halite with thicker mudstone intercalations, in which the gamma values of the halites range from ~15 to 35 API units (e.g. halites within the Cleveleys Mudstone Member, and large parts of the Fylde and Mythop halite members).
3. Halitic mudstone or mudstone, with gamma values greater than ~ 35 API units.

Analogous onshore sections (e.g. Wilson 1993), suggests that within these categories halite is likely to display two main lithological textures:

1. 'Massive' or 'layered', poorly bedded clean halite (e.g. Arthurton 1973).
2. Displacive halite crystals set in a mudstone matrix 'haselgebirge facies' (e.g. Wilson & Evans 1990). The halite crystals, both flat-sided and 'hoppered', grew displacively from saline groundwaters in the host mud or silt sediment (e.g. Wilson & Evans 1990). The halite crystals vary both in size and amount and may form either the dominant component of the rock (argillaceous halite), or constitute a relatively minor proportion (halitic mudstone).

Clean halite is believed to comprise mainly 'layered' halite (Arthurton 1973), whereas argillaceous halite is likely to display both massive and haselgebirge facies textures. Halitic mudstones are believed to display both haselgebirge facies and other textural associations of mudstone and halite (e.g. halite veins in a mudstone matrix). Regional correlations suggest that massive halite in the basin centre commonly passes laterally into haselgebirge facies, and thence into dolomitic siltstone (Arthurton 1980), and finally dolomitic sandstones ('skerries' of onshore usage). Near the Triassic basin margin, dissolution of halite, shortly after deposition, led to the formation of ancient collapse breccias (Wilson 1993).

The offshore succession is subdivided by the recognition of major regionally persistent halite units. These are defined on the arbitrary basis of having average salt contents greater than 50% (in practice halite contents are generally considerably higher than this), because of their relative ease of recognition on lithological and wireline logs. Thinly interbedded halitic mudstones lying directly above and below units dominated by clean halite or argillaceous halite are generally included within mudstone lithostratigraphic units; the named halite units are recognised by the incoming of thicker bedded clean or, locally, argillaceous halite. The lithostratigraphic boundaries thus defined are not true bed-by-bed correlations but merely reflect the gross lithofacies changes across the basin. However, wireline log signatures are commonly sufficiently sensitive to lateral facies changes to facilitate true bed-by-bed correlations across the basin. Five major dominantly halitic units can be identified (Figure 3.2).

| | **110/2-5** | **110/2-6** | **110/2a-8** | **110/3-2** | **110/3b-4** | **110/6b-1** | **110/8a-5** | **110/9-1** | **110/13-8** | **113/27-2** | **113/27-3** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Warton Halite** | N/A | N/A | 175 | N/A | N/A | N/A | 110 | N/A | 269 | 88 | N/A |
| **Preesall Halite** | 165 | N/A | 128 | 595 | 95 | 280 | 262 | 131 | 143 | 402 | 255 |
| **Mythop Halite** | 125 | N/A | N/A | 242 | 146 | 80 | N/A | 59 | 53 | 89 | 162 |
| **Rossall Halite** | 75 | 96.2 | N/A | N/A | 87.5 | 75.6 | 68.7 | 28.1 | 40.6 | 25 | 93.7 |
| **Fylde Halite** | 96.8 | 100 | N/A | N/A | 116.8 | 48.7 | N/A | N/A | N/A | N/A | 115.6 |

Table 3.1 Thickness of the main halitic units as proven in wells from the East Irish Sea Basin (mostly from outwith the study area).

Thickness of the five main halitic units to be found in the full offshore MMG succession are given in Table 3.1, and a description of each halite is given below, from top to bottom.

### 3.1.1 Warton Halite Formation

The Warton Halite Formation occurs widely in the deeper parts of the East Irish Sea Basin, but has largely been removed from structurally high areas. It consists mainly of clean halite though with numerous lateral persistent mudstone partings averaging 3 m thick (a maximum of 12 m thick measured in well 110/13-8). Partings have abrupt upper and lower contacts with the halite. The persistence of the mudstone partings enables basinwide correlation. Gypsum veins and patches occur in small amounts, throughout the halite and mudstone partings.

### 3.1.2 Preesall Halite Formation

The Preesall Halite Formation is the thickest halite unit within the MMG of the East Irish Sea Basin (Table 3.1). It is present over much of the basin except in marginal areas and over prominent structural highs where it has been removed by erosion. The Preesall Halite thickens northwards and shows the greatest variation in thickness of all the units in the MMG. It is the least argillaceous halite within the MMG, comprising clean halites with thin partings of mudstone, usually less than 3 m thick, though reaching 15 m thick in well 113/27-1. Mudstone units exceeding 15 m thick are thought to comprise collapse breccia from the overlying mudstones due to wet rockhead conditions where the halites have been dissolved. There are over twenty individual mudstone partings, occurring singly or in groups of up to five, within the Preesall Halite, tending to thicken northwards. They can be correlated across large parts of the basin and commonly pass laterally into thin (less than 2 m thick) dolomitic silts and very fine sandstone units.

### 3.1.3 Mythop Halite Member

The Mythop Halite Member is present over much of the East Irish Sea Basin except where removed by later erosion. It comprises individual layers of argillaceous halite separated by thicker persistent mudstone layers and is distinguished by having the highest mudstone content of the main MMG halite units. It also contains minor siltstones, sandstones, anhydrite and dolomite. Individual halites are between 1 and 30 metres thick, thickest in the northern part of the basin. The mudstones in this unit are up to 35 metres thick.

### 3.1.4 Rossall Halite Member

The Rossall Halite Member occurs over most of the East Irish Sea Basin except for the southernmost part. It is generally the thinnest major halite unit of the basin and has less numerous and thinner mudstone partings than the Fylde Halite Member. It also contains isolated beds of siltstone and small anhydrite occurrences. Four main leaves of relatively clean halite are intercalated with three laterally persistent mudstones (4 - 6 m thick) in the north and centre of the East Irish Sea Basin. The upper boundary of the Rossall Halite is sharp, but its base is less so, the lower halite leaves passing into halitic mudstones and dolomitic siltstones.

### 3.1.5 Fylde Halite Member

The Fylde Halite Member is the lowest major halite unit of the MMG. It shows an upward increase in the abundance and thickness of persistent mudstone partings (3-6 m thick), and the thicker halite beds become more argillaceous upwards. It occurs in the north and the central parts of the East Irish Sea Basin but it is absent onshore and is also probably absent in more marginal parts of the offshore basin.

Figure 3.3 illustrates sample well logs from two wells in the central part of the East Irish Sea Basin. Both wells prove a thick MMG succession (> 1150 metres thick), with four of the main halite units present, but important differences are evident. In well 113/27-3, much of the upper MMG, including the Warton Halite, has been removed by erosion, with Quaternary strata resting on the Preesall Halite. In well 113/27-2 a more complete upper MMG succession is preserved, including the Warton Halite, but the lowermost MMG is absent, with loss of the Fylde Halite and possibly much of the Rossall Halite. This may be explained by the well location, passing through the eastern bounding structure of the Tynwald Fault Zone, where the lowest part of the MMG is faulted out.

The successions proved in these two wells are much thicker and probably more complete than would be found in the target zone in the study area (see below). Nevertheless it is clear that even in the deeper parts of the basin, the effects of subsequent erosion play an important part in determining the stratigraphical range of the preserved succession.

## 3.2 NATURE OF THE MERCIA MUDSTONE GROUP IN THE NEARSHORE AREA

Available well control is situated mostly in the deeper basinal areas to the south and west of the study area. The MMG thins significantly northeastwards across the study area and so observed well sequences will not be representative of the target zone.

Published work by Jackson & Johnson (1996), based upon the deep well information and interpretation of 2D seismic data, suggests that the five main halite units extend across much of the study area, into the target zone (Figure 3.4). Such an interpretation requires that much of the MMG succession is present across the study area albeit in a progressively more condensed form to the northeast. If this were the case, then in the target zone, most of the halite units would be present, but much thinner than proved in well 113/27-2.

In an alternative scenario, which we consider more likely, thinning of the MMG is not principally stratigraphical, but is instead largely a consequence of post-depositional erosion. This removed the upper part of the succession, cutting progressively more deeply northeastwards across the study area, and removing the upper halitic units.

A regional seismic line (Figure 3.5) shows the MMG thinning from over 2000 m thick in the southwest to less than 800 m thick in the northeast, much of the thinning taking place across the Tynwald Fault Zone. It is the thinner nearshore succession, 10 km or so to the east of the Tynwald Fault Zone, that lies within the target zone. Here the base of the MMG lies at a depth of about 800 m, becoming gradually shallower northeastwards. The nature of the MMG succession hereabouts is uncertain due principally to the lack of local borehole information. As discussed above, the lack of clear eastwards stratigraphical thinning or pinchout (Figure 3.5) suggests that the observed thinner succession is probably mainly a consequence of erosion of the upper MMG sequence, rather than by severe stratigraphical thinning of the whole succession. The corollary of this is that the preserved succession would largely be lower MMG, with the lower halite units most likely to be present. Well 113/28a-3 is some 15 km to the south of the target zone (Figure 3.1), but penetrates a similar thickness of MMG, and may well prove a succession comparable to that of the target zone. Detailed geophysical logs are not currently available for this well, but a lithological log, based on well cuttings (Figure 3.6), permits assessment of the general geological succession. The well proves probable Quaternary strata resting upon MMG, within which a dominantly halitic unit, 100m thick, is evident. This is described on the log as the Rossall Halite, though the reasoning behind this is uncertain. Nevertheless, the presence of a single halitic unit is consistent with the upper part of the MMG having been removed by erosion. Because geophysical logs are not currently available for this well, the exact nature of the halitic unit is uncertain. Drill cuttings from the unit comprise 80% salt, suggesting a predominantly clean halite with only minor mudstone content (the observed 10% of claystone cuttings will at least in part be derived by caving from the overlying Singleton Mudstone). The seeming absence of the Fylde Halite may be due to faulting (as with the succession in well 113/27-2), or may reflect a relatively marginal location in the early depositional basin (exemplified by the onshore succession, where the Fylde Halite is wholly absent).

A more detailed view of the MMG succession in the target zone is given in Figure 3.7. Structurally the succession seems to vary laterally, between flat-lying coherently bedded strata (Stations 550 to 450) and seemingly folded or distorted beds (Stations 450 and 400). The situation is complicated by the likely presence of overlying Quaternary, drift-filled channels (Figure 3.5). These induce clear velocity pushdown effects (false downward bending of reflectors on travel-time sections, notably in the underlying Ormskirk and Calder sandstones) that give a misleading impression of folding and stratal disruption. Nevertheless the seismic reflections are perhaps more confused than might be expected just from velocity effects and real stratal deformation cannot be ruled out; indeed it may have been the case that the Quaternary channels preferentially eroded previously disrupted ground. A possible explanation of such disruption would be collapse following salt solution. This may have occurred during the Quaternary when the top of the MMG would have been exposed to wet rockhead conditions. The presence of collapse breccia in some of the offshore wells is consistent with this type of process. On the other hand, halokinesis (in the sense of density-driven salt flow) cannot be ruled out. A more thorough evaluation of these features would involve detailed mapping of the disturbed zones to assess their morphology and how they correlate spatially with fault zones and also the overlying Quaternary channel system.

To conclude, our preferred model requires that the currently observed northeastward thinning of the MMG is largely a consequence of later erosion. This implies that the succession in the target zone would comprise lower MMG, and that any included halite would be referable to one of the lower main halitic units. The presence of a single main halitic unit in well 113/28a-3 is consistent with this view. The lithological log from well 113/28a-3 (based on cuttings) suggests that much of the unit comprises clean halite. This could be tested when geophysical logs become available. Correlation of the well sequence with that in the target area requires more detailed seismic interpretation (also see 3.3). Seismic data indicate the presence in the target zone of quite flat-lying strata, and also possibly disturbed beds. The nature of the latter is uncertain and requires more detailed mapping and velocity modelling.

Overall levels of confidence related to the nature of the MMG succession in the target zone are provided below (refer to Appendix 1 for definition of the levels):

MMG present as mapped: Level 1/2

MMG thicknesses: Level 1/2

Preserved MMG is predominantly Lower MMG: Level 3

Significant halite units present in the succession: Level 3/4

Major clean halite unit present (e.g. Rossall Halite): Level 4

Presence of flat-lying strata with minimal faulting or disruption: Level 1/2

## 3.3 REQUIREMENTS FOR ADDITIONAL WORK TO REDUCE UNCERTAINTY

A significant step in reducing uncertainty would be obtain more well information (Table 3.2), and in particular to establish continuous seismic ties from key wells. The most useful well is likely to be 113/28a-3, which may have a succession quite representative of the target zone. We need to obtain a full suite of geophysical logs for this well. However the ease of tying from this well across the target zone is uncertain as a number of quite large structures lie in its vicinity. Data from the recently drilled well 113/22-1 (Figure 3.1) would also be useful in constraining seismic picks by establishing ties from the west across the smaller northerly prolongation of the Tynwald Fault Zone. Once these ties are established the target zone could be mapped in detail, concentrating on the seismic stratigraphy of the Mercia Mudstone Group, intra-formational structure, possible velocity pushdown effects and seismic attributes. The current 2D seismic grids held by Nirex (Figure 3.8) are probably sufficient to do this.

A detailed assessment of halite occurrences at an analogue site such as Walney Island, where a number of close-spaced wells have been drilled, may cast further light upon the possible configuration of halites in the target zone.

More specialist processing work which may ultimately be required for site identification and characterisation could include:

1. Reprocessing of selected seismic lines to improve shallow imaging (improved noise rejection, muting, velocity analysis, deconvolution, migration if appropriate). As well as improving imaging of the MMG succession, this should also benefit imaging of the Quaternary channel system, helpful in evaluating the abovementioned velocity-induced artefacts.

2. A more ambitious step would be to perform trace inversion on selected seismic lines, with the aim of explicitly deriving acoustic properties characteristic of halite. In principal, trace inversion could extract halite occurrences from seismic data but this requires carefully conditioned datasets, with preserved reflection amplitudes, and also requires good well calibration. In practice its efficacy would be seriously compromised by the absence of a well in the target zone.

N.B. Processing work would require access to pre-stack datasets and associated recording geometry information.

| Well Name | Current Owner | Drill Date |
|---|---|---|
| **113/22-1** | **Burlington** | **01/08/2005** |
| **113/22-1Z** | **Burlington** | **13/08/2005** |
| 113/28-2 | Kerr McGee | 30/04/1994 |
| 113/28- 2 | Kerr McGee | 30/04/1994 |
| **113/28a-3** | **Kerr McGee** | **03/02/1996** |
| 113/29- 2 | Kerr McGee | 20/10/1992 |
| 113/29a-3 | Kerr McGee | 02/05/1996 |
| 113/26a-2 | Burlington | 25/10/1993 |
| 113/26a-P1 | Burlington | 22/07/2000 |
| 113/26a-P2 | Burlington | 23/08/2000 |
| 113/26a-P3 | Burlington | 06/12/2000 |
| 113/26a-P4 | Burlington | 19/02/2001 |
| 113/27a- 4 | Burlington | 05/09/1996 |
| 113/27a- 5 | Burlington | 16/07/2001 |
| 113/27a-Q2 | Burlington | 10/08/2001 |
| 113/27a-Q3 | Burlington | 24/04/2003 |

Table 3.2 Recommended exploration wells (key wells in bold)

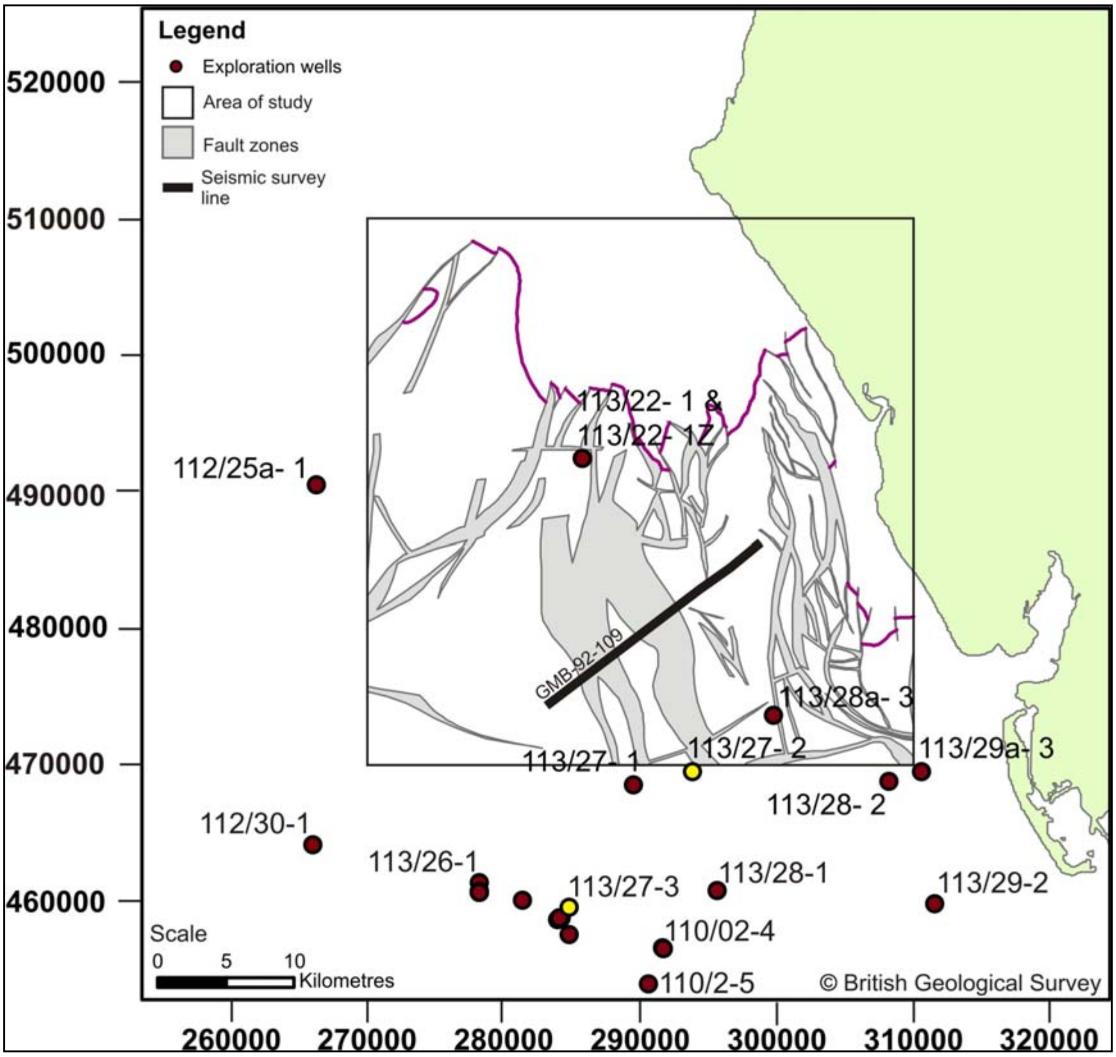


Figure 3.1 Map showing the study area with exploration wells (those shown in Figure 3.3 highlighted in yellow) and illustrated seismic line.

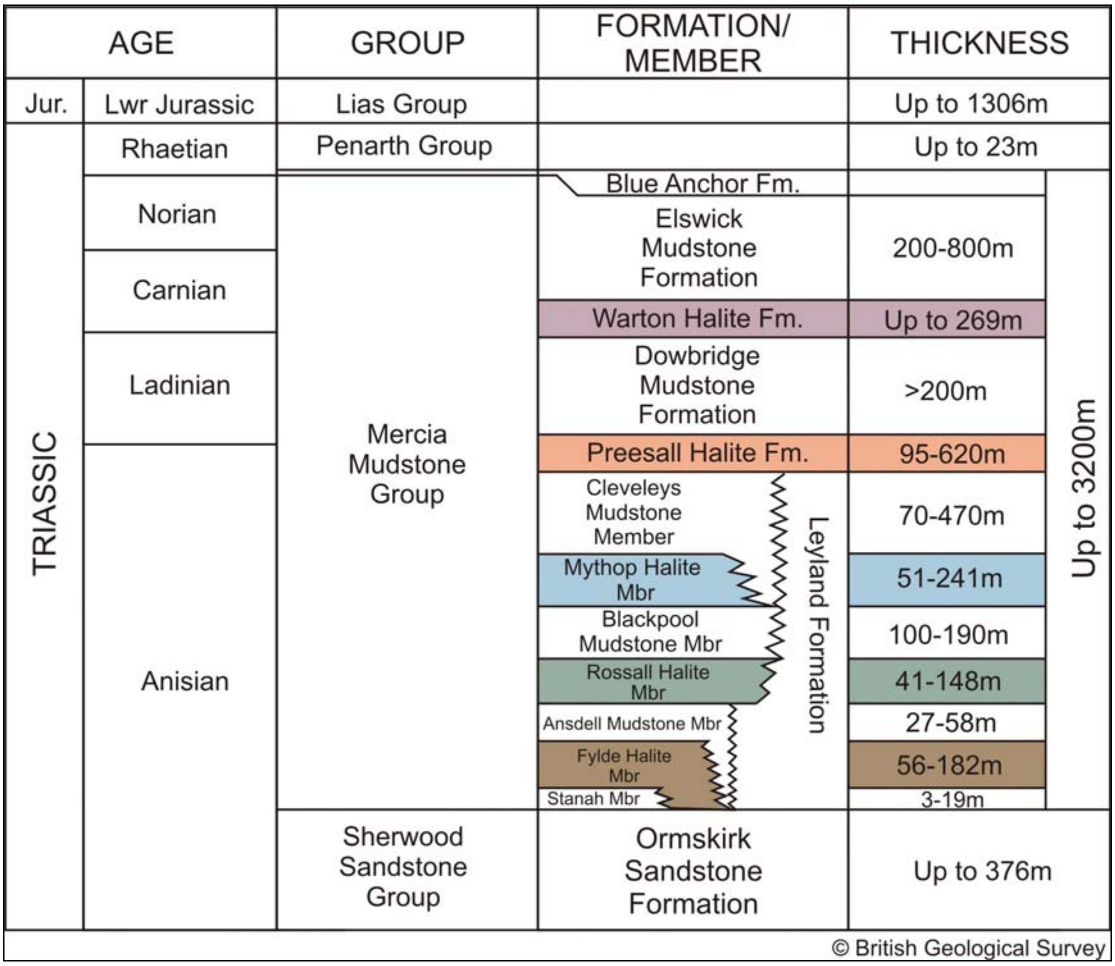


Figure 3.2 Stratigraphy of the full Mercia Mudstone Group succession of the offshore East Irish Sea Basin (adapted from Jackson et al. 1995 and Jackson & Johnson 1996). Note the full succession is not present in the target zone of the study area.

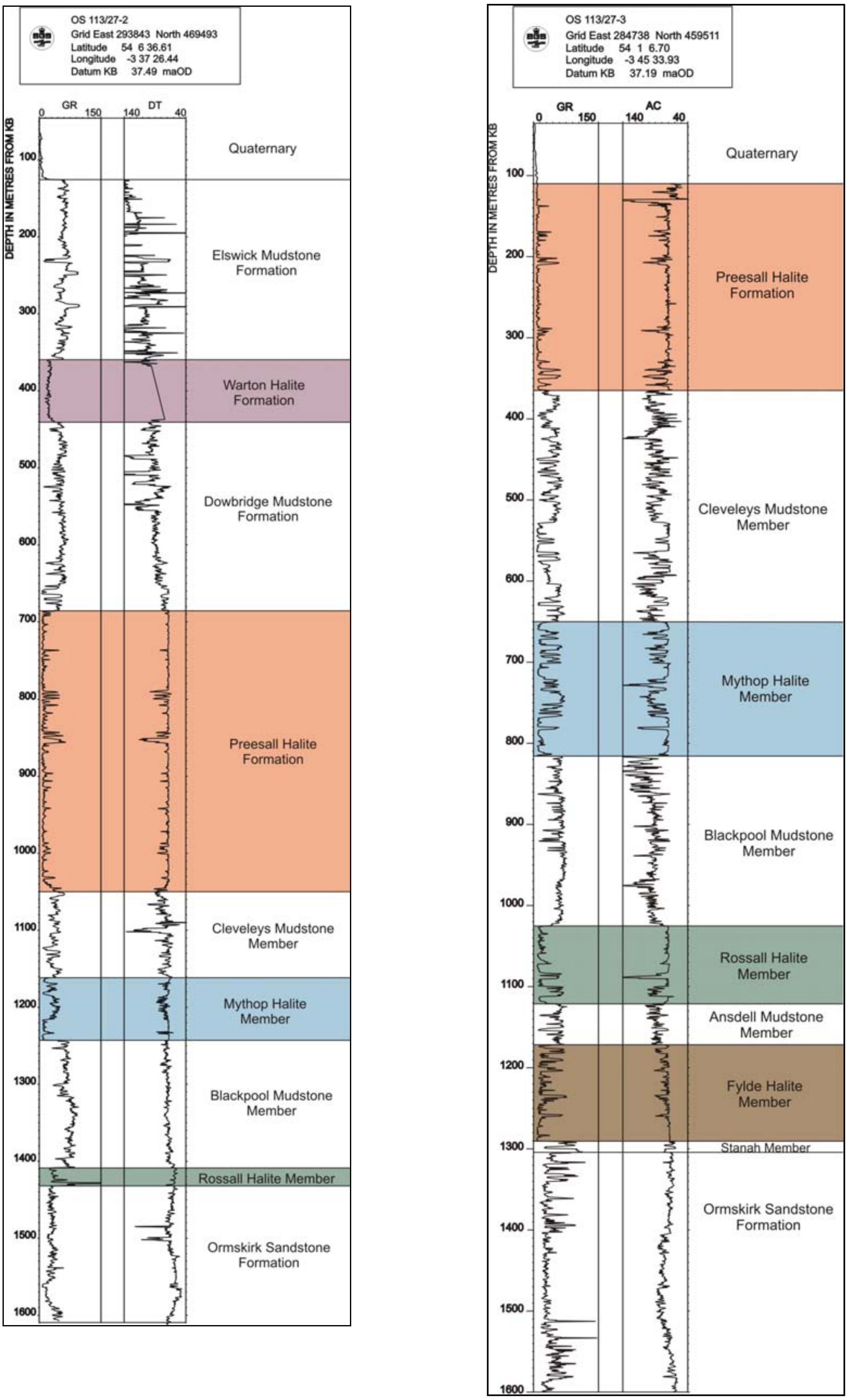


Figure 3.3 Mercia Mudstone Group stratigraphy in wells 113/27-2 and 113/27-3 (see Figure 3.1 for location). Note the MMG in the target zone of the study area is much thinner and less complete than the successions shown here.

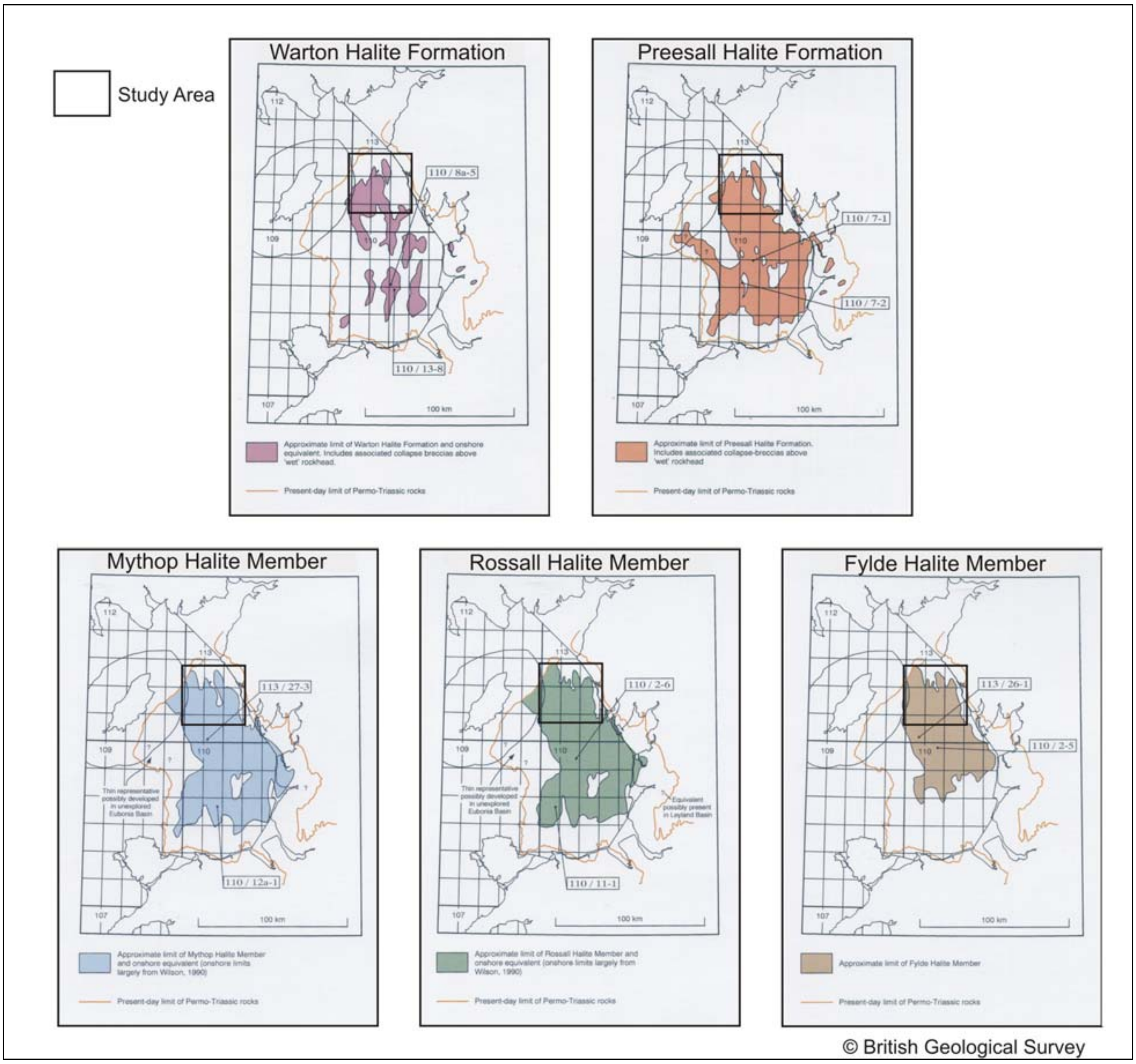


Figure 3.4 Possible extents of the main halite units within the Mercia Mudstone Group of the East Irish Sea Basin as proposed by Jackson and Johnson (1996)

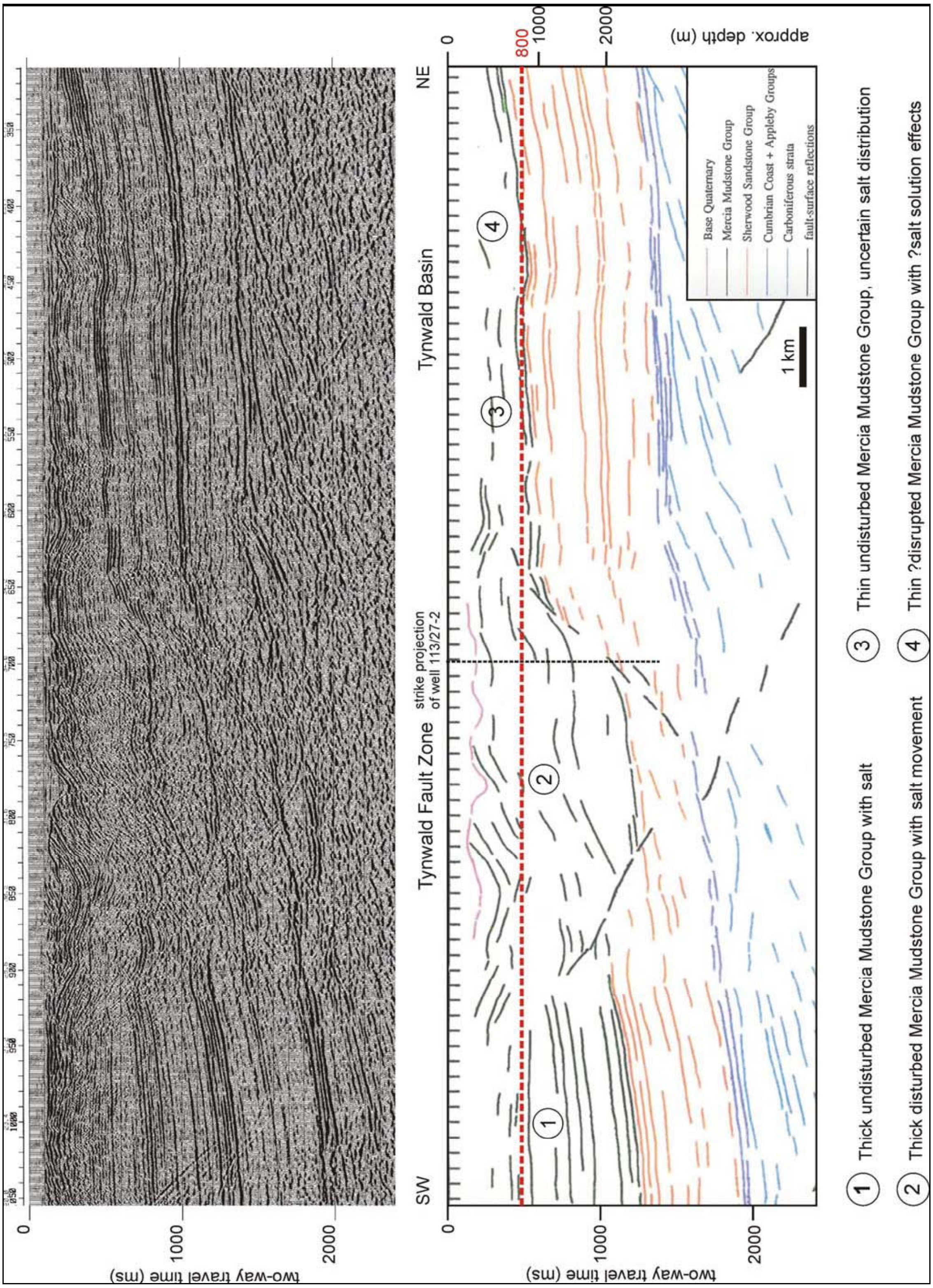


Figure 3.5 Seismic line GMB-92-109 (see Figure 3.1 for location) across the study area showing the Mercia Mudstone Group thinning eastwards towards the Cumbrian coast.

| Well Registration Number | 113/28a - 3 |
|---|---|
| Interpretation | Composite |
| Date Coded | 01/03/1999 |
| Depth Units | Feet |

| Datum | KB |
|---|---|
| Datum Elevation | 122.00 |
| Loggers TD | 0.00 |
| TWT Scale | |
| Thickness Type | |

| | | | | Litho Stratigraphy | | Chronostraigraphy | | | | Lithology Components | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Top Down Hole Depth | Top Vertical Depth (MSL) | Top TWT (msec) | Thickness | Upper Litho | Lower Litho | Upper Chrono | | Lower Chrono | | 1 | % | 2 | % | 3 | % | 4 | % |
| 213.0 | 91.00 | | 147 | * | | Q | 0 | | 0 | SAND | 100.00 | | | | | | |
| 360.0 | 238.00 | | 180 | SING | | TU | 0 | | 0 | CLST | 90.00 | ANHY | 10.00 | | | | |
| 540.0 | 418.00 | | 100 | ROSH | | TU | 0 | | 0 | HALI | 80.00 | ANHY | 10.00 | CLST | 10.00 | | |
| 640.0 | 518.00 | | 325 | MMG | | TU | 0 | | 0 | CLST | 90.00 | ANHY | 10.00 | | | | |
| 965.0 | 843.00 | | 15 | TPSF | | TU | 0 | | 0 | CLST | 90.00 | DOLO | 10.00 | | | | |
| 980.0 | 858.00 | | 634 | ORMF | | TL | 0 | | 0 | SDST | 70.00 | CLST | 20.00 | DOLO | 10.00 | | |
| 1614.0 | 1,492.00 | | 206 | STBS | | TL | 0 | PU | 0 | SDST | 70.00 | CLST | 30.00 | | | | |
| 1820.0 | 1,698.00 | | 4 | | | | 0 | | 0 | | | | | | | | |
| 1824.0 | 1,702.00 | | 0 | | | | 0 | | 0 | | | | | | | | |

Figure 3.6 Lithological log (based on drill cuttings) from well 113/28a (modified from http://www.og.dti.gov.uk/information/well_data/bgs_tops/geological_tops/geological_tops.htm). Note the halite unit between 418 and 518 m below OD.

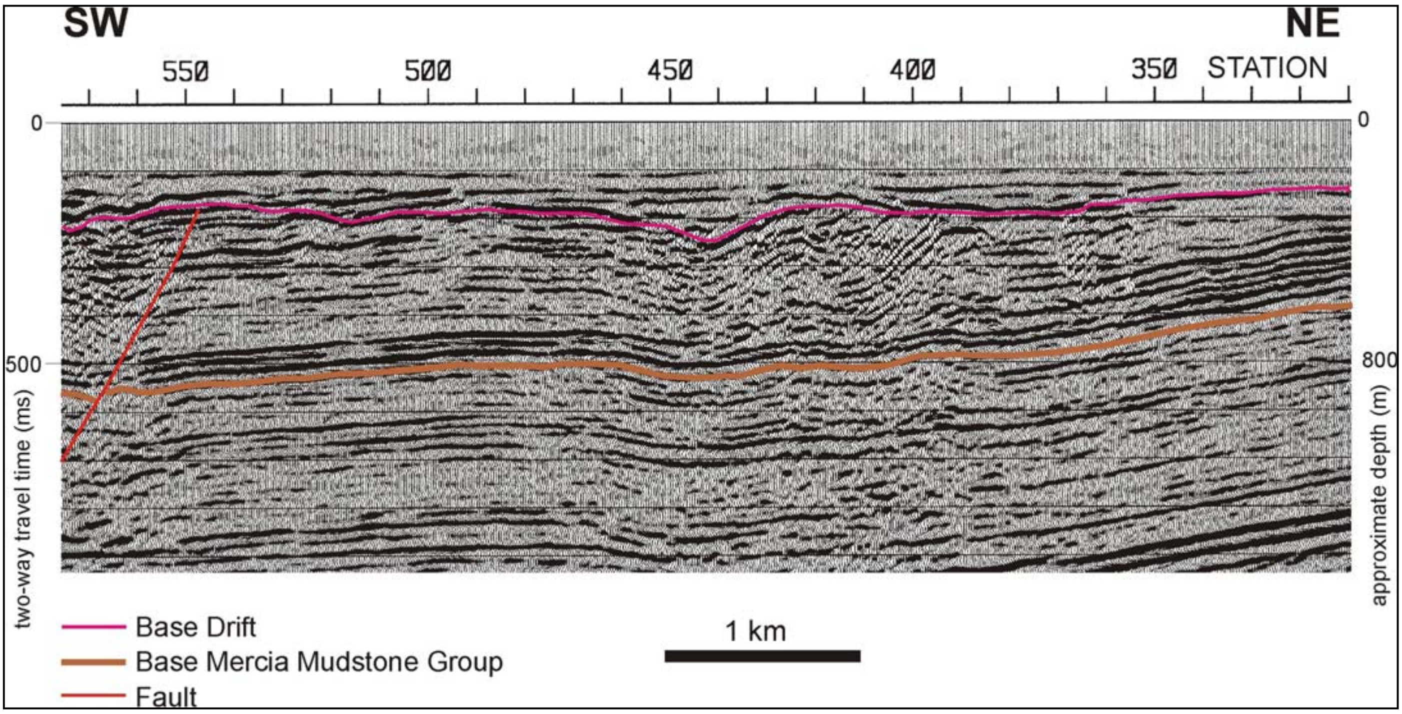


Figure 3.7 Seismic line GMB-92-109 showing detail of the Mercia Mudstone Group east of the Tynwald Fault Zone

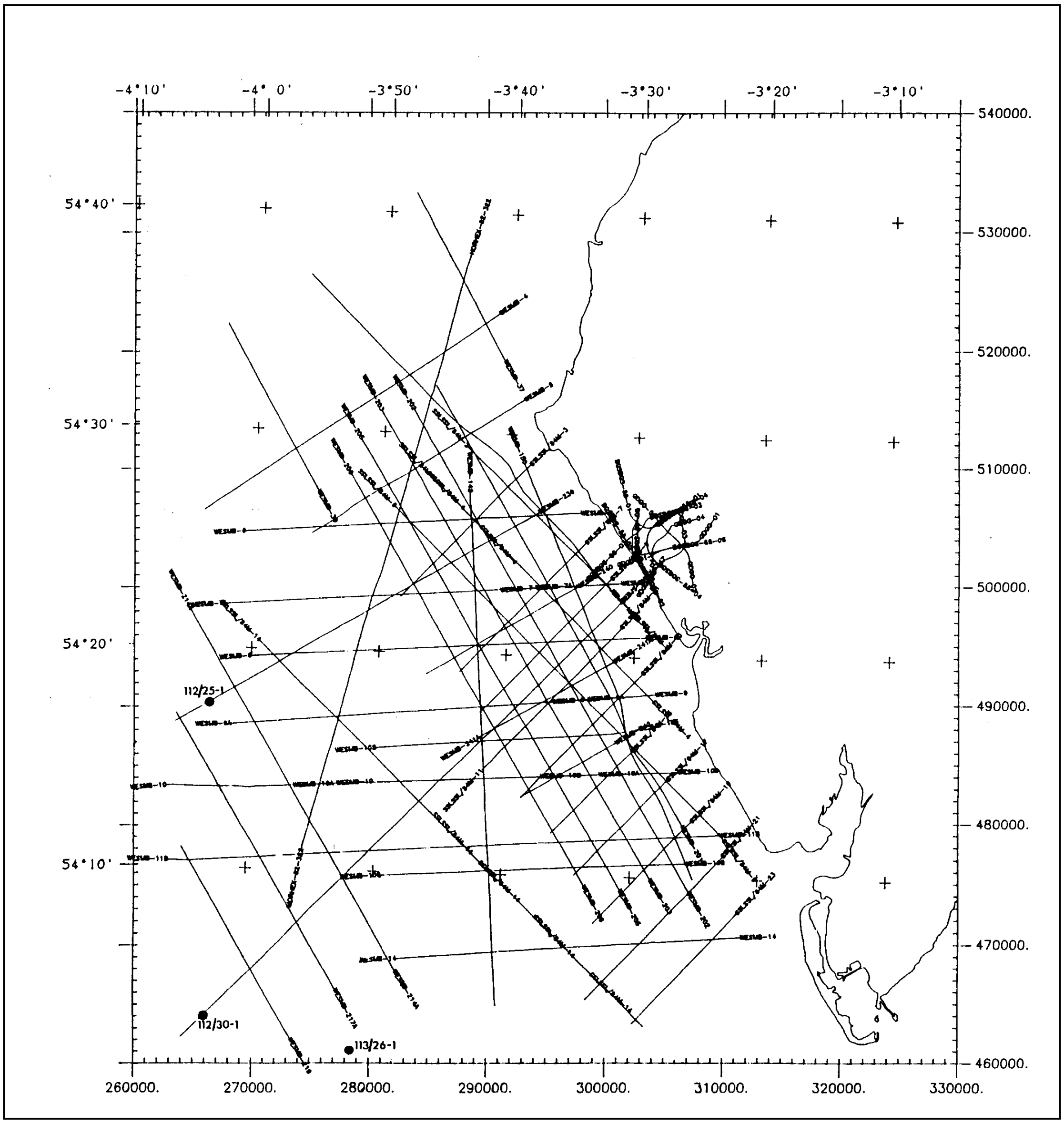


Figure 3.8 Simplified seismic line map showing the study area. Data coverage corresponds to that used by Chadwick et al (1991). Additional data in the near shore area and onshore, acquired for UK Nirex as part of the Sellafield investigations, are not shown.

# 4 Brine Bearing Basins On-Shore UK

WG Darling and IN Gale

This chapter provides an assessment of the locations of dense brine bodies present in onshore UK to depths of up to about 2 km. The evidence on which knowledge of the locations of these dense brine bodies is based is explained and levels of confidence are given for interpretations and statements, in accordance with the categorisation developed by Nirex and BGS. This is tabulated in Appendix 1.

Many of the interpretations fall into category 2. This indicates that "Direct data available from the study area" but there is "Low confidence derived from uncertainty over interpretation". This categorisation is used in many cases where there are a few water quality analyses distributed both laterally and vertically in different geological formations. Interpretations are therefore uncertain, especially where there are no supporting potentiometric head measurements to indicate the direction of groundwater flow.

## 4.1 SOURCES OF INFORMATION

The data used in the compilation of this section of the report were largely collected during a study of the geothermal potential of the United Kingdom – 1977 to 1986. Deep basin hydrogeology, brine chemistry, temperature distribution and groundwater movement were assessed to provide a quantification of the low-enthalpy geothermal resources of the UK. Sources of data on deep basin groundwater (including brines) were extensively sought and included samples from onshore oil, gas and coal exploration programmes. To supplement this limited, and geographically limited dataset, four deep (around 2000m) research boreholes were drilled and extensively sampled. Additional samples of brine were collected on the back of ongoing oil, gas and coal exploration programmes with the co-operation of the companies involved, and from tin mines in Cornwall.

Data from these many sources are stored on a BGS database and are published in catalogues of geothermal data (Burley and Edmunds, 1978; Burley and Gale, 1982; Burley, et al., 1984). The results of the geothermal research program are summarised in Downing and Gray (1986), which contains a copy of the Geothermal Map of the UK (Gale, 1985) and a list of reports issued in the BGS series "Investigation of the Geothermal Potential of the UK".

The BGS multidisciplinary study of mineralization in the Cheshire Basin provided opportunities to collect additional limited data and, through borehole log interpretation and groundwater flow modelling, an improved understanding of the flow dynamics in a density-driven flow system.

All other sources of data are referenced including the data collected by Nirex waste repository investigations. The latter studies are not described in detail as the data and interpretations are well known by the client.

## 4.2 OCCURRENCE OF BRINES

Brines are defined here as having a chloride concentration >60 g/L which approximates to a NaCl salinity >100 g/L, (SEC >160 mS/cm). Salinity values derived from a variety of sources in different units are converted, for comparison, to concentration of Cl in g/L.

A significant source of well-constrained data is the geothermal investigations undertaken in the early 1980s. This is available in a series of reports and papers and largely summarised in Downing and Gray (1986). The report contains the Geothermal Map of the United Kingdom, the key points being summarised in Table 4.1. Brines are found in the Triassic sandstones in the Wessex and Larne Basins and the Permian sandstones in the Yorkshire/Lincolnshire Basin. Brines are not found (except very locally) in the shallower Worcester Basin but indirect evidence indicates that they occur in the Cheshire Basin. The densest brines are found in the Triassic sandstones in the Wessex Basin where the total dissolved solids (TDS, approximately equal to NaCl salinity) values of 300 g/L (over 8 times the salinity of seawater) are measured.

Table 4.1. Summary of data from the Geothermal Map of the United Kingdom.

| Basin | Location | Formation | Depth interval (m) | Date | Temp. (°C) | TDS[1](Cl) (g/L) | Comments |
|---|---|---|---|---|---|---|---|
| Wessex | Basin | Sherwood Sst. | Top from 600 to 2200 and thickness of 50 to 250 m | Various | 40 to 80 | 100 to 300 (CL. 60 to 180) | |
| | Marchwood No.1 | Sherwood Sst. | 1672 to 1686 | 1980 | 74 | 103 (Cl. 60) | TD 2609 m in Devonian |
| | Soton. W Esplanade | Sherwood Sst. | 1725 to 1749 | 1981 | 76 | 125 (Cl. 75) | TD. 1823 m in Devonian |
| Worcester | Basin | Permo-Triassic Sst. | Top from 700 to 900 and thickness of 250 to 1500 m | Various | | 6 to 29 (Cl 4 to 17) | |
| Cheshire | Basin | Permo-Triassic Sst. | Mercia mudst. Up to 2000 m thick overlying Permo-Triassic Sst. to 4000 m | | Up to 80 | | No brine samples |
| E Yorks. & Lincs. | Cleethorpes No. 1 | Sherwood Sst. | 1093 to 1490 | 1984 | 44 to 55 | 80 (Cl. 50) | TD 2092 m in Upper Coal Measures |
| | Cleethorpes No. 1 | Basal Permian Sands | 1858 to 1884 | 1984 | 64 | 235 (Cl. 140) | |
| Larne N. Ireland | Larne No. 2 | Triassic Sst. | 960 to 1247 | 1981 | 40 | 200 (Cl. 120) | TD 2873 m in Permian |

[1] TDS. Total dissolved solids: approximately equal to NaCl salinity

Of necessity, this study focussed on aquifers in deep basins, where the majority of data are to be found, but also included other formations where water could be sampled. Non-aquifers at depths of a couple of kilometres, where groundwater movement is likely to be limited, may also contain connate brines but have yet to be sampled.

It must however be remembered that it is likely that brines will be found at depth ***anywhere*** in the UK especially in low permeability rocks where movement of interstitial waters would be on a time scale of millions of years, allowing abundant time for water–rock interaction. [Level of confidence. 5]

In a study of palaeowaters in the British Isles, Darling et al (1997) state that groundwater circulation patterns established since the end of the Pleistocene (c. 10 ka) in response to the temperate marine climate and sea levels have been disturbed by abstraction of water in the last 100 years. It is argued that palaeowaters, both fresh and saline, have become a factor in groundwater development so available data, based on isotopic evidence ($\delta^{18}O$, $\delta^{2}H$ and $^{14}C$) were synthesised to better understand distribution and evolution. Although some of the brines are geologically ancient, they are potential sources of geothermal energy or other uses and hence pumping will disturb the hydraulic balance that has existed for millennia. [Level of confidence. 3]

The locations of the 55 sites where brines have been sampled are shown in Figure 4.1 representing a total of 197 samples of brine. These are discussed in the following sections and, where possible, the areal extent of brines is estimated.

### 4.2.1 Wessex Basin

Brines are found in the Triassic Sherwood Sandstone Group; data being derived from oil and gas exploration boreholes as well as research holes drilled by BGS at Winterborne Kingston, Marchwood and Western Esplanade, the latter two for geothermal research. Downing and Penn (1992) considered that the brines are a mixture of Triassic meteoric water and Jurassic seawater with influxes of meteoric water in the early Cretaceous and Tertiary. However, dating by $^{4}He$ accumulation gives a tentative median age of c.15 Ma and a maximum age of 85 Ma (Edmunds; 1986), i.e. considerably younger. At the best-constrained sites at Marchwood and Southampton (Western Esplanade), the brines have a Cl concentration of 63 to 76 g/L, located at depths of around 1600 to 1700 m. Brines of much higher concentrations (110 to 180 g/L) are found at similar (1550 m) and deeper (2400 m) depths in the Winterbourne Kingston, Mappowder and Wytch Farm boreholes. No correlation between depth and concentration can be seen. An interpretation of the areal extent of brines in the Sherwood Sandstone Group in the Wessex Basin is shown in Figure 2.2 (after Downing and Gray; 1986). A large part of the basin contains brines with salinities greater than 110 g/L (Cl >60 g/L). [Level of confidence. 2]

### 4.2.2 Worcester Basin

Formation waters in the Permian approach the salinity of seawater but the isotopically depleted, relatively low-Cl waters in the overlying Triassic strata imply Quaternary rather than Tertiary recharge. No evidence of brines (Cl >60 g/L) in the deeper Worcester Basin has been found. [Level of confidence. 2], though the existence of brines with Cl concentrations of up to 187 g/L in shallow groundwaters of the Mercia

Mudstone Group in the Droitwich area has been noted (Edmunds et al, 1969; Poole and Williams, 1981).

### 4.2.3 Yorkshire and Lincolnshire Basin

Samples of brines are relatively plentiful in this area due to the extensive oil and coal exploration in the Carboniferous and the geothermal exploration borehole at Cleethorpes into the Triassic and Permian sandstones. The brines in the Cleethorpes borehole in the onshore extension of the North Sea basin are very different in the Triassic (Cl 30.2 g/L) and Permian (Cl 130 to 140 g/L) formations. A possible relationship between the Triassic groundwater, the highly saline Permian brines and the underlying Upper Carboniferous formation waters was postulated by Darling and Edmunds (1987). From isotopic evidence the Permian brines are remnants of halite-enriched basin brine that has undergone flushing by meteoric waters since at least the late Pleistocene and the Carboniferous and Triassic waters represent intermediate stages of flushing.

The base of the Basal Permian Sands (the aquifer sampled) is at a depth of 1890 m and the formation is only about 26m thick at Cleethorpes, so there is little potential for vertical stratification of the brines. [Level of confidence. 5] The estimated areal extent and thickness of the formation is shown in Figure 4.3 and the depth of the formation in Figure 4.4. [Level of confidence. 2] The formation thins to the north of the Humber and thickens towards the coast of Lincolnshire, to the north of Skegness, where it is likely to be found between 1750 and 1800 m. The only measurement of the salinity of the brine is from the Cleethorpes borehole. Brines could be expected to occur along the coast between Grimsby and Skegness in the Permian Sands, the areal extent being uncertain. [Level of confidence. 2] It is possible that estimates of salinity, and hence the extent of the brine, could be better defined from further interpretation of borehole geophysical logs.

The samples of brines collected from oil and gas exploration boreholes in East and North Yorkshire at depths of between 900 and 2200 m (the majority being from depths greater 1400 m) have chloride concentrations ranging from 94 to 195 g/L, the highest value from the Basal Permian Sandstone and the lowest value being a sample from the Permian Lower Magnesian Limestone. A sample from a second borehole at the latter location, but from the deeper Millstone Grit formation, has a chloride concentration of 166 g/L. The majority of the other samples are from the Upper Permian Magnesian Limestones, but there is one from the Triassic sandstone (116 g/L) and another one from the Millstone Grit (112 g/L). Brine concentrations do not appear to be related to geological formation, but there is a trend for increased salinity with depth.

### 4.2.4 East Midlands coal mines and oilfields

As part of the geothermal investigations in the early 1980s, Darling and Edmunds (1987) gathered data and formation water samples from the East Midlands coal and oil exploration activities. Samples were collected from the full Carboniferous sequence from the Westphalian Coal Measures to the Carboniferous Limestone, as well as from the Upper Permian Magnesian Limestone. Sample depths are largely in the range of 900 to 1800 m and NaCl salinities of brines range from 60 to 200 g/L (Cl. 35 to 120 g/L). The postulated regional groundwater flow is shown in the schematic cross-section (Figure 4.5) through the East Midlands (after Downing et al; 1987).

[Level of confidence. 2] This interpretation is based on both the water analyses and the pressure measurements from drill-stem tests. In general, the salinity of brines increases ***upwards*** from the Carboniferous Limestone (NaCL 100 g/L. Cl. 60 g/L) through the Millstone Grit (>180 g/L. >110 g/L) to greater than 200 g/L (Cl. 120 g/L) in the overlying Coal Measures. An interpretation of the available data (Figure 4.6) from the three main divisions of the Carboniferous was made in Downing and Gray (1986). The origin of these brines was attributed to diagenesis of formation waters and concentration through argillaceous beds acting as semi-permeable membranes (Downing; 1969), though it is not clear how the necessary over-pressuring would have developed.

The hydraulic head in the Derbyshire Dome drives the regional groundwater flow. Groundwater discharge, around the contact with the overlying Millstone Grit Series, as thermal springs at Matlock ($20^oC$) and Buxton ($28^oC$) indicates a minimum circulation depth of 600m. Radiocarbon measurements at Buxton suggest a bulk age of ~3000 years (Evans et al, 1979). Head-driven flow seems to dominate density-driven flow in this area, whereas the reverse situation is indicated in the Cheshire Basin (see next section). This is possibly due to the lack of halite deposits and the geological variability of the Upper Carboniferous restricting the formation of density-driven flow. In the north of the area where the facies are dominantly argillaceous, the brines are very saline indicating little groundwater movement (Downing; 1969). The outlet for this slow upward movement of groundwater is probably through the overlying Permian and Triassic formations and it is speculated by Downing (1969) that this may be reflected in the regional heat-flow anomaly in Lincolnshire. [Level of confidence. 2]

### 4.2.5 Cheshire Basin

Sampling of shallow waters from the basin reveals the presence of brines with Cl concentrations up to 250 g/L, on geochemical and isotopic evidence derived from interaction with halite in the Mercia Mudstone Group during Quaternary times (Lucey, 1987; Tellam, 1995). Because of the lack of actual measurements of the salinity of brines in the deep Cheshire Basin, estimates were made from geophysical logs of the few deep boreholes available (Plant et al; 1999). Estimates of salinity (Table 4.2) are variable but many of the shallower results range from NaCl 20–30 g/L (Cl. 10-20 g/L) whilst the deeper results are in the range of NaCl 60–80 g/L (Cl. 35-50 g/L). There does not appear to be any correlation between salinity and Permo-Triassic formation. Anomalously high salinities of around NaCl 140 – 170 g/L (Cl. 80-100 g/L) are calculated in the Elworth Borehole, which penetrates the Tarporley Siltstone and the Helsby Sandstone. Insufficient data are available to be able to comment on this observation. No isotopic data are available for the deeper central part of the basin.

In order to gain some insight into the movement of groundwater and the nature and origin of the brines, a cross-section model was constructed across the basin (Plant et al; 1999). Where not overlain by the Mercia Mudstone Group (and the halite units this incorporates) the shallow, freshwater, current recharge-driven system dominates.

Beneath the Mercia Mudstone Group, dense brines originating from the salt beds drive the flow ***downwards*** from the central part of the basin generating flow cells, which rise towards the margins of the basin, particularly along deep boundary faults (Figure 4.7 and 4.8). [Level of confidence. 5] Initial runs of the model suggested that the basin should contain brines at halite saturation but the limited evidence, described above, indicated that this was not the case so different scenarios were modelled. Using an input density of 1050 kg/m$^3$ produced a large mixing vortex on the eastern half of the basin. This preliminary scenario modelling suggests that brine-driven flow may take the order of 10 Ma to settle; a long time in relation to climate change, and hence change in the recharge/discharge regime.

Discharge from the basin is likely to be into the active, relatively rapidly moving near-surface meteoric water system where dilution precludes detection. One exception to this may be the saline (Cl. 11 g/L) spring at Aldersley [34565 35652]. This spring is located on the eastern side of an inlier of Coal Measures rocks and it is postulated that this represents diluted brine from the confined Permo-Triassic basin (Plant et al; 1999). [Level of confidence. 2]. The relatively depleted stable isotopic composition of the spring water (Lucey, 1987) indicates that a proportion must be of Pleistocene age (i.e. >10 ka old) by comparison with other Triassic groundwater of known age (Darling et al. 1997 and references therein).

Table 4.2. Salinity calculated from electrical borehole logs in deep boreholes in the Cheshire Basin (Plant et al; 1999). [Level of confidence. 2]

| Borehole | Formation | Depth to top of formation (m below ground level) | Mean temperature (°C) | Calculated NaCl (Cl) salinity (g/L) |
|---|---|---|---|---|
| Prees | Tarporley Siltstone | 1731 | 53 | 20 (12) |
| (SJ53SE3) | Helsby Sandstone | 1932 | 56 | 21 (13) |
| | Wilmslow Sandstone | 2164 | 59 | 28 (17) |
| | Silicified Wilmslow Sandstone | 2396 | 62 | 78 (44) |
| | Chester Peddle Beds | 2750 | 66 | - |
| | Collyhurst Sandstone | 2889 | 70 | 50 (30) |
| Burford | Malpas Sandstone | 668 | 26 | 14 (8) |
| (SJ65SW13) | Lower Tarporley Siltstone | 751 | 28 | 34 (20) |
| | Helsby Sandstone | 837 | 30 | 80 (48) |
| | Wilmslow Sandstone | 1039 | - | - |
| Elworth | Tarporley Siltstone | 1089 | 36 | 140 (85) |
| (SJ76SW52) | Helsby Sandstone | 1318 | 39 | 170 (100) |
| Knutsford | Helsby Sandstone | 715 | 27 | 26 (16) |
| (SJ77NW4) | Wilmslow Sandstone | 909 | 31 | 26 (16) |
| | Silicified Wilmslow Sandstone | 1500 | 39 | 21 (13) |
| | Chester Pebble Beds | 1803 | 43 | 66 (40) |
| | Kinnerton Sandstone | 2000 | 45 | 42 (25) |
| | Collyhurst Sandstone | 2230 | 51 | 20 (12) |
| Collinge | Kinnerton Sandstone | 230 | 20 | 38 (23) |

### 4.2.6 Northern Ireland

Geologically, Northern Ireland can be regarded as a continuation of the Midland Valley of Scotland. It is underlain by Permo-Triassic basins extending to depths of over 2 km and, in the Larne Basin to over 3 km deep along the north-east coast. The Permo-Triassic formations crop out along the western and southern margins of the province (Figure 4.9 taken from Downing and Gray; 1986) and are extensively overlain by Tertiary volcanics, which attain thicknesses of up to 800m.

Brines have been obtained from the Sherwood Sandstone in deep boreholes at Ballymacilroy (NaCl. 120 g/L. Cl. 70 g/L) and Larne (NaCl. 200 g/L. Cl. 120 g/L). Although the brines in the two boreholes sampled are between 3 and 6 times the salinity of seawater, their isotopic compositions is similar to that of present day meteoric waters. Low temperature gradients in the sandstones also indicate that deep groundwater circulation is still occurring (Bennett 1983). The brines from these two sites differ greatly in salinity but are considered to be related in origin; the higher salinity at Larne probably being related to halite deposits which do not occur at Ballymacilroy. The extent of brines is likely to be restricted to the Larne Basin to the north-east of Lough Neagh. [Level of confidence. 2]

### 4.2.7 East Kent Coal Basin

Water samples from Carboniferous strata in the Betteshanger Colliery at depths of about 500 m have a NaCl salinity of 5.2 to 8.5 g/L (Cl. 3 to 5 g/L) but further inland at the Snowdon Colliery have a NaCl salinity of 11 to 15 g/L (Cl. 7 to 9 g/L) at 900 m, indicating the source of salinity is unlikely to be mixing with seawater. Stable isotope enrichment at Snowdown implies the age of the waters in the basin rises with depth (Darling and Edmunds, 1987).

### 4.2.8 South eastern England: mudrocks

Pore waters extracted from plastic mudrocks by squeezing for geochemical analysis suggest that they were emplaced by recharge during the Pleistocene (Bath; 1995).

### 4.2.9 South western granites

The Hercynian granites of SW England contain thermal waters, sampled in mine workings in the Carnmenellis Granite to depths of 900 m. The highest recorded temperature is 53$^{o}$C and NaCl salinities about 19 g/L (Cl. 11 g/L) (Edmunds; 1986). Accumulation of $^{4}$He in the water indicates an ancient saline component, perhaps as much as 1 Ma in age, but the presence of $^{3}$H implies a drawdown of modern water associated with mining activities.

### 4.2.10 Sellafield and Dounreay

The Ordovician Borrowdale Volcanic Group at Sellafield again contains an interface between very old saline waters from the E Irish Sea Basin and relatively recent recharge (Bath et al., 1996). The basin, which developed in the Triassic, extends beneath the Irish Sea and would be expected to contain formation brines beyond radiocarbon measurement (i.e. >40ka.) in Triassic and older rocks.

Similarly at Dounreay in the Moine metasediments there is some evidence of palaeowaters at depth (Darling et al, 1997) though these are lower salinity than at

Sellafield and there is evidence of deeper fresh water circulation, particularly associated with fault zones (Bath et al., 2005).

### 4.2.11 Scottish Midland Valley: Carboniferous

There are few records of brines from the Midland Valley, but the presence of Carboniferous strata in a context of overall geological complexity suggests that isolated pockets of brine may exist. For example, a water with a NaCl salinity of 42 g/L, (Cl. 25 g/L) on stable isotope evidence unrelated to sea water mixing, was recorded from Fife (Darling and Edmunds, 1987). A sample collected from a drill stem test in Glenrothes Borehole recorded a chloride concentration of 68 g/L.

### 4.2.12 North East Coal Basin

Chloride concentrations of up to 122 g/L were reported from Carboniferous and Permian strata in coal mines of the North East by Sheppard and Langley (1984). The highest values were found in workings extending up to 10 km offshore.

### 4.2.13 Lancashire Coal Basin

Tellam (1995) alludes to brines from the Lancashire Coalfield with Cl concentrations in excess of 100 g/L.

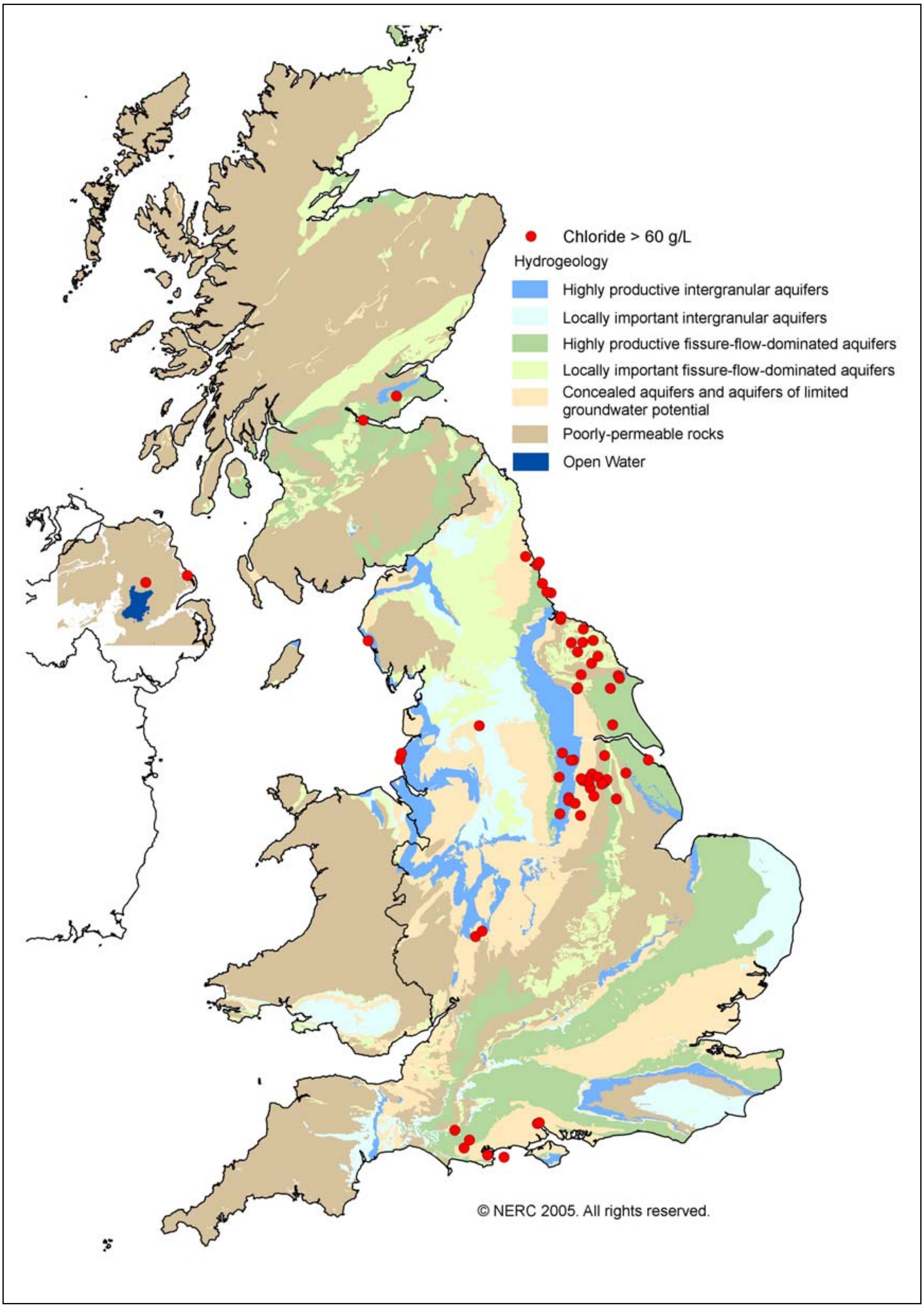


Figure 4.1. Location of brines with Cl > 60 g/L, where sampled, in the UK. Compiled from BGS database of groundwater quality.

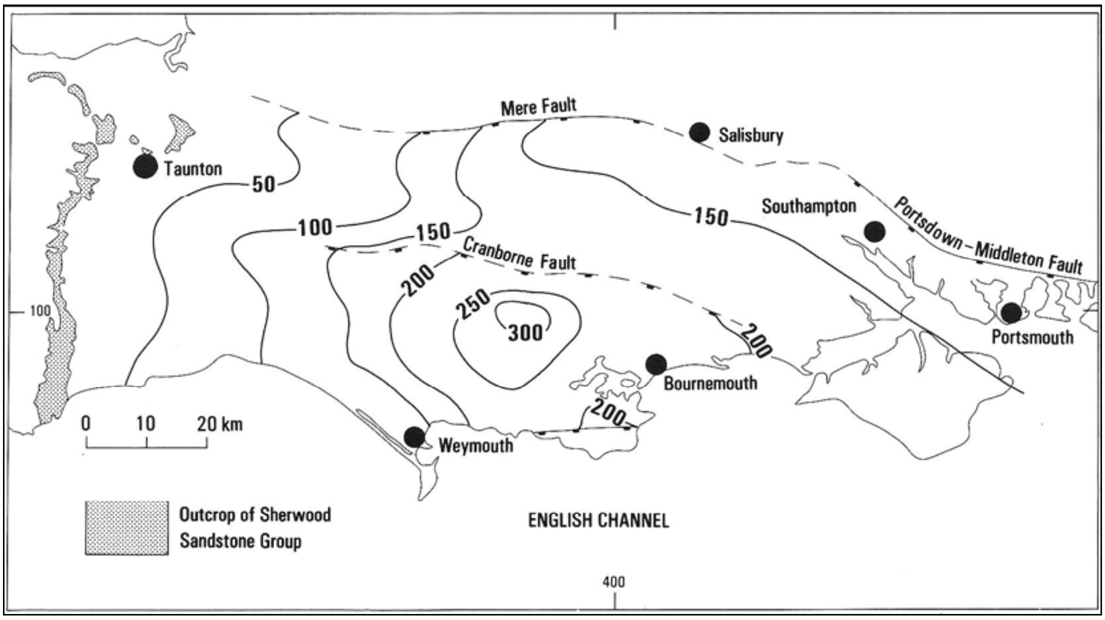


Figure 4.2. Salinity (NaCl) of groundwater in the Sherwood Sandstone Group in the Wessex Basin (g/L). [Source: Downing and Gray, 1986]

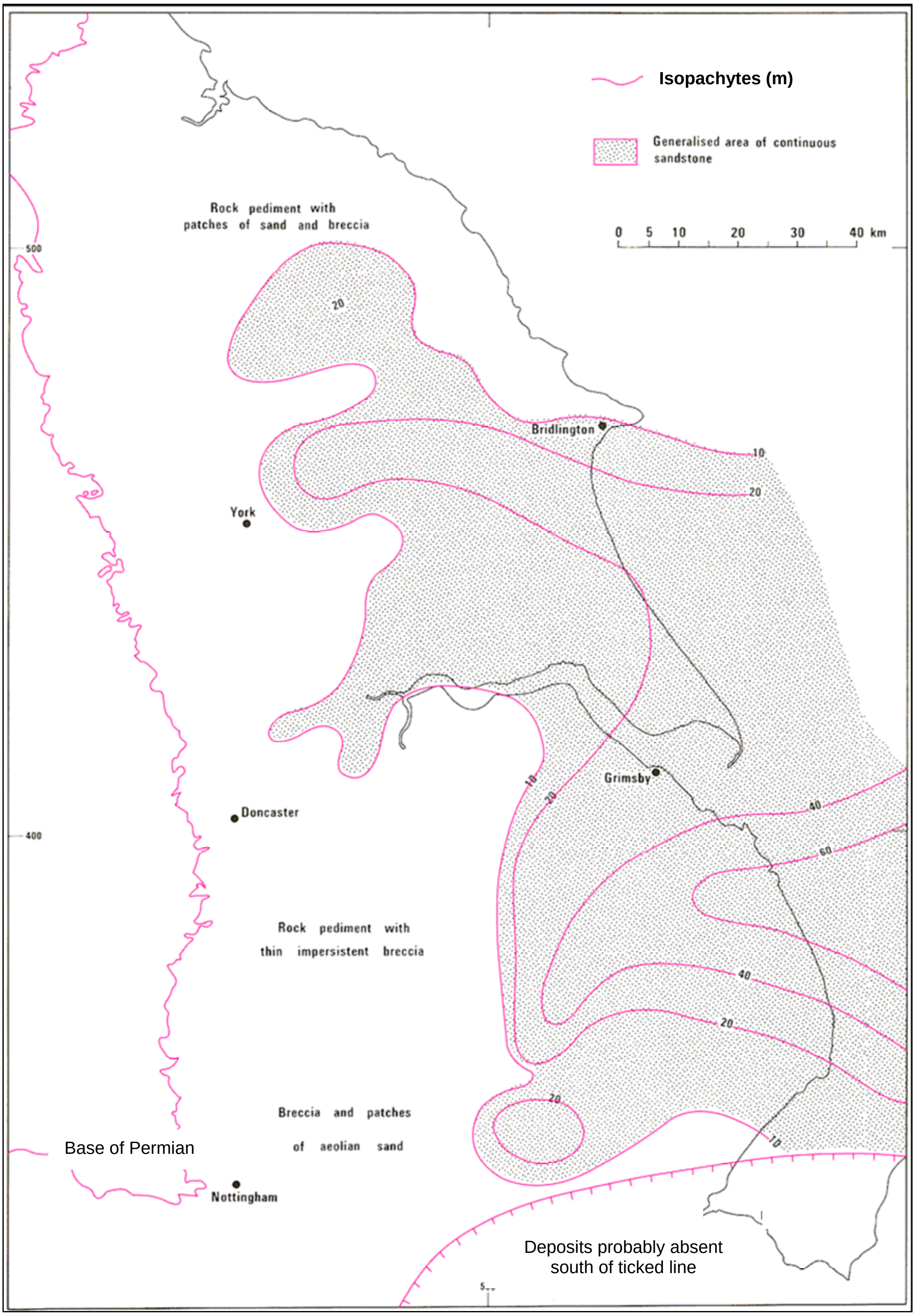


Figure 4.3. Isopachytes and lithofacies of the Basal Permian Sands and Breccia in the East Yorkshire and Lincolnshire Basin (m). [Source: Downing and Gray, 1986]

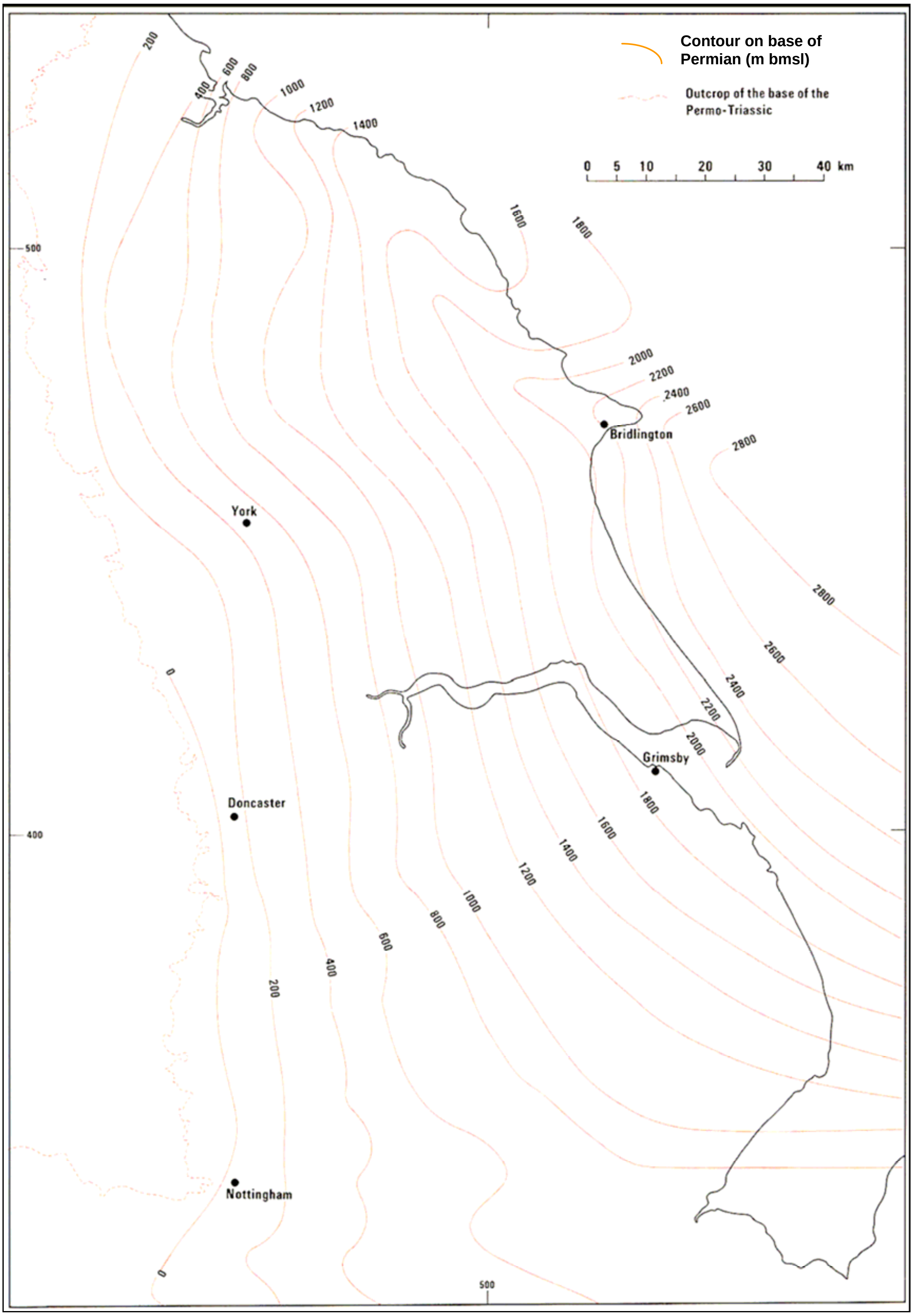


Figure 4.4. Structure contours on the base of the Permian in the East Yorkshire and Lincolnshire Basin (m bmsl). [Source: Downing and Gray, 1986]

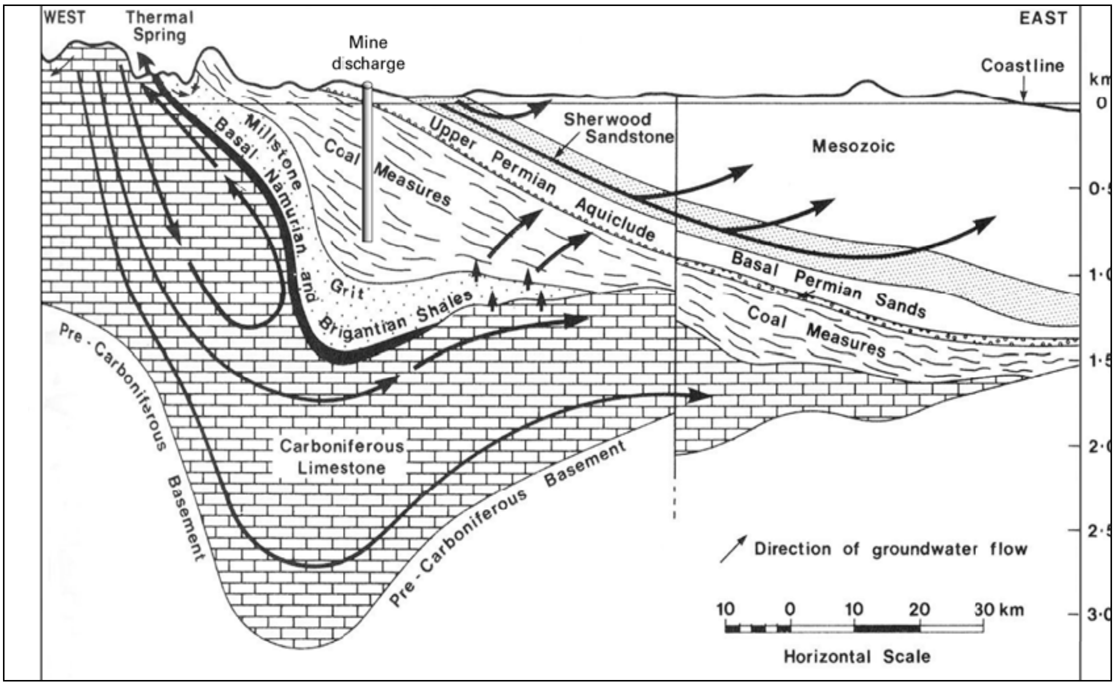


Figure 4.5. Schematic cross-section through the East Midlands showing the principal directions of groundwater flow. [Source: Downing et al., 1987]

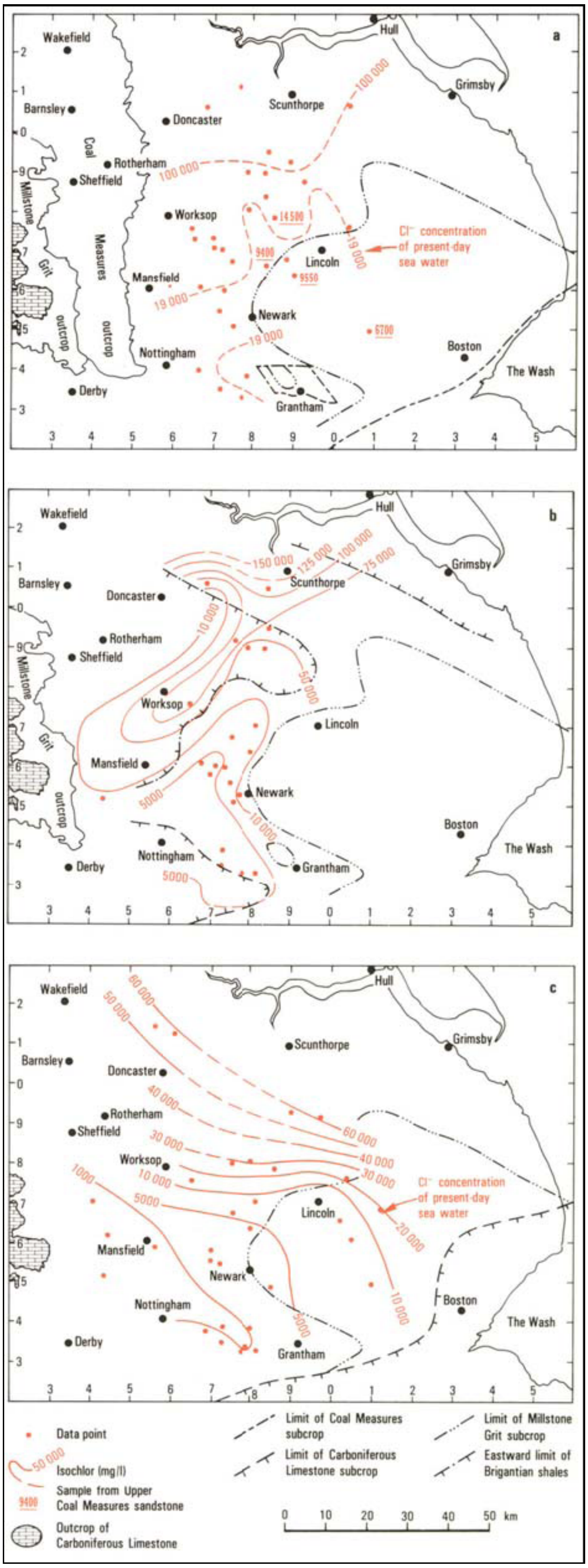


Figure 4.6. Chloride concentration (mg/L) of groundwaters from the Carboniferous of the East Midlands. a) Coal Measures, b) Millstone Grit and c) Carboniferous Limestone. [Source: Downing and Gray, 1986]

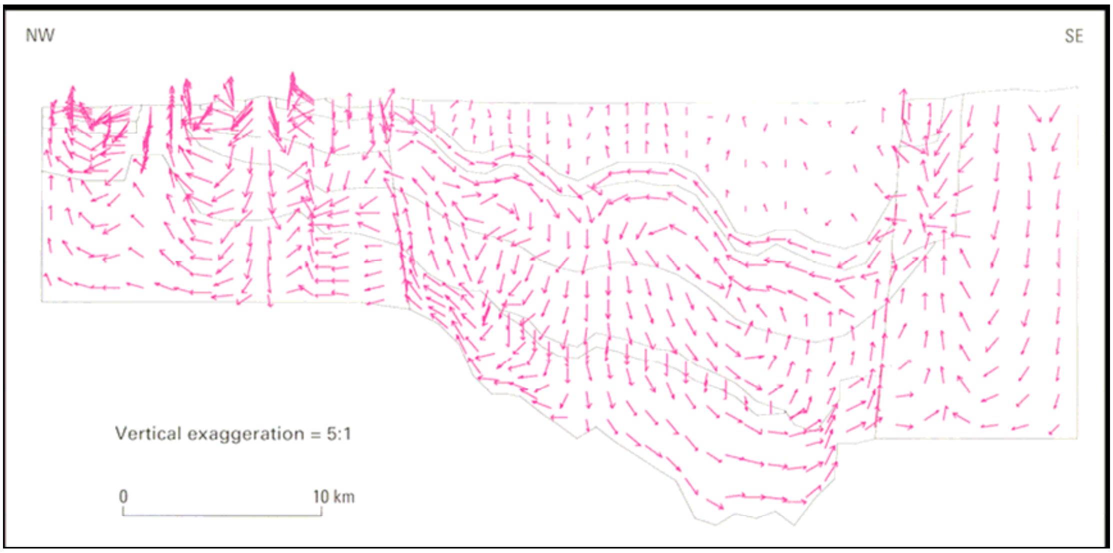


Figure 4.7. The Darcy flow field represented by logarithmically scaled vectors for a source zone in the lower part of the Mercia Mudstone Group with a brine density of 1050 kg/m$^3$. [Source: Plant et al., 1999]

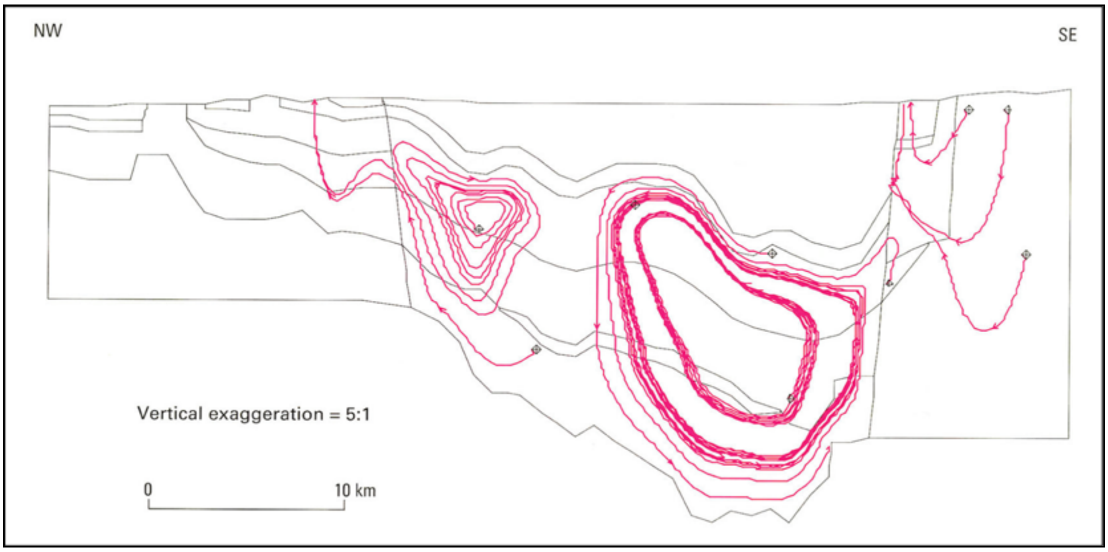


Figure 4.8. The Darcy flow field represented by a selection of particle pathlines for a source zone in the lower part of the Mercia Mudstone Group with a brine density of 1050 kg/m$^3$. [Source: Plant et al., 1999]

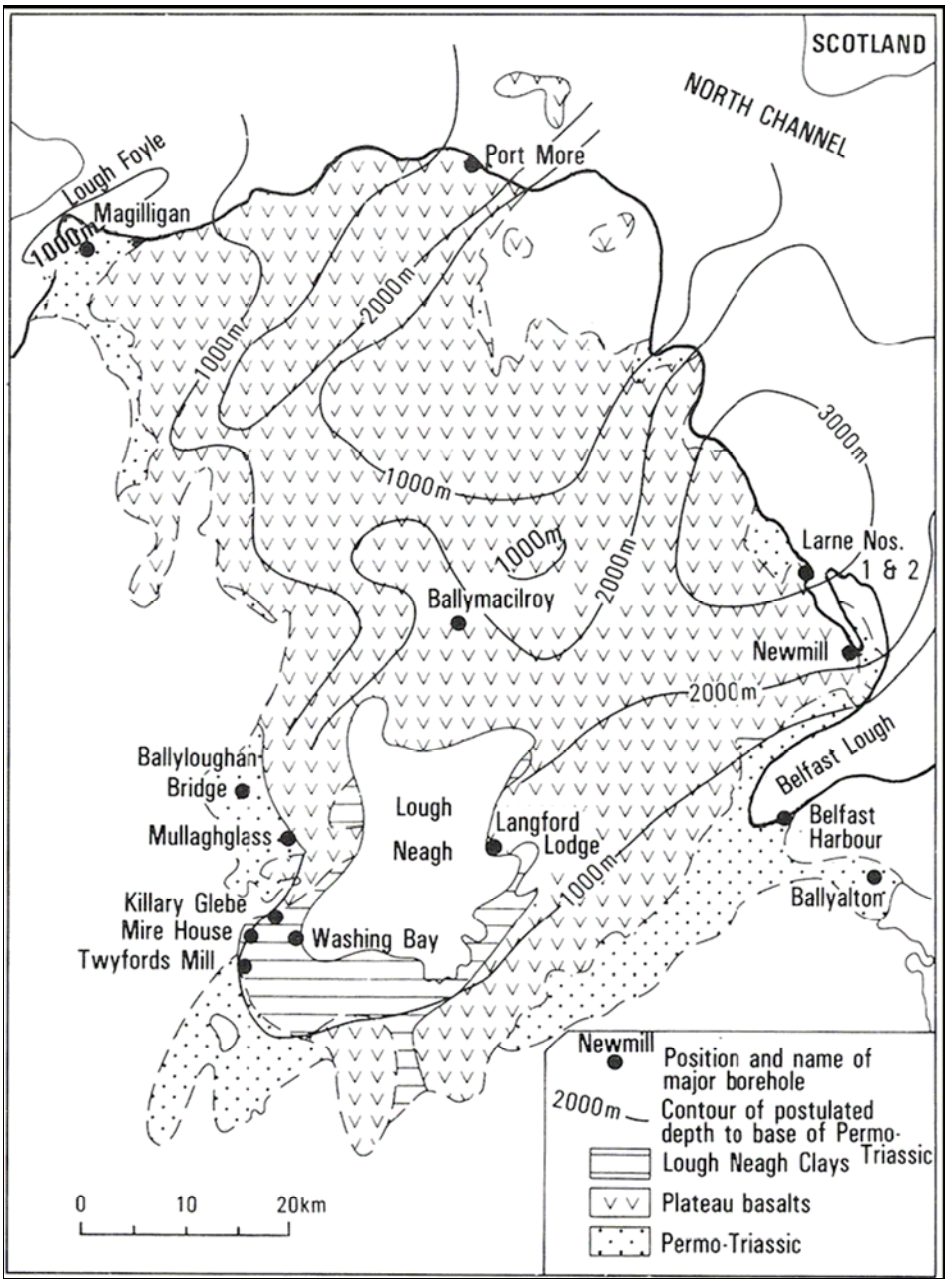


Figure 4.9. Permo-Triassic basins in Northern Ireland. [Source: Downing and Gray, 1986]

# 5 Near Off-Shore Brine Basins

GA Kirby

This chapter provides an assessment of the locations of dense brine bodies present in the near offshore area of the UK, within 40 km of the coast, to depths of up to about 2km. Information on brine contents is primarily restricted to fluids in known and potential hydrocarbon reservoir rocks, dominated by sandstones of the Permo-Triassic succession, but also including Carboniferous sands. The evidence on which knowledge of the locations of these dense brine bodies is based is explained and levels of confidence assigned to this knowledge evaluated. However it is stressed that it is possible that brines will be found at depth anywhere in the deep subsurface and particularly in low permeability rocks. There is however no data to detail this. Of the low permeability rocks, the Mercia Mudstone Group in particular is likely to be brine bearing, as it is onshore; it is less likely that Jurassic mudstones are significantly brine bearing, even where deeply buried as in Cardigan Bay. There is no data for brines in basement rocks; it is thought that they are only likely to have a possibility of being brine bearing where they are in contact with overlying salt bearing sedimentary formations.

## 5.1 SOURCES OF INFORMATION

The information used in compiling this section of the report comprised the following:

- United Kingdom Offshore Regional Reports:

  The Central North Sea (Gatliff et al; 1994);

  The English Channel (Hamblin et al; 1992);

  The western English Channel and its western approaches (Evans; 1990);

  Cardigan Bay and the Bristol Channel (Tapppin et al; 1994);

  The Irish Sea (Jackson et al; 1995);

  Malin and Hebrides (Fyfe et al; 1993);

  The Hebrides and West Shetland (Stoker et al; 1993).

- UKOOA report (Johnson et al; 1994).
- GESTCO report (Brook et al; 2003).
- The Millennium Atlas: Petroleum Geology of the central and northern North Sea (Millennium Atlas)
- Geological Society Memoir 14. United Kingdom Oil and Gas Fields. 25 Years Commemorative Volume (Abbotts; 1991).
- Geological Society Memoir 20. United Kingdom Oil and Gas Fields. Commemorative Millennium Volume (Gluyas and Hichens; 2003).

The principal source of information on brine contents is the Geology of the North Sea summary volumes, which detail the salinity of formation waters in producing fields offshore. These values can be considered to be accurate and reliable. These fields are concentrated in the North Sea and Irish Sea and of these, there are only a small number with such information within 40 km of the coast (Table 5.1). There was no information on salinities available to this study in other offshore areas. However, detailed examination of individual well records and geophysical logs may provide a significant amount of additional data.

Table 5.1: Salinity measurements in Hydrocarbon fields (from summary tables in Geological Society Memoirs 14 (Abbotts; 1991) and 20 (Gluyas and Hichens; 2003))

| **Area** | **Field** | **Type** | **Salinity NaCl equivalent g/L (Cl. g/L)** | **Reservoir** |
|---|---|---|---|---|
| **North Sea** | Amethyst West | Gas | 145 (87) | Leman sandstone |
| | Camelot Central South | Gas | 180 (108) | Leman sandstone |
| | Rough | Gas | 200 (120) | Leman sandstone |
| | Boulton | Gas | 200 (120) | Westphalian C/D |
| | Murdoch | Gas | 200 (120) | Westphalian B |
| | Schooner | Gas | 93.7 (56) | Barren Red and Westphalian |
| | | | | |
| **Irish Sea** | Douglas | Oil | 270 (162) | Ormskirk sandstone |
| | Hamilton | Gas | 300 (180) | Ormskirk sandstone |
| | Lennox | Gas | 280 (168) | Ormskirk sandstone |
| | North Morecambe | Gas | 270 (162) | Ormskirk & St Bees |
| | South Morecambe | Gas | 300 (180) | Ormskirk & St Bees |

## 5.2 GENERAL

Permo-Triassic strata are considered to be the most likely brine bearing strata in near offshore areas; these are in many cases contiguous with onshore equivalents, which are also known locally to be brine bearing (see chapter 4). They are widely distributed offshore, with the base of these strata at depths ranging from seabed to locally 11 km in Cardigan Bay, but mostly in the range 0 to 4 km (Figure 5.1). These strata comprise an alternation of mudstones, sandstones and, locally, evaporites. The distribution of these different lithologies is locally well constrained by the extensive well, seismic and field data resulting from hydrocarbon exploration, notably in the Southern North Sea and Irish Sea, and a standard stratigraphy exists for these different areas. Elsewhere, e.g. Cardigan Bay and to the west of Scotland, the distribution of Permo – Triassic strata has been mapped on seismic, but is only poorly-constrained by well data, and hence the distribution of facies here is more uncertain.

Thick and extensive sand units occur at two principal levels, towards the base of both the Permian and the Triassic successions. The distribution of these is discussed below together with any information on salinities and relevant physical properties.

## 5.3 PERMIAN SANDS:

### 5.3.1 Southern North Sea

The **Leman Sandstone** (Figure 5.2) forms the principal gas-bearing reservoir of the southern North Sea, and is the offshore equivalent of the basal Permian Sands of the onshore east Yorkshire and Lincolnshire basin. It is an aeolian deposit and thicknesses increase in an offshore direction from less than 50m to greater than 200m. There are 19 gas fields that lie within 40 km of the coast, having a wide distribution in this zone, and salinities range from 145 to 200 g/L NaCl (Cl. 87 to 120 g/L) (average 175 g/L NaCl (Cl. 105 g/L)). Porosities range from 10 – 25%, and permeabilities 1 – 1000 mD, although values are generally in the range 100 – 200 mD (all parameters from Geological Society Memoirs 14 (Abbotts; 1991) and 20 (Gluyas and Hichens; 2003), and can be considered to be reliable level of confidence 1)). The reservoir is overlain by thick Zechstein evaporitic deposits that act as an effective seal to vertical movement of fluids and gasses.

### 5.3.2 Irish Sea

The distribution of Lower Permian strata of the Irish Sea is constrained from seismic mapping and borehole provings. Deposits infill a series of narrow approximately north south trending fault-bounded depressions concentrated on the southern margin of the Irish Sea and also southeast of the Isle of Man, with thicknesses ranging locally up to 1150m, although generally in the range 500 to 200m. Facies range from alluvial fans close to the controlling faults to aeolian deposits in the depocentres, with a generalised vertical succession of breccias at the top and base, with a commonly thick succession of aeolian and minor fluvial sandstones between. These are the equivalents of the onshore basal Permian breccias and the Collyhurst and Kinnerton Sandstones (lower part). There are no available measurements of salinities, but the stratigraphically younger and structurally higher Triassic Ormskirk Sandstones are highly saline; it is thought likely therefore that these Permian strata are also brine bearing. It is possible that estimates of salinity and porosity could be determined from an analysis of borehole geophysical logs. The reservoir is overlain by mudstones, siltstones and evaporites of the upper Permian succession which act as an effective barrier to vertical movement of fluids, except in the south where this succession is replaced by sandstones, as at Formby close onshore.

### 5.3.3 Elsewhere

The distribution of Permian sands elsewhere offshore is much less well-constrained. It is possible that the basal (upper) Permian Watcombe, Teignmouth, Netherton and Exe breccias of southwest England pass offshore into thicker aeolian deposits similar to the Dawlish sandstone onshore, and that these may be brine bearing, but their distribution is uncertain. The Permian succession in basins to the west and south of Wales is inferred and where present is thought to be thin. The few well provings reveal the presence of some thin sands, and it is possible that these will be brine bearing. Little is known of the distribution of Permian strata to the west of Scotland.

## 5.4 TRIASSIC SANDS

### 5.4.1 Southern North Sea

The Bunter Sandstone of the southern North Sea (Figure 5.3) is the onshore equivalent of the Sherwood Sandstone of the east Yorkshire and Lincolnshire basin. Although these strata have been partially flushed by meteoric waters onshore, it is considered that due to their generally greater depth and distance from crop offshore, salinities are likely to be higher. There were no direct measurements of salinity for gas fields within 40 km of the coast for this study, but fields further offshore (Esmond, Forbes, Gordan & Hewett) have values in the range 130 – 205 g/L NaCl (Cl. 78 to 123 g/L). Porosities range from 21 to 23 % in Hewett, and permeabilities of 500 mD.

The top of this sandstone lies at depths ranging from 200 to 2200m bOD, and thicknesses range up to 350m. It is overlain by the thick mudstone succession of the Mercia Mudstone Group which is likely to act as an effective seal to vertical movement of fluids. Alluvial sandstones are also present to the north, off the eastern coasts of northern England and Scotland, although thicknesses and properties are uncertain on the basis of available data.

### 5.4.2 Irish Sea

The Triassic Ormskirk Sandstone of the Irish Sea forms the principal hydrocarbon reservoir, and is highly saline, with values ranging from 270 to 300 g/L NaCl (Cl. 162 to 180 g/L) (average 284 g/L NaCl (Cl. 170 g/L)). Porosities range from 9 to 22% and permeabilities from 50 to several thousand mD. All parameters are taken from the Geological Society Memoir volumes 14 (Abbotts; 1991) and 20 (Gluyas and Hichens; 2003), and are considered to be accurate and reliable (level of confidence 1). The top of this sandstone lies at depths ranging from 250 to 3000m, and the thickness ranges up to 250m. This is the upper part of the Sherwood Sandstone Group and is more porous and thickly bedded than the remainder of this group, comprising a mixture of aeolian, fluvial and floodplain sediments. There are also significant sections of sands and conglomerates in the lower part of the Sherwood Sandstone Group, which as a whole ranges up to greater than 2000m thick, distribution being strongly fault controlled. There were no salinity measurements available for this section but values would be expected to be similarly high based on the salinity of the brines present in the Sherwood Sandstones Group rocks at Sellafield and the presence of brines at higher levels (level of confidence 3). Depositional environments ranged from aeolian to fluvial and alluvial. The Orsmkirk Sandstone is also here overlain by the dominantly argillaceous Mercia Mudstone Group that may act as an effective barrier to vertical movement of fluids.

### 5.4.3 Cardigan Bay and Bristol Channel

The Sherwood Sandstone is also known to exist in the Central Irish Sea, St Georges Channel, South Celtic Sea and Central Somerset basins, and comprises coarse-grained sandstones with interbedded mudstones. Thicknesses are thought to range up to 200m, and depths to the top up to 6 km. There is no data available on salinities to this study, but it is thought that high values are likely in the deeper parts of the basin (level of confidence 3), where saline fluids are likely to have been expelled from the overlying Mercia Mudstone into the sandstones, and, particularly because there is salt intrusion along some of the basin-controlling faults. Argillaceous Mercia Mudstone Group sediments overlie the Sherwood Sandstone.

### 5.4.4 English Channel

The Sherwood Sandstone also extends offshore from the Wessex Basin, and is likely to exist to the southwest, offshore Devon and Cornwall. As onshore equivalents are highly saline, it is thought that these sandstones offshore are also likely to contain brines. As in the onshore succession, the sandstone is overlain by the argillaceous Mercia Mudstone Group succession.

### 5.4.5 Elsewhere

Permo-Triassic rocks extend offshore to the west of Scotland. Sandstones have been identified from the few boreholes and from the limited onshore exposures. Some of these are likely to be the equivalents of the Ormskirk and lower Sherwood Sandstone Group succession of the Irish Sea, and are thought likely to be brine bearing, although there are no data to support this.

## 5.5 OTHER BRINE-BEARING SANDSTONES OFFSHORE

Sandstones in the four hydrocarbon fields in Carboniferous strata of the North Sea (Boulton, Murdoch, Schooner and Trent) are everywhere highly saline, ranging from 94 to 200 g/L NaCl (Cl. 56 to 120 g/L) equivalent. Porosities range from 10 – 13%. All parameters are taken from the Geological Society Memoir volumes 14 (Abbotts; 1991) & 20 (Gluyas and Hichens; 2003), and are considered to be accurate and reliable. Reservoirs occur as thin and variably discontinuous sands interbedded with mudstones and siltstones. Carboniferous rocks are widely distributed in the subsurface of the North Sea and possibly elsewhere in the UK and it is thought likely that all are likely to be brine bearing. Mapping of the distribution of these units was beyond the scope of this study however.

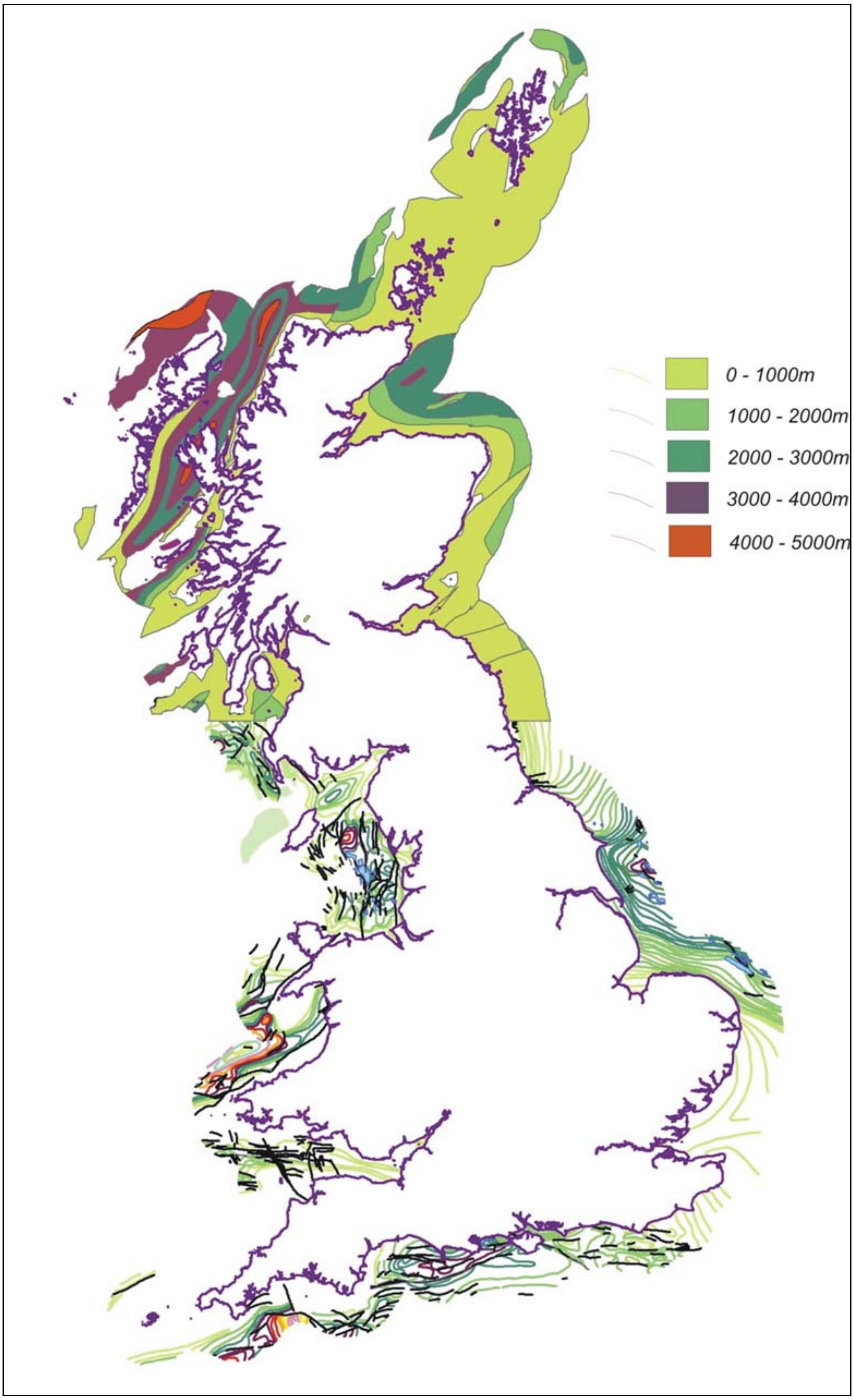


Figure 5.1: Depth to Variscan Basement within 40 km of coast (data from a variety of sources, currently being compiled by BGS). Permo-Triassic rocks lie above this unconformity surface, although may not be present everywhere. Hydrocarbon fields within 40 km of coast highlighted in blue.

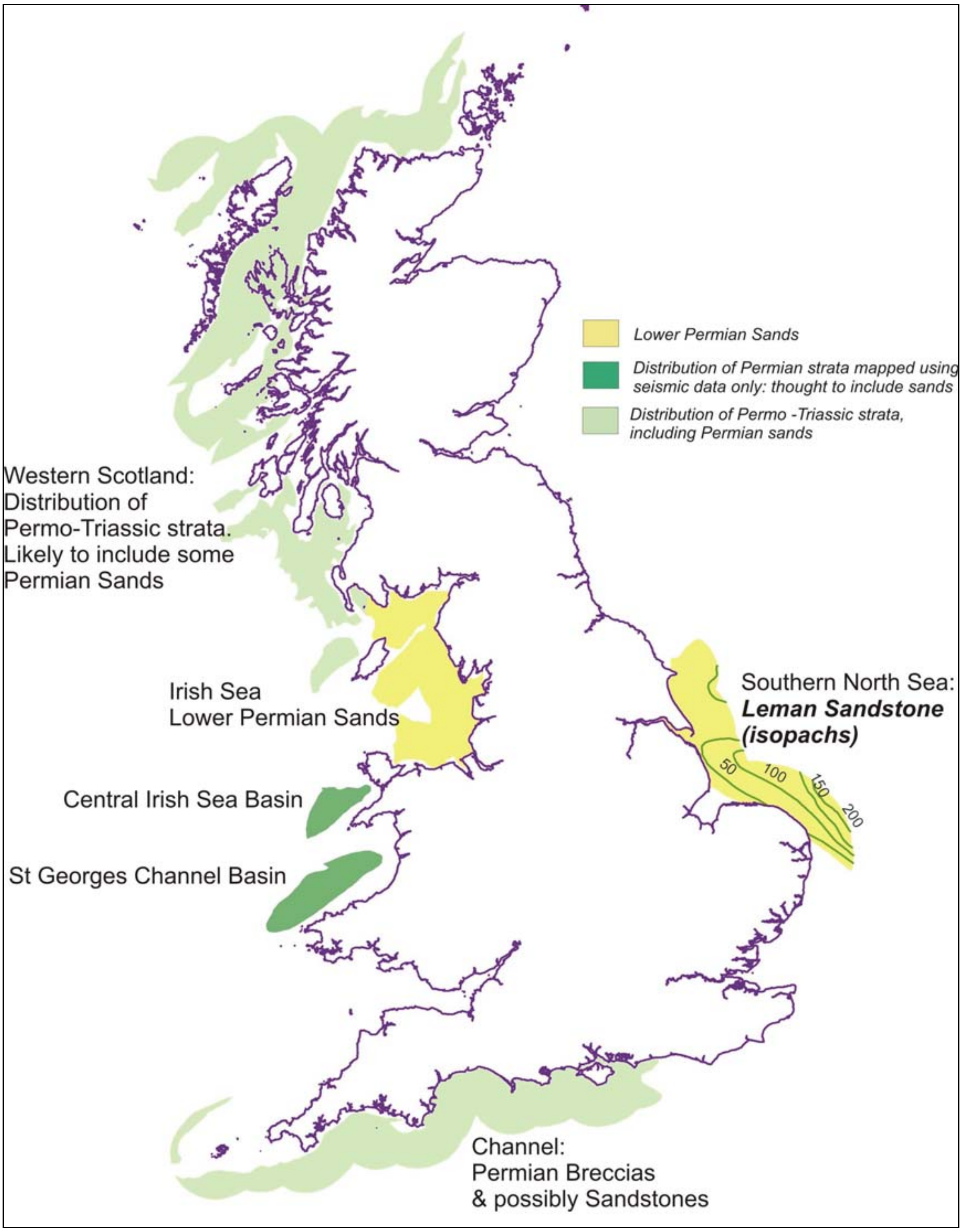


Figure 5.2: Distribution of Permian Sands within 40 km of coast. Distribution from Offshore Regional Reports.

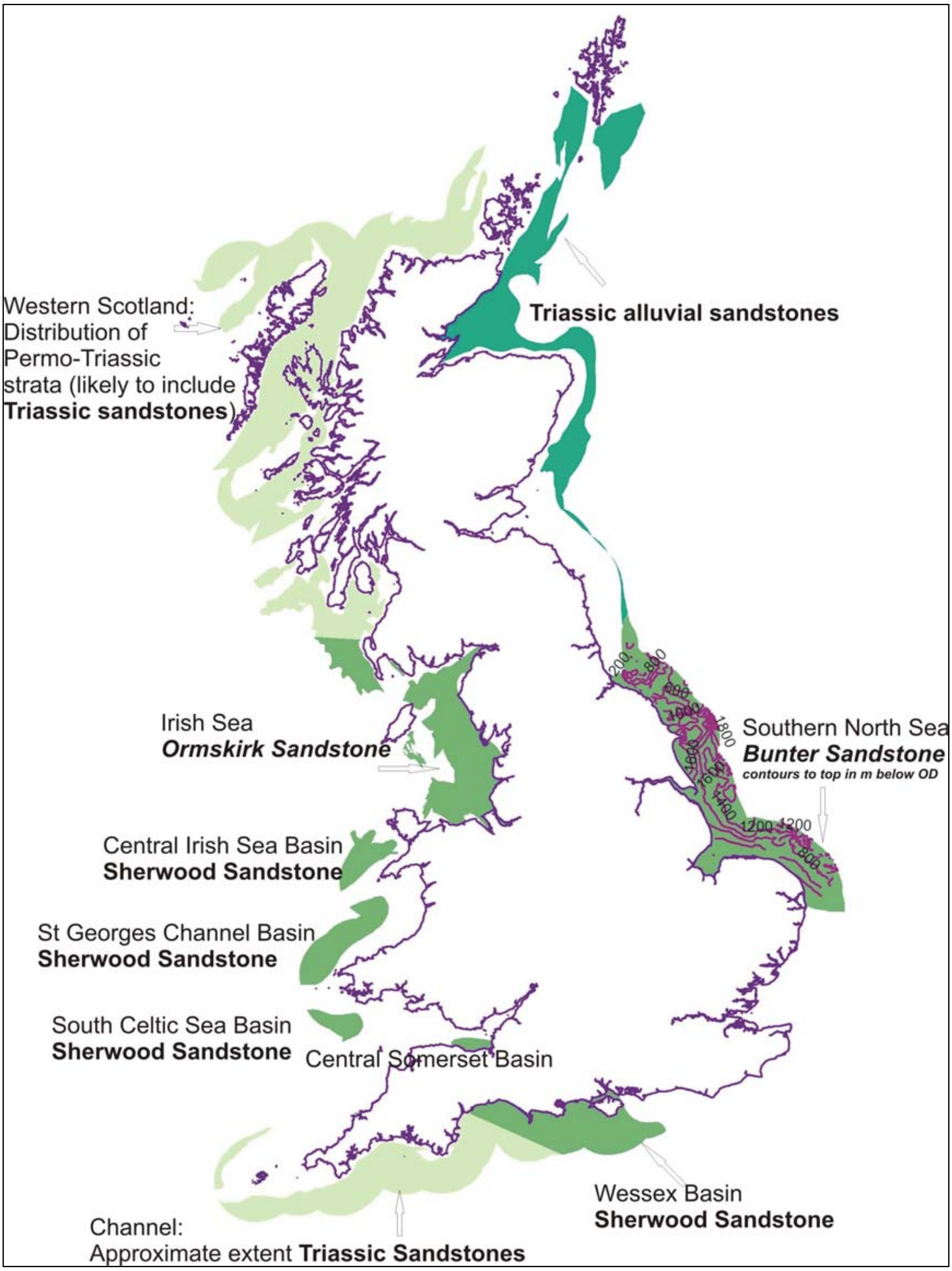


Figure 5.3: Distribution of Triassic Sands within 40 km of coast. Pale green denotes areas of Triassic strata likely to contain sandstones, dark green the principal thick Triassic sandstone with different local names and turquoise the alluvial facies mapped in the central North Sea. Alluvial facies distribution from Millennium Atlas, remainder from Offshore Regional Reports.

# 6 Additional Information to reduce uncertainty

There are two main areas where addition work using existing data sets could be undertaken to reduce some of the uncertainties. The first relates to the structural and stratigraphic understanding of the off-shore Sellafield area and would involve a re-interpretation of seismic information. The second relates to the use of mud, geological and wireline logs from, primarily, hydrocarbon exploration boreholes, to improve interpretations in the off-shore Sellafield area and for the estimation of groundwater salinities.

## 6.1 SEISMIC INFORMATION

As noted in Chapters 2 and 3 above our understanding of the off-shore Sellafield geology is largely based on seismic interpretations that were undertaken 10 to 15 years ago with little borehole control. Table 3.2 identifies a number of boreholes that post date these interpretations and a significant step in reducing uncertainty would be obtain more well information and to establish continuous seismic ties from key wells. The most useful well is likely to be 113/28a-3, which may have a succession quite representative of the target zone. However the ease of tying from this well across the target zone is uncertain as a number of quite large structures lie in its vicinity. Data from the recently drilled well 113/22-1 (Figure 3.1) would also be useful in constraining seismic picks by establishing ties from the west across the smaller northerly prolongation of the Tynwald Fault Zone. Once these ties are established the target zone could be mapped in detail, concentrating on the seismic stratigraphy of the Mercia Mudstone Group, intra-formational structure, possible velocity pushdown effects and seismic attributes. In conjunction with the control provided by the additional boreholes, the current 2D seismic grids held by Nirex (Figure 3.8) are probably sufficient to do this and some additional detail could be extracted by reprocessing and reinterpretation of the existing seismic data.

A detailed assessment of halite occurrences at an analogue site such as Walney Island, where a number of close-spaced wells have been drilled, may cast further light upon the possible configuration of halites in the target zone.

More specialist processing work, which would require access to pre-stack datasets and associated recording geometry information, could be undertaken to further improve understanding in the area. This could include:

- Reprocessing of selected seismic lines to improve shallow imaging (improved noise rejection, muting, velocity analysis, deconvolution, migration if appropriate). As well as improving imaging of the MMG succession, this should also benefit imaging of the Quaternary channel system, and be helpful in evaluating the abovementioned velocity-induced artefacts.
- A more ambitious step would be to perform trace inversion on selected seismic lines, with the aim of explicitly deriving acoustic properties characteristic of halite. In principal, trace inversion could extract halite occurrences from seismic data but this requires carefully conditioned datasets, with preserved reflection amplitudes, and also requires good well

calibration. In practice its efficacy would be seriously compromised by the absence of a well in the target zone.

A new seismic interpretation, during which the availability of newer data and its purchase could be investigated, in conjunction with the control provide by the additional boreholes will reduce the depth uncertainties associated with the stratigraphic surfaces noted in Chapter 2.

## 6.2 BOREHOLE INFORMATION

As well as the importance of information from the boreholes noted in section 6.1 to control any new seismic data interpretation that is undertaken to improve confidence in the geological understanding in the off-shore Sellafield area, if available detailed log information for well 113/28a-3 would be invaluable in confirming the interpretations of the Mercia Mudstone Group succession presented in this report. If no direct measurements are available from this borehole estimates of groundwater salinity in the Ormskirk and St Bees Sandstones could be derived from geophysical wireline logs.

For the rest of the UK land mass and near off-shore area a detailed examination of individual borehole records and wireline geophysical logs could be undertaken and should provide a significant amount of additional data on the broader distribution and chemical composition of brines both on and off shore. As well as the probability that there are direct determinations of salinity available that have not been available for this study the geophysical logs can be used to derive estimates of groundwater salinity. Clearly it is impractical to try and examine all relevant borehole records but a study targeted at appropriately sited boreholes should provide useful data. It should be noted that BGS does not hold all borehole information and some information that we hold is confidential and thus any such study, particularly involving more recently drilled boreholes, is likely to require approaches to third parties.

# Appendix 1 Levels of Confidence

Where appropriate, throughout this report the uncertainty of the interpretations and statements provided has been assessed and reported as a Level of Confidence based on the 6 categories, defined in the table below, developed by Nirex and BGS for this project.

| Level of Confidence | Data | Interpretation |
|---|---|---|
| 1 | Direct data available from the study area | High confidence derived from the availability of a consistent and coherent interpretation of the data |
| 2 | Direct data available from the study area | Low confidence derived from uncertainty over interpretation |
| 3 | Data only available from analogue area | High confidence - coherent and consistent. Confidence that the data can be applied to the study area |
| 4 | Data only available from analogue area | Low confidence - uncertainty over whether data can be applied to the study area |
| 5 | No data available | Expert judgement can be applied with confidence |
| 6 | No data available | Low confidence. Expert judgement is ambiguous |

# Glossary

| | |
|---|---|
| BGS | British Geological Survey |
| MMG | Mercia Mudstone Group |
| OD | Ordnance Datum |
| TD | Total Depth |
| TDS | Total Dissolved Solids |
| TWTT | Two Way Travel Time |

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