SEALING CAPACITY OF THE MERCIA MUDSTONE GROUP IN THE EAST IRISH SEA BASIN: IMPLICATIONS FOR PETROLEUM EXPLORATION

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In the East Irish Sea Basin of the UK Continental Shelf, hydrocarbon accumulations in the Triassic Sherwood Sandstone Group (SSG) are sealed by the Triassic Mercia Mudstone Group (MMG). The MMG comprises alternating mud- and halite-dominated intervals. Where halites overlie the SSG (e.g. in the Morecambe and Millom gasfields), seal integrity is excellent; however, where the SSG is overlain by mudstones of the MMG (e.g. in the Douglas and Lennox oilfields), seal integrity is variable and is controlled by the capillary entry pressure of hydrocarbons into the pore network of the mudstones.

Mercury porosimetry was used to characterise the pore network of the Mercia Mudstone samples from several localities in the East Irish Sea Basin. This data was used to assess seal quality, and thus to calculate theoretical hydrocarbon column heights supportable for a given seal. It appears that the sealing quality of the MMG mudstones and siltstones varies principally with the nature of the pore-throat network. Fracture filling and pore-plugging by bitumen representing an earlier oil charge may also have improved seal integrity by blocking pore throats.

INTRODUCTION

The East Irish Sea Basin is a relatively mature hydrocarbon province which includes the *Morecambe* and *Millom* gasfields in the north and the *Lennox* and *Douglas* oilfields in the south (Fig. 1), together with several other as-yet undeveloped discoveries. Many untested exploration leads remain in this area, where reservoir rocks are present in the Early Triassic Sherwood Sandstones sourced from the Carboniferous Hollywell Shale and its equivalents of the Namurian Bisat Group (Fig. 2). A regional seal is provided by the Triassic Mercia Mudstone Group (MMG). This paper focuses on a quantitative assessment of the sealing potential of the MMG, which is considered to be one of the key areas of uncertainty in basin exploration.

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For a detailed review of the geology of the East Irish Sea Basin, the reader is referred to Jackson *et al.* (1995) and Jackson and Johnson (1996). The present-day basin fill (Fig. 2) consists of Permo-Triassic red beds which unconformably overlie a previously uplifted, folded and eroded Carboniferous marine sequence. This uplift occurred at the end of the Carboniferous (i.e. Variscan). Post-Carboniferous extension related to Atlantic rifting led to the reactivation of north-south trending faults; major faults, such as the Formby Fault, were active syn-depositionally during the Permian. The Permian Collyhurst Sandstone Formation comprises syn-rift fluvial-alluvial sandstones at the basin margins and playa-lake deposits towards the basin centre. The Upper Permian (Manchester Marl Formation) comprises a post-rift sequence of playa mudstones and evaporites.

Rifting and subsidence continued during the Triassic with the deposition of a thick red-bed sequence. The Lower Triassic Sherwood Sandstone Group (St Bees Sandstone and Orsmkirk Formations) comprises a syn-rift, sandstone-dominated sequence of fluvial, aeolian and playa deposits. The upper part (Ormskirk Sandstone Formation) occurs basin-wide, and is the reservoir for most of the hydrocarbons found to date. The Upper Triassic Mercia Mudstone Group comprises a post-rift sequence of mudstones and interbedded evaporites deposited in ephemeral lakes. This group forms a regional seal for the Sherwood Sandstone Group across much of the basin.

The Mercia Mudstone Group consists of alternating mud- and halite-dominated members (Fig. 2). Across the basin, the overall sequence of members in the MMG varies as the halite units pinch-out towards the basin-margins.

This Permo-Triassic sequence was inverted in the Late Cretaceous — Early Tertiary during an episode of rapid thermal uplift, resulting in the removal of most of the Jurassic sediments. Although uplift also occurred during the Variscan and Cimmerian movements, the magnitude of these earlier events has been masked by the more severe Late Cretaceous — Early Tertiary inversion.

In the northern part of the basin (e.g. the *Morecambe, Millom* and *Calder* (well *110/7a-8*) gasfields), the reservoir facies (the Ormskirk Sandstone Formation of the Sherwood Sandstone Group) is directly overlain by the Fylde Halite Member of the Leyland Formation at the base of the Mercia Mudstone Group. This halite provides an excellent hydrocarbon seal. The Fylde Halite Member pinches out southwards; there, the Sherwood Sandstone Group is capped by the Ansdell Mudstone Member of the Leyland Formation. This unit has questionable and variable sealing capacity. Several exploration wells have encountered hydrocarbons within these mudstones, indicating that they do not behave as a perfect hydrocarbon seal. For this study, core material was utilised to make a preliminary appraisal of variation in seal integrity across the basin. Mercury porosimetry measurements on MMG cuttings from across the basin provided a more detailed picture of MMG seal integrity than that provided by the preliminary core-based studies.

MERCIA MUDSTONE GROUP STRATIGRAPHY

The East Irish Sea Basin underwent subsidence during the Mid-Late Triassic (Ziegler, 1990), and represents the thickest depocentre for the Mercia Mudstone Group. Subsequent erosion, coupled with the fact that most wells have been drilled on relative highs, means that only the lower and middle parts of the Group have been penetrated. These wells indicate a maximum thickness of 2,030m, although seismic reflection data indicate that up to 3,200 m of Mercia Mudstone Group is preserved in the Keys Sub-basin in the northern part of the East Irish Sea Basin (Fig. 1).

The Mercia Mudstone Group was deposited in an extremely low-relief setting; there were alternating episodes of halite precipitation and deposition of lacustrine laminae, coupled with the intermittent deposition of fine-grained aeolian loess. Halites are more common and thicker in the northern part of the basin. Arthurton (1980) and Wilson (1990) concluded that during periods of halite deposition, brine pans occupied the centre

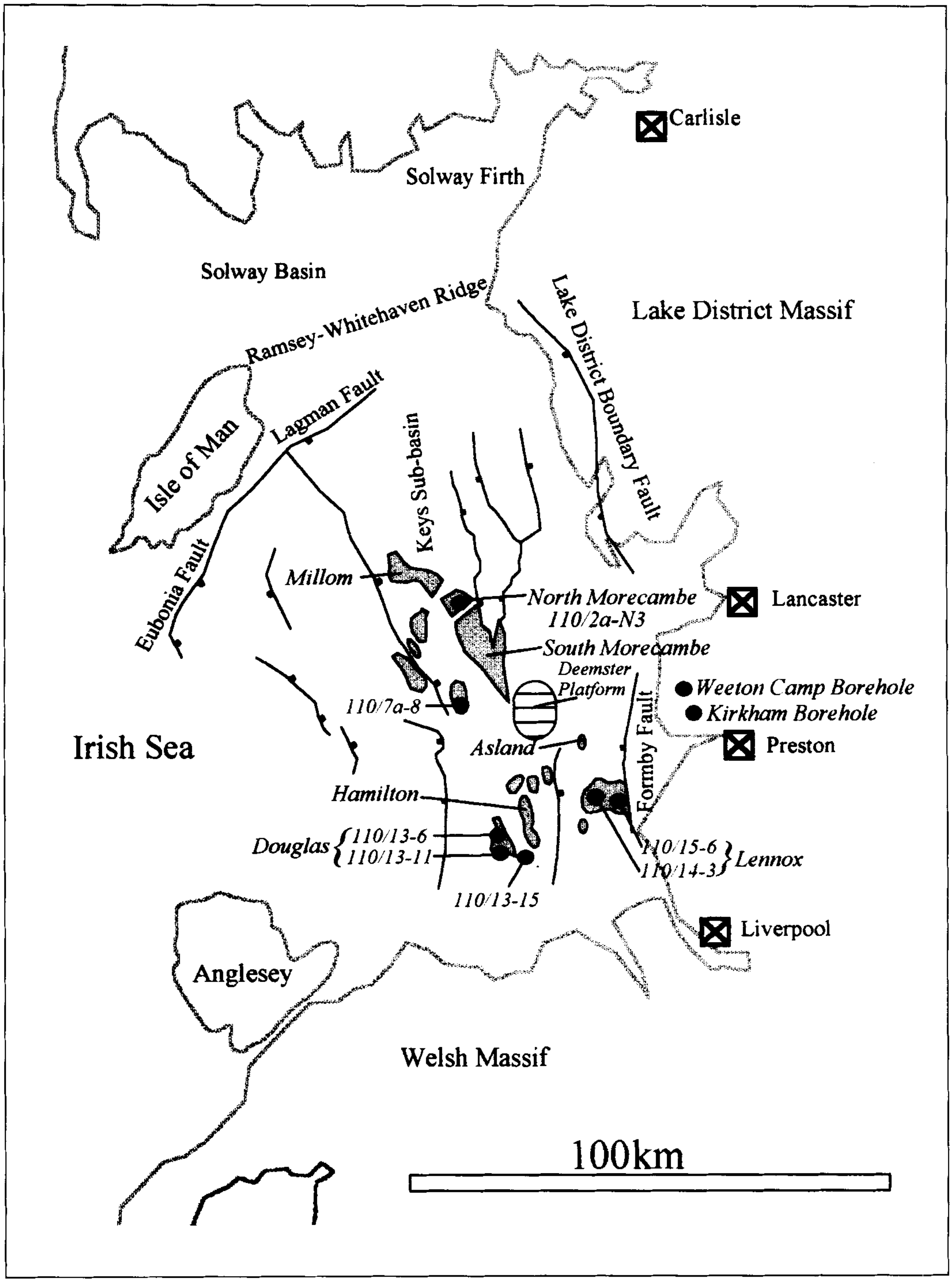


Fig. 1. Regional map of the East Irish Sea Basin showing major hydrocarbon discoveries (shaded), principal basin-bounding faults, and wells from which core has been examined (dark, shaded circles).

of the basin, and interfingered laterally with large, shallow lakes within which thinly-interbedded, red-green siltstone and mudstone laminites accumulated. Massive, red mudstones were deposited around the lakes, and are interpreted to represent wind-blown loess (Arthurton, 1980; Wilson, 1990).

The Mercia Mudstone Group is poorly fossiliferous, and its subdivision is consequently based solely on lithostratigraphic boundaries (Warrington *et al.*, 1980) (Fig. 2). This stratigraphy is based mainly on that known from the Fylde area of NW Lancashire (Evans and Wilson, 1975; Warrington *et al.*, 1980), and has been reconstructed from an extremely faulted sequence which is further complicated by halokinesis. Faulting and salt movement makes correlation of the MMG difficult. The areal extent of individual halite members increases upwards within the MMG (Fig. 3). In the following section, the MMG sequence is briefly described from bottom to top:

The Leyland Formation comprises seven alternating mudstone and halite members, and overlies the Sherwood Sandstone Group across the basin. In relatively unfaulted sections so far drilled, it has a maximum thickness of 594m. The halite members pinch-out towards the basin margins, and pass laterally into the informally-defined L1 and L2 units of the Leyland Formation. The L1 unit consists of micaceous siltstones at the base which pass upwards into mudstones; the unit shows a distinctive upward-decreasing gamma-ray profile. The L2 unit consists of interbedded red mudstones and siltstones with thin sandstones, limestones and dolomites.

The Stanah Member caps the SSG in the basin centre, and consists of a silty or dolomitic interval up to 15-m thick into which hydrocarbons have seeped locally (e.g. in the *North Morecambe* field). Its silty nature and the presence of gas "shows" indicates that the member is not a good hydrocarbon seal. The Stanah Member is confined to the northern and central part of the East Irish Sea Basin (Fig. 3).

Overlying the Stanah Member is the Fylde Halite Member, which is up to 182-m thick and comprises halite with mudstone intercalations; it is restricted to the north and centre of the basin (Fig. 3).

The overlying Ansdell Mudstone Member is 42- to 82-m thick, and comprises a relatively thin unit of dominantly red-brown mudstones with rare siltstones and halites. The Ansdell Mudstone is both over- and underlain by halite-dominated members (the Fylde and Rossall Members), and is restricted to the north and centre of the basin. Beyond the limits of the Fylde Halite Member, the Ansdell Mudstone Member passes laterally into the upper part of the dominantly grey L1 mudstones of the Leyland Formation.

The Ansdell Mudstone is overlain by the Rossall Halite Member which is up to 148-m thick, and which comprises four principal halites separated by thin, laterally-persistent mudstones with rarer siltstones and anhydrites. The halites thin southwards, and pass laterally into thin dolomitic siltstones. The Rossall Halite is absent in the southern part of the basin (Fig. 3). Beyond the current distribution of the halite, the "equivalent" mudstones and siltstones are included in undivided Leyland Formation.

The overlying Blackpool Mudstone Member comprises a thick (99-265m) unit of red-brown, silty to micaceous mudstones. Rare, thin (1- to 4-m thick) halites and sandstones occur within this member, which is confined to the north and central part of the basin where it occurs between the Rossall and Mythop Halite Members. The Mythop Halite comprises a 51- to 241-m thick, halite-dominated sequence; the halites are separated by significant and laterally persistent mudstones with minor siltstones, sandstones, dolomites and anhydrites. This member has the highest percentage of mudstone of any of the Mercia Mudstone Group halites.

The Cleveleys Mudstone Member varies from 117m to 503m in thickness, and forms the uppermost member of the Leyland Formation. It consists of interlaminated green and red silty mudstones and siltstones with local halites in the north, passing southwards to similar mudstones and siltstones with thin dolomites, limestones and sandstones.

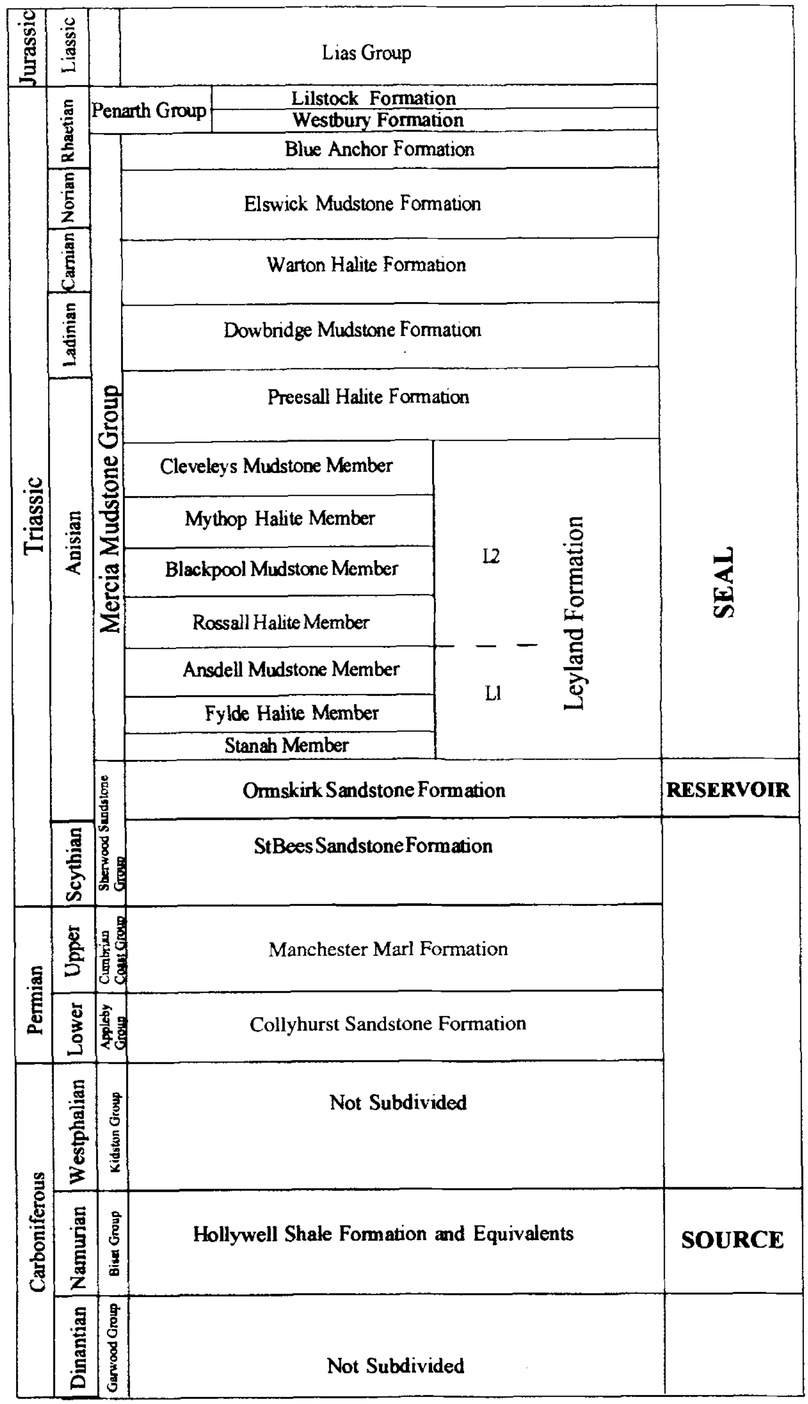


Fig. 2. Schematic stratigraphic column for the East Irish Sea Basin (after Jackson and Johnson, 1996).

The remainder of the Mercia Mudstone Group comprises five formations, which are, from bottom to top, the Preesall Halite, Dowbridge Mudstone, Warton Halite, Elswick Mudstone and the Blue Anchor Formation (Fig. 2).

The Mercia Mudstone Group has been deformed by folding, faulting and halokinesis. Thus the distribution of halite members within this Group, mapped using composite log data, can only be used as a general guide to the extent of the different sealing sequences. Moreover, well coverage is relatively sparse in some areas, leading to some further generalisation.

MATERIALS AND METHODS

Wireline logs and cuttings data were used to subdivide the Mercia Mudstone Group into halite- and mud-dominated intervals, while Repeat Formation Test (RFT) pore fluid-pressure measurements and pressure profiles were used, in conjunction with the hydrocarbon distribution in the wells, to provide an overview of the one-dimensional seal integrity.

Since seals are rarely cored, this study has been limited to core from two offshore wells (*110/2a-N3* and *110/13-11*) and the British Geological Survey boreholes at *Weeton Camp* and *Kirkham* on the Fylde Peninsula (Fig. 1). The Stanah Member was sampled from *110/2a-N3*, while extensive core from the Ansdell Mudstones was logged, and sampled for petrography and mercury porosimetry, from *110/13-11* and the onshore boreholes. (Detailed sedimentological logs and full mercury porosimetry data are available from the authors on request.) Also, cuttings of Ansdell Mudstones from several other offshore wells in the East Irish Sea (from blocks 110/7, 110/9, 110/12 and 110/14) were sampled and analysed by mercury porosimetry, and this data was also utilised.

Sealing lithologies are those which have pore throats which are too small and too poorly connected to allow the movement of hydrocarbons. Sealing surfaces typically do not behave like an impermeable plastic sheet, but more like a fine mesh screen (Downey, 1984). A seal retains hydrocarbons only until the hydrocarbons exert sufficient buoyancy pressure to pass through the water-wet rock pores (Watts, 1987). Laboratory experiments and theory allow an exact description of seal capacity to be made (Downey, 1984; Noble *et al.*, 1993). Fundamentally, the quality of a seal at a given time is determined by the minimum pressure required to displace connate water from pores or fractures in the seal, thereby allowing hydrocarbon leakage. This minimum entry pressure (or "capillary entry pressure") thus describes the buoyancy pressure of the hydrocarbon phase in a reservoir which must be attained to allow hydrocarbons to penetrate through an adjacent surface.

The buoyancy forces of a hydrocarbon column in a static accumulation are given by the product of the hydrocarbon column height, and the difference in density between the hydrocarbon and the reservoir pore water. For the rock to behave as a seal, the buoyancy forces must be matched or exceeded by the resistance of the capillary entry pressures which characterize the pore structure of the adjacent lithology.

The displacement pressure necessary to force hydrocarbons through various rocks under specified conditions of temperature and pressure can be measured in the laboratory, and these type of measurements provide quantitative data about the capacity of a seal to entrap hydrocarbons. Unfortunately, such small-scale data may be of limited use for extrapolation to an entire sealing surface (Downey, 1984), because the data may not represent the weakest point in the surface. However, in the absence of a better technique, these kind of measurements are often used to assess a seal by industry researchers.

Pressure data

Repeat Formation Test pressure data were examined from the *Calder, Lennox* and *Douglas* fields, each of which has a different sealing sequence. Plots of depth *versus* pressure, with lithostratigraphy and hydrocarbon distribution superimposed, can be used

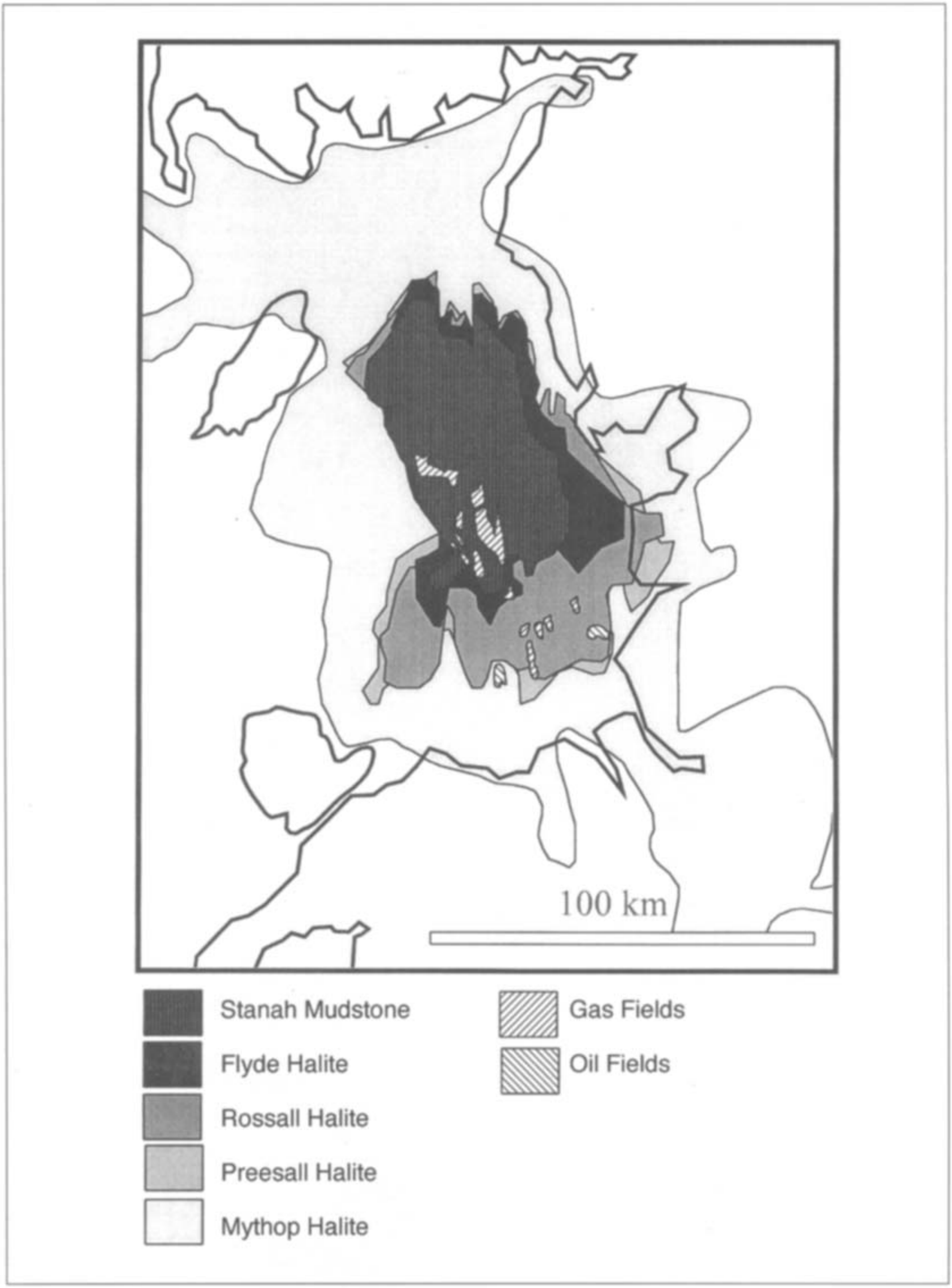


Fig. 3. Map of the East Irish Sea Basin, showing the extent of individual members of the Mercia Mudstone Group (based on wireline logs and Jackson and Johnson, 1996) in relation to oil and gas discoveries.

to illustrate how formation pressure and hydrocarbon distribution vary in response to changes in the lithostratigraphy of the overlying Mercia Mudstones (Fig. 4).

Mercury porosimetry measurements

Mercury injection porosimetry was performed on six Mercia Mudstone samples from wells *110/13-11* (one sample), *110/2a-N3* (three samples) and the *Weeton Camp* and *Kirkham* boreholes (one sample each). These data are used to assess the ability of the mudstones to support hydrocarbons in different parts of the East Irish Sea Basin.

Pore-size distribution and threshold capillary entry pressures were determined for each sample. One-inch core plugs were taken perpendicular to the bedding, and were oven dried at 100°C. The samples were sealed on all sides except one with epoxy resin in order to constrain the pore size of these thin beds. Mercury injection threshold pressures were used to calculate the theoretical height of hydrocarbon column supportable by a given seal. Such data can be used to classify seals, and therefore provide a method of ranking the sealing capacity of a given lithology using the classification scheme summarized in Table 1.

Table 1. Seal classification scheme (after Sneider *et al.*, 1991).

Class of Seal	*Air/Hg Capillary Entry Pressure (psia)*	*Oil Column Height (m)*	*Gas Column Height (m)*
A	>1,373	>305	>145
B	687-1,373	152-305	73-145
C	137-687	30-152	15-73
D	69-137	15-30	8-15
E	14-69	<<15	<<8
F	<<14	Waste zone rock	

The height of both oil and gas columns supported at hydrocarbon saturations beneath the threshold pressure were calculated for each sample using the technique described by Sneider *et al.* (1991).

RESULTS

Pressure data from the East Irish Sea Basin

RFT pore-pressure data from well *110/7a-8* in the *Calder* field are shown in Fig. 4a. All pressure measurements were made in Sherwood Sandstones that contain a gas and oil column. The pressure readings follow a typical gradient for a hydrocarbon column with overpressure increasing towards the top of the column due to hydrocarbon buoyancy. The reservoir in this well underlies a thick sequence (300m) of halites and halite-dominated mudstones. No hydrocarbon shows are reported above the top of the Sherwood Sandstone. The halite sequence therefore acts as a very efficient seal for the hydrocarbons in the Sherwood Sandstones at the *Calder* accumulation.

RFT pressure data from well *110/15-6* (*Lennox* field) are plotted in relation to hydrostatic and lithostatic gradients and the lithostratigraphy in Fig. 4b. These data show increasing pressure (relative to the regional hydrostatic gradient) towards the top of the reservoir. Composite logs indicated the presence of gas in the Ansdell Mudstones, indicating that this mudstone does not provide a completely effective seal for the gas in the Sherwood Sandstone at this location.

Well *110/14-3* on the *Lennox* field encountered the same sealing sequence as well *110/15-6* (i.e. the Ansdell Mudstone Member overlain by the Rossall Halite Member and the

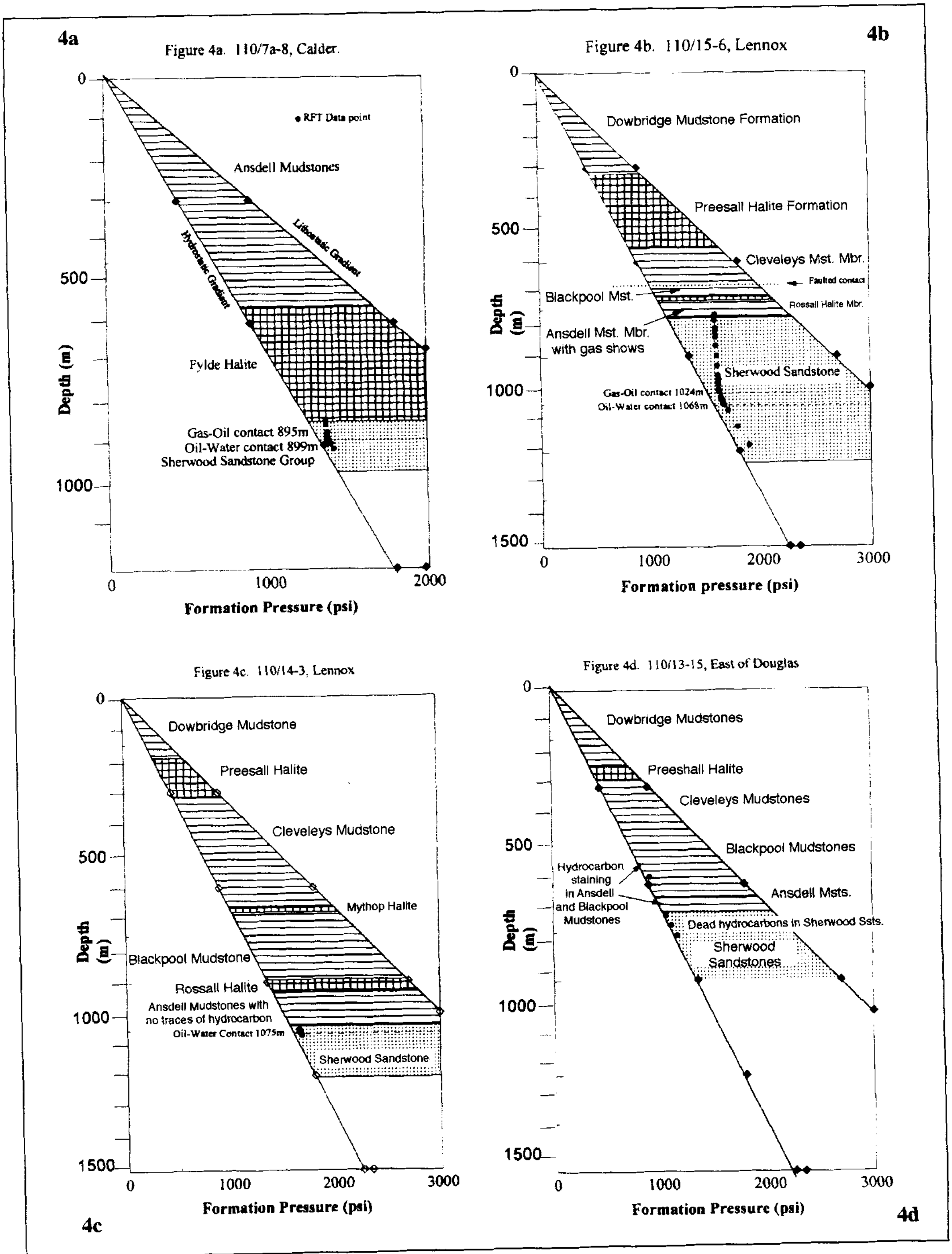


Fig. 4. Plots of repeat formation test pressure data *versus* depth with lithostratigraphy indicated: (a) well *110/7a-8* in the *Calder* field; (b) well *110/15-6* (*Lennox* field); (c) well *110/14-3* (*Lennox* field); (d) well *110/13-15* (east of the *Douglas* field).

Blackpool Mudstone Member). A gas-oil column is supported in the *110/15-6* well, and unspecified hydrocarbon shows were recorded in the Ansdell Mudstone Member. In contrast to this, well *110/14-3* encountered a thin oil column without gaseous hydrocarbons in the Ansdell Mudstone Member.

The 9-m high oil column in *110/14-3* does not appear to provide the buoyancy required to overcome the capillary entry pressures of the Ansdell Mudstones above the accumulation. The oil and gas column in *110/15-6* lies beneath an interval of hydrocarbon-stained Ansdell Mudstones. This suggests that the capillary entry pressure of the Ansdell Mudstones has at some time been exceeded by the pressure exerted by the buoyant hydrocarbon column in this area. This could have been caused by the current column or, by a previously-existing accumulation that was subsequently exhumed.

In contrast to the above wells, well *110/13-15* (east of the *Douglas* field: Fig. 4d) encountered dead hydrocarbons in the Sherwood Sandstone and hydrocarbon staining in both Ansdell and Blackpool Mudstone Members of the Leyland Formation. No halite was penetrated between the Ansdell and Blackpool Mudstones in this well. The absence of live hydrocarbons in the Sherwood Sandstones may be due to the poor sealing potential of the Mercia Mudstones. The Mercia Mudstones in *110/13-6* and *110/13-11* both show hydrocarbon stains in the Ansdell Mudstone but, in contrast to *110/13-15*, not in the Blackpool Mudstones. Consequently, where the Rossall Halite is present above the Ansdell Mudstone, it acts as a vertical seal preventing hydrocarbon migration into the overlying Blackpool Mudstone; however, where the halite is absent, the barrier to vertical fluid migration is removed, and hydrocarbons are able to migrate upwards into the Blackpool Mudstone.

Core material

Mercia Mudstone Group cores from the *Weeton Camp* and *Kirkham* boreholes and the *110/2a-N3* and *110/13-11* wells were logged. The *Weeton Camp* and *Kirkham* boreholes on the Fylde Peninsula represent the onshore equivalent of the Ansdell Mudstone Member of the offshore Leyland (L1) Formation. Differences between the onshore and offshore cores, however, may exist due to facies variations across the basin and due to variations in compaction and cementation caused by different burial histories.

Well *110/2a-N3*

(i) Core description

This well was drilled by British Gas Exploration and Production on the *North Morecambe* field, and Mercia Mudstone core from 1,973 to 1,979m was examined. Core from the base of the Stanah Member comprises three units: the lowermost unit consists of brecciated mudstones within a matrix of fine-grained sandstones and mudstones; this is overlain by a very fine-grained, green mudstone; this is capped by a red mudstone (Fig. 5).

The Stanah Member in *110/2a-N3* is 6-m thick, and underlies a 250-m thick sequence of halites. A 1.8-m thick sequence of interbedded and brecciated dark-grey mudstones and pale-grey sandstones and siltstones directly overlies the Sherwood Sandstone Group. This interval shows sand injection features and soft-sediment deformation, and constitutes a poor-quality seal directly overlying the reservoir (Fig. 5). The overlying 4.5m of core comprises homogeneous mudstones. The lowermost 0.9m of this mudstone is pale green-grey in colour while the remainder of the core is deep rusty-brown/red.

(ii) Petrography

In thin section, the brecciated silty mudstone at the base of the core comprises a patchwork of very fine-grained, dark chocolate-brown mudstone and poorly-sorted, very fine- to medium-grained sandstones and siltstones with interstitial micro-dolomite rhombs. These rhombs were precipitated very early, prior to compaction, and occupy most of the

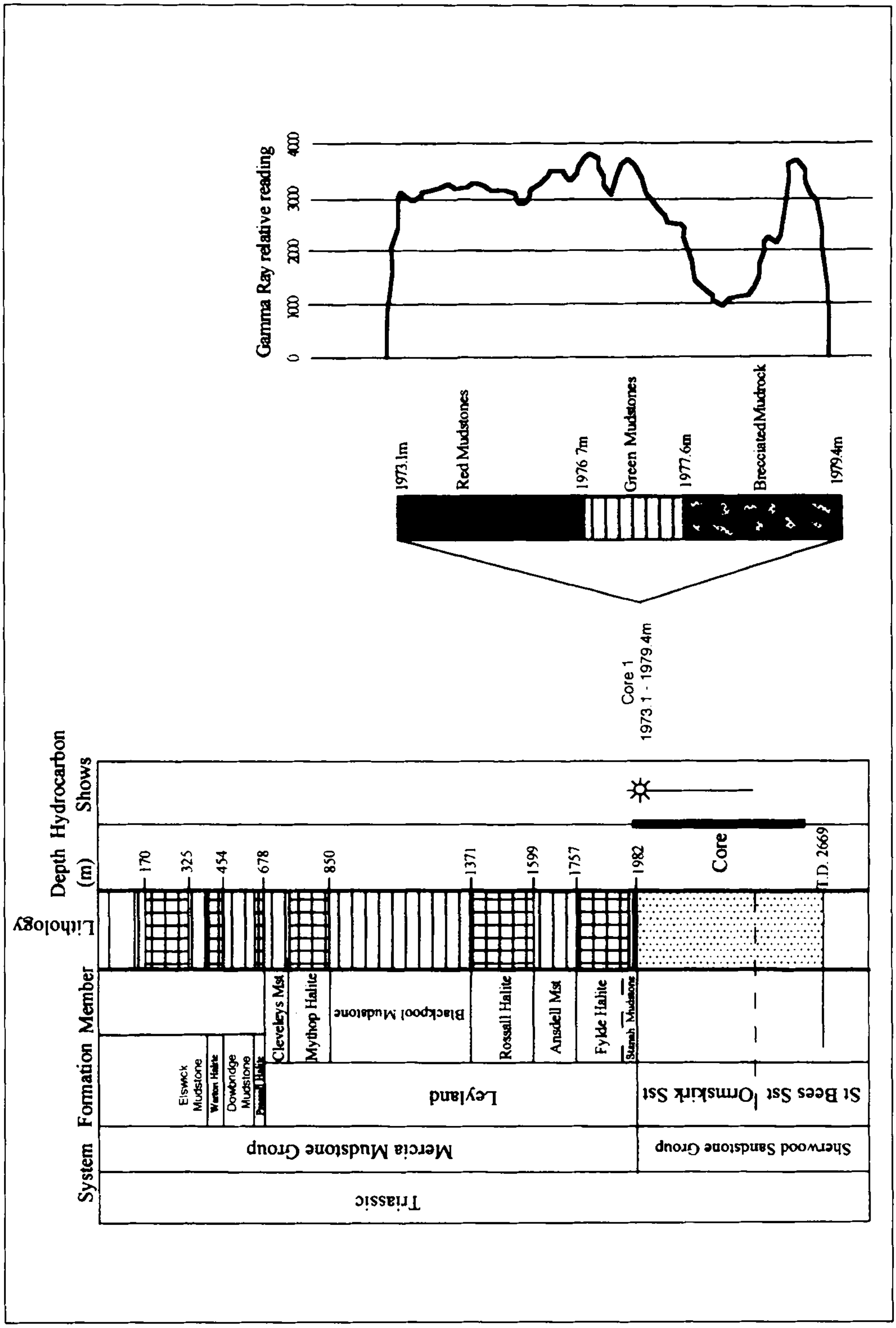


Fig. 5. Details of core examined from well *110/2a-N3*.

intergranular pore space, resulting in low porosity. The overlying mudstones vary only in colour and comprise poorly-laminated mudstones and claystones with occasional subrounded quartz grains.

(iii) Mercury porosimetry

Mercury porosimetry data from the green mudstone at 1,975.76m (Fig. 6a) show that the sample has a peak pore-throat size of 0.003 microns and a threshold pressure of 17,700 psi. Mercury porosimetry data from the red mudstone at 1,975.31m (Fig. 6b) show a peak-pore throat size of 0.0035 microns and a threshold pressure of 17,700 psi. Measurements made on the brecciated mudrock from 1,976.52m (Fig. 6c) show a peak pore-throat size of 0.0045 microns and a threshold pressure of 15,600 psi.

Weeton Camp borehole

(i) Core description

This borehole was drilled by the British Geological Survey in NW Lancashire on the eastern margin of the East Irish Sea Basin, and the Sherwood Sandstone was encountered at a depth of 159.5 m. Mercia Mudstone core from 103 m to 159.5 m was examined and logged.

The lowermost 9m of the Mercia Mudstone Group (150-159m) comprises thinly (up to 5-cm thick) interbedded and strongly laminated mudstones and siltstones, with occasional very fine-grained sandstones and a 1-m thick brecciated mudstone. Colour varies according to lithology, with mudstones being red or green-grey, and siltstone/sandstone intervals being buff coloured. Sandstone and siltstone lenses show rippled surfaces with extensive bioturbation and occasional halite pseudomorphs around which bedding is contorted, indicating early salt dissolution and soft-sediment deformation/collapse. Above this (136-150m), the core contains grey-green massive mudstones with occasional fine-grained sandstones and siltstones. Halite pseudomorphs and angular, calcite-filled fractures are common, together with sharp-based siltstone lenses. Between 136 and 128m, grey-green mudstones dominate, and are interbedded with thin (up to 1-cm thick) siltstone stringers and one- or two-cm thick horizontal gypsum veins. Red and green mudstones with common gypsum layers and thin, silty intervals continue up to 113m. From 113 to 103m, relatively homogeneous red mudstones dominate. These contain gypsum/anhydrite layers and disseminated gypsum/anhydrite within the mudstone and in fractures.

(ii) Petrography

In thin section, the siltstone laminae contain approximately 10% visible porosity, although comparisons between these and offshore samples are tenuous due to the shallower depths of burial of the borehole samples. Mudstone and siltstone intervals are poorly-sorted and show strong compaction even at shallow depths. Poly- and monocrystalline quartz grains constitute approximately 90% of identifiable fragments in the sandstone and siltstone grade layers.

Highly birefringent flecks of interstitial gypsum/anhydrite cement are common in the siltstones adjacent to gypsum/anhydrite layers. Marked porosity variations (10% in siltstones, compared with zero visible porosity in mudstones) were observed between the mudstone and siltstone layers. These are due to variations in grain size and sorting between the layers. Vuggy pores are lined with calcite pseudomorphing a hopper-shaped mineral (probably early halite).

The red mudstones at 103-115 m contain disseminated and fracture- filling gypsum cements. Similar textures were described in the Permian Eden Shales by Shearman *et al.* (1972). This work demonstrated how the volume increase accompanying the hydration of anhydrite to gypsum resulted in fracturing, and the precipitation of gypsum in the resulting fractures.

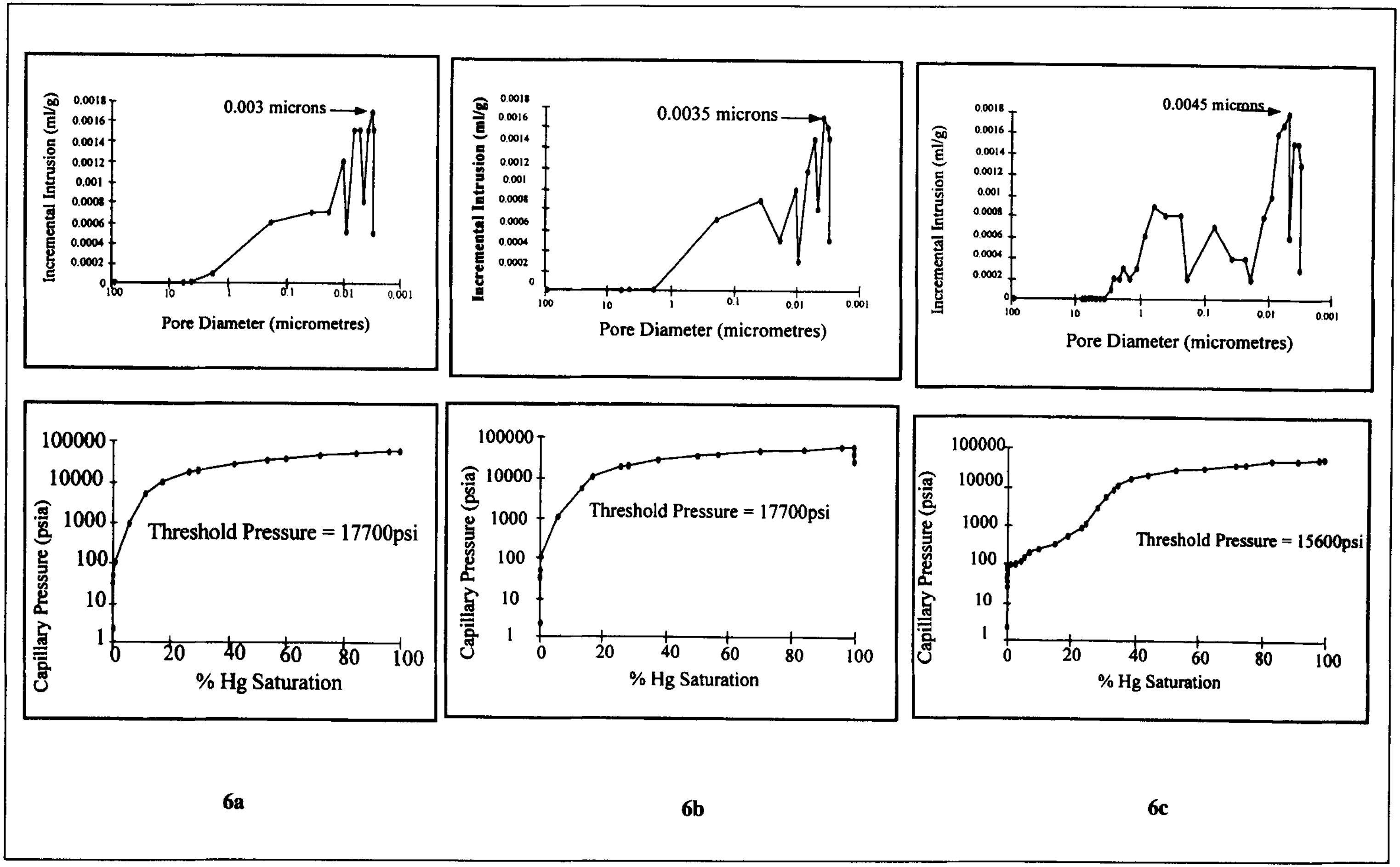


Fig. 6. Plots of Mercury Porosimetry data showing pore-throat size distributions and cumulative mercury injection curves.

(a) Stanah Mudstone Member, well *110/2a-N3* (1,975.76m). (b) Stanah Mudstone Member, well *110/2a-N3* (1,975.31m). (c) Brecciated mudrock, Stanah Mudstone Member, well *110/2a-N3* (1,976.52m).

(iii) Mercury porosimetry

Mercury injection results for the Weeton Camp mudstone sample (Fig. 6d) show that the sediment has a range of pore aperture sizes between 0.045 and 0.009 microns, with a poorly-defined threshold pressure greater than 5,303 psi. The sample was selected as representative of a typical Mercia Mudstone from this borehole.

Kirkham borehole

(i) Core description

This well was drilled by the British Geological Survey in NW Lancashire on the eastern margin of the East Irish Sea basin, and the Sherwood Sandstone was encountered at a depth of 366m. Core from the lowermost Mercia Mudstone Group (339.4-367.1m) was examined. This comprises grey-green mudstones with thin, rippled, cross-bedded sandstone and siltstone lenses (Fig. 7a). Bioturbation and load casts are common in siltier, buff-coloured intervals. Sandstone intervals are largely confined to the lower 4.5m of the MMG, while thin, laterally-discontinuous lenses of sandstone and siltstone occur above this level. Other prominent features include burrows in silty lenses, hopper-shaped voids (possibly after halite dissolution) and calcite-filled fractures which are both parallel and perpendicular to bedding in the grey-green mudstones.

(ii) Petrography

In thin section, mechanical compaction is poor and is accompanied by minor cementation in the sandstone stringers, while mudstones have undergone strong mechanical compaction and cementation by radiating, dendritic crystals of dolomite. Fractures filled with euhedral calcite and vuggy pores after halite dissolution are also present in the mudstones.

(iii) Mercury porosimetry

Mercury porosimetry for the laminated siltstones (Fig. 6e) shows a range of pore aperture sizes from 0.02 to 0.009 microns, and a poorly- defined threshold pressure greater than 5,030 psi.

Well *110/13-11*

While drilling the *110/13-11* well on the *Douglas* oil discovery, strong gas "shows" were encountered in the Mercia Mudstone Group, and consequently core was cut from the Ansdell Mudstone Member of the Leyland (L1) Formation. A summary core log for the Mercia Mudstone Group from this well is shown in Fig. 8.

(i) Core description

The Ansdell Mudstone examined is typified by a sample taken for Hg porosimetry at 775.4m (Fig. 7b), which illustrates the undeformed, highly laminated mudstones and siltstones that comprise most of the studied sequence. Other common features include burrows and rippled surfaces in the siltier intervals, and soft-sediment deformation in the siltstones and mudstones.

The core is mainly dark-grey or green/grey with some calcite-filled veins. Several mudstone intervals display strong sediment deformation and appear to be pyritized. The pyrite occurs both along thin veins and in disseminated form throughout the sediment. Desiccation cracks in the mudstones are common indicating subaerial exposure. Coarser intervals are heavily cemented (often silicified). Chocolate-brown dolomitic mudstone intervals are locally present.

(ii) Petrography

A photomicrograph of a siltstone from 776.3m is shown in Fig. 7c. Extensive interstitial cements (early anhydrite and later quartz) have occluded all porosity; these cements

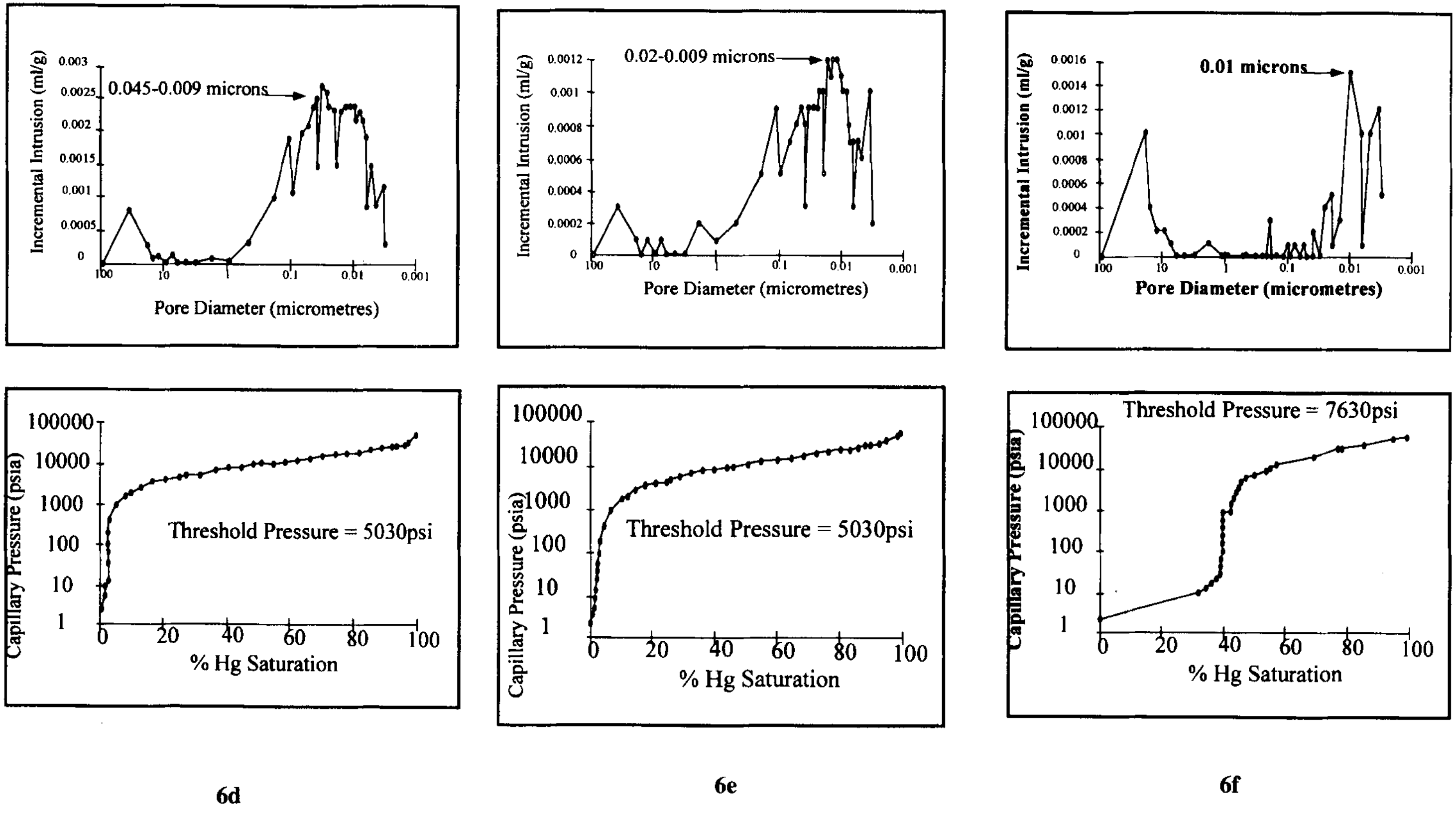


Fig. 6 (cont.). Plots of Mercury Porosimetry data showing pore-throat size distribution and cumulative mercury injection curves. (d) Ansdell Mudstone, *Weeton Camp* borehole. (e) Ansdell Mudstone, *Kirkham* borehole. (f) Ansdell Mudstone, well *110/13-11*.

appear to have been precipitated prior to mechanical compaction, as evidenced by the lack of grain-grain contacts between the relatively well-sorted and sub-rounded quartz grains.

Anhydrite occurs as an interstitial, pore-filling cement and as microcrystalline ovoid patches up to 2-3mm across. These patches are extensions of anhydrite-filled fractures. Authigenic bitumen is also present, and occurs as an interstitial and fracture-filling mineral throughout the sampled Leyland (L1) Formation. The paragenetic relationship between anhydrite and bitumen is unclear, with some examples showing anhydrite predating bitumen and others showing the reverse (Fig. 7c).

An important feature in the *110/13-11* well is the appearance of bitumen-filled fractures in both siltstone and mudstone intervals (see Figs. 7d and 7e, respectively). These fractures comprise sub-horizontal zones of anastomosing veins up to 1-mm thick and at least 15-mm long (i.e. the width of a thin section). The fractures cross-cut all the diagenetic minerals, and therefore represent a relatively late event in the paragenetic history of the samples. Fractures occur both between grains and within individual grains of quartz. Not all of the fracture network is bitumen-filled; however, it is possible that some of the fractures along which bitumen is absent were produced during sampling due to the removal of overburden stress. This is supported by the observation that these empty fractures are frequently seen to be continuations of bitumen-filled fractures (Fig. 7d).

The lack of shear or displacement along these fractures points towards their formation by pore-fluids pressure locally exceeding lithostatic pressure, causing hydraulic fracturing of the rocks. Partings formed when fluid pressures exceed the tensile strength of the host rock have been termed hydrofractures (Phillips, 1972). If this is the causative mechanism for the fractures, we may speculate that liquid hydrocarbons were present as pore fluids at the time of fracturing, because their degraded remnants (bitumen) now fill the fractures. This process relies on hydrocarbons immediately filling fractures prior to fracture closure.

(iii) Mercury porosimetry

A representative laminated siltstone sample from 775.4m had a peak pore aperture size of 0.01microns and a threshold pressure of 7,630 psi (Fig. 6f).

Regional implications

The sampled Ansdell Mudstones may not be completely representative of those present in other parts of the basin. However, they illustrate that the units overlying the Sherwood Sandstones in the East Irish Sea Basin comprise interbedded mudstones and siltstones, some of which are stained with bitumen. The presence of bitumen indicates that capillary

Fig. 7. Photomicrographs of thin sections:

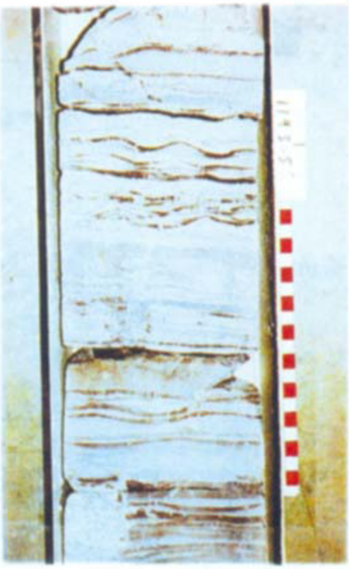
(a) Mercia Mudstone sample from *Kirkham* borehole at 363-364 m. Note interbedded very-fine sands, silts and muds, rippled surfaces (upper part) and load casts (middle part).

(b) Ansdell Mudstone Member, core sample from well *110/13-11* at 775m, showing interbedded rippled and partially bioturbated mudstones and siltstones.

(c) Silty interval in the Ansdell Mudstones of well *110/13-11* at 776.3 m. Ppl, field of view is 1.5-mm wide. Note strongly compacted, sub-rounded and partially-sutured quartz grains with interstitial anhydrite and bitumen cements. Bitumen appears to be surrounded by, and therefore to pre-date poikilotopic anhydrite.

(d) Bitumen-filled inter- and intra-grain fractures from well *110/13-11* at 776.3 m. Note that not all fractures are filled with bitumen possibly due to fracturing during section preparation. Field of view is 1.5-mm wide.

(e) Bitumen-filled, bed-parallel hydrofractures in silty mudstones from well *110/13-11* at 773.5 m. Note preferential bitumen along finer siltier (more micaceous) layers. Field of view is 1.5-mm wide.



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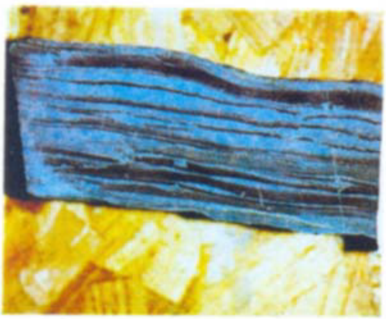

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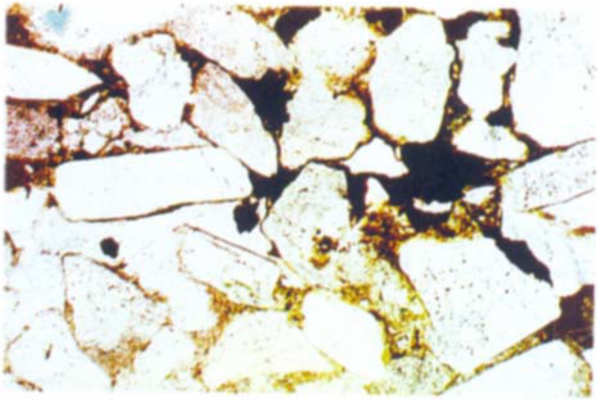

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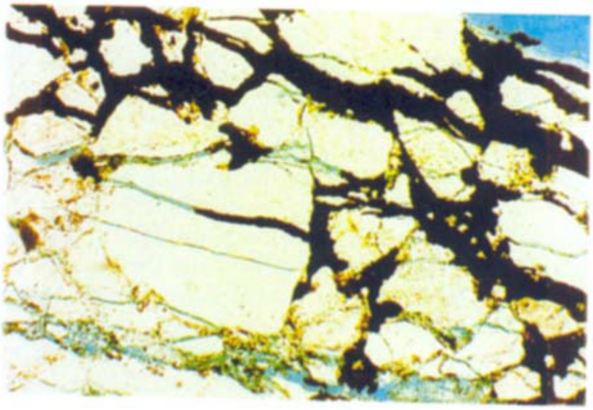

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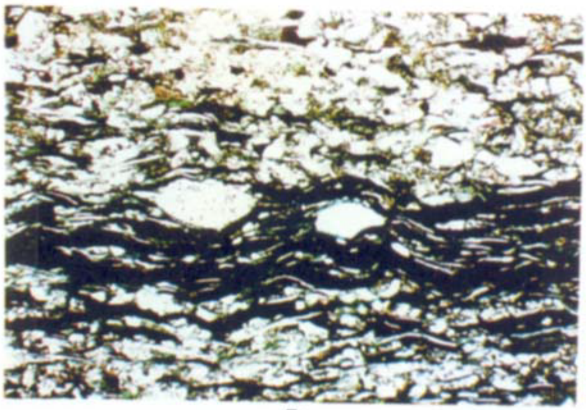

7e

entry pressures for the Mercia Mudstone Group have at some stage been exceeded. This raises questions about the integrity of the Ansdell Mudstone as a seal for the Sherwood Sandstone reservoir, particularly for gas-bearing structures.

The presence of bitumen-filled fractures indicates that mobile hydrocarbons were present when fracturing took place. A potential mechanism for producing these horizontal fractures (hydrofractures) is outlined below.

Hydrocarbon column height (HCH) calculations

The examined samples represent a range of seal types with variable lithologies and hence variable pore-network characteristics. Samples can be compared directly by examining the hydrocarbon column supported at a given mercury saturation. From Fig. 9, the following hierarchy of seal quality can be deduced:

10/2a-N3 (red mudstone) = *110/2a-N3* (green mudstone) > *110/13-11* >> *Kirkham* = *Weeton Camp* > *110/2a-N3* (brecciated mudrock).

If the *110/13-11* sample is representative of the Mercia Mudstone Group offshore, then hydrocarbon saturation in the pore network would appear to be critical to the seal integrity in the southern East Irish Sea Basin. At low oil saturations (0-20%), the seal will support a small hydrocarbon column (Fig. 9). The sample does not behave as a perfect seal under these conditions, but acts as a low-permeability zone overlying the reservoir. At increasing oil saturations (>40%), the capillary entry pressure (and hence the hydrocarbon column height supported) increases rapidly, resulting in a Class A seal when 50% of the pore volume is occupied by hydrocarbons.

The change in sealing behaviour of the *110/13-11* sample with increasing hydrocarbon saturation appears be a function of the pore network throat diameter and its distribution in the sample. Fig. 6f shows two distinct peaks — at approximately 20 microns (representing large pore throats and fractures), and 0.01 microns (representing small pore throats). This bimodal pore-throat distribution and the Hg-injection curve for *110/13-11* may be related as follows. With increasing pressure, the mercury infiltrates the largest pore throats (20 microns), and flows into them at low capillary pressures (<<10psi) until the 20-micron pore network is saturated. The smaller pore throats (0.01 microns) require pressures of at least 1,000 psi to be filled with mercury.

DISCUSSION

The following factors have been considered by previous researchers (Downey, 1984; Sneider *et al.*, 1991; Watts, 1987) to be critical for seal integrity, and are discussed below with reference to the East Irish Sea Basin:

(1) pore throat capillary entry pressures; (2) facies variations across the basin; (3) the occurrence of faults and fractures; (4) hydrocarbon saturation in pores in the mudstones; (5) the maximum burial depths experienced; (6) variations in seal thickness.

Pore throat capillary entry pressures

In making mercury injection measurements on core samples, we attempted to recreate reservoir/seal conditions and so to study how the rocks behave at depth. Mercury porosimetry data can only be applied with conviction to conditions at depth if we know that laboratory conditions are analogous to those existing in the subsurface. Despite some concerns, Hg-injection constitutes the best method available for comparing the sealing capacities of different samples. However, limitations include:

(i) During core recovery, the core is subjected to a huge pressure release as it reaches the surface; this may affect the pore network.

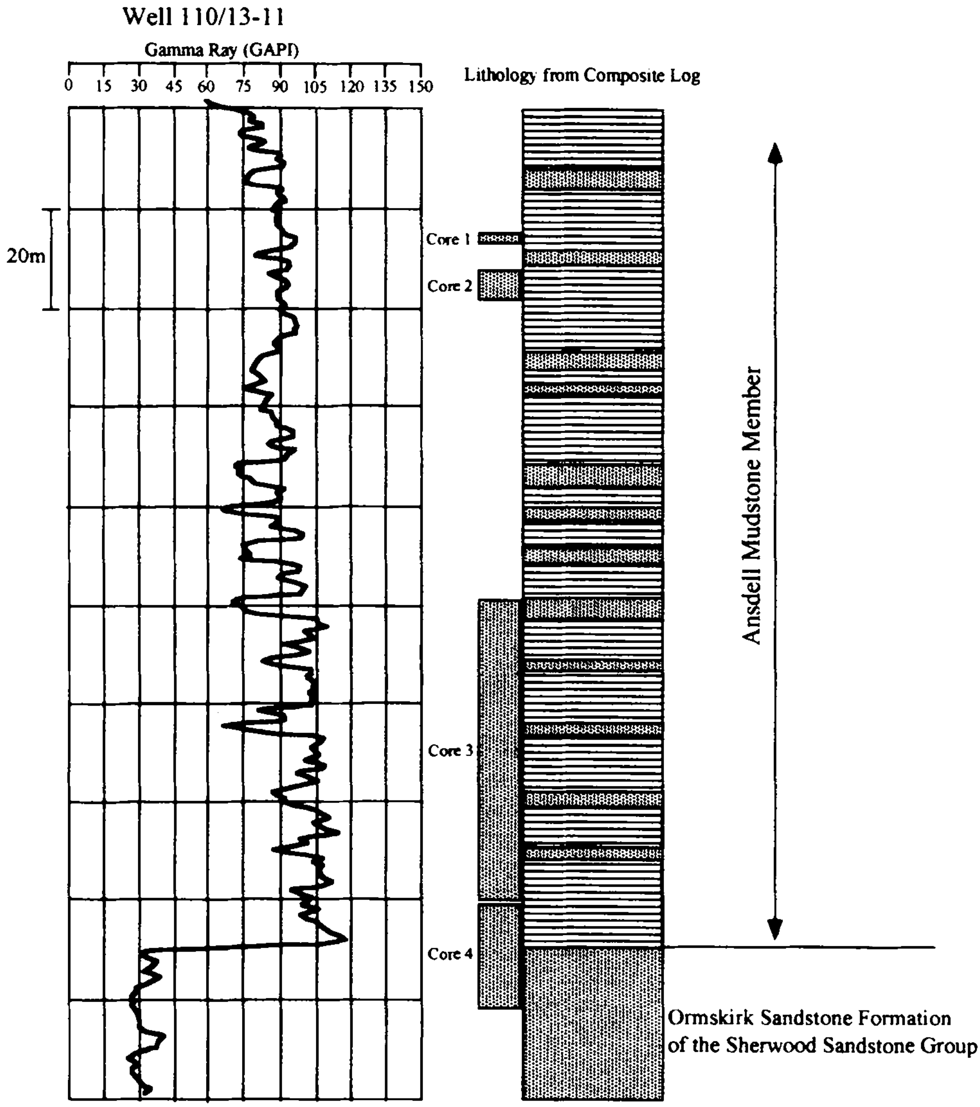

Fig. 8. Summary log of well *110/13-11*, showing core intervals examined and characteristic decreasing-upwards gamma-ray response of the Ansdell Mudstones.

(ii) Drying of samples may trigger clay reactions, which may also affect the nature of the pore network.

(iii) Calculations of hydrocarbon column height assume a 35°API oil. If a different density hydrocarbon is present, then a different HCH would be predicted (*Douglas* oils are 44°API; *Hamilton* oils are 40 ° API).

(iv) A key point regarding seal-capacity testing was raised by Downey (1984) and Watts (1987), who suggested that the rate of hydrocarbon leakage in any accumulation is governed by the *weakest point* in the seal at the reservoir-seal interface. If coring does not sample this weakest point (and this is very unlikely to happen), the Hg-injection data will not be representative of the true seal potential.

Despite these uncertainties and in the absence of alternative techniques, mercury injection data provide an estimate of seal quality which can be used in hydrocarbon exploration. The technique is not restricted to core samples, but can also be applied to drill cuttings, providing comparable measurements on both sample types if the samples are from a homogeneous rock unit (Schowalter, 1979; Sneider and Neasham, 1993). Cuttings may also provide a more representative sample base for this type of analysis, because they comprise a wider portion of the seal's lithology. Mercury porosimetry could be applied to samples from a wider area in the East Irish Sea Basin to produce a more precise model of seal integrity.

However, the mercury porosimetry data from the cuttings samples have not been compared with the core data because of the following differences in the results:

(i) The threshold pressures are poorly defined in comparison with the sharp "breaks of slope" seen in the core data;

(ii) wider ranges of pore-throat radius were recorded;

(iii) the results of analysis on cuttings samples suggest they are mildly effective seals (i.e. the cuttings do not represent good sealing lithologies).

The use of cuttings data to predict hydrocarbon column heights is a potentially risky practise; however, this data can be used for relative comparisons of seal quality within a basin.

Mercury porosimetry data were used to calculate the heights of hydrocarbon columns supportable. These "heights" are of comparative not absolute values. (For example, the data can be used to rank areas by the risk attached to seal integrity.) The reason for this is that only a very small sample of the top-seal is analysed, which may not be representative; for example, the seal elsewhere may contain facies variations and fractures, which will lead to weaknesses. Estimates of hydrocarbon column heights supportable are therefore maximum values.

Facies variations

The most important facies variation in the East Irish Sea Basin is the presence or absence of halite above the Sherwood Sandstone Group. If halite overlies the SSG, then an excellent seal exists with an extremely high capillary entry pressure. This is the case within the area outlined by the extent of the Fylde Halite in Fig. 3. In this area, the Fylde Halite acts as the seal above the SSG (and the thin Stanah Member). Beyond this area, the SSG is capped by a variety of mudstones. These were sampled from four wells, and were found to be very variable. This facies variation effects seal integrity by causing variations in the primary texture of sediments. The texture controls the nature of the pore network, and hence the capillary entry pressure required to force hydrocarbons into the seal.

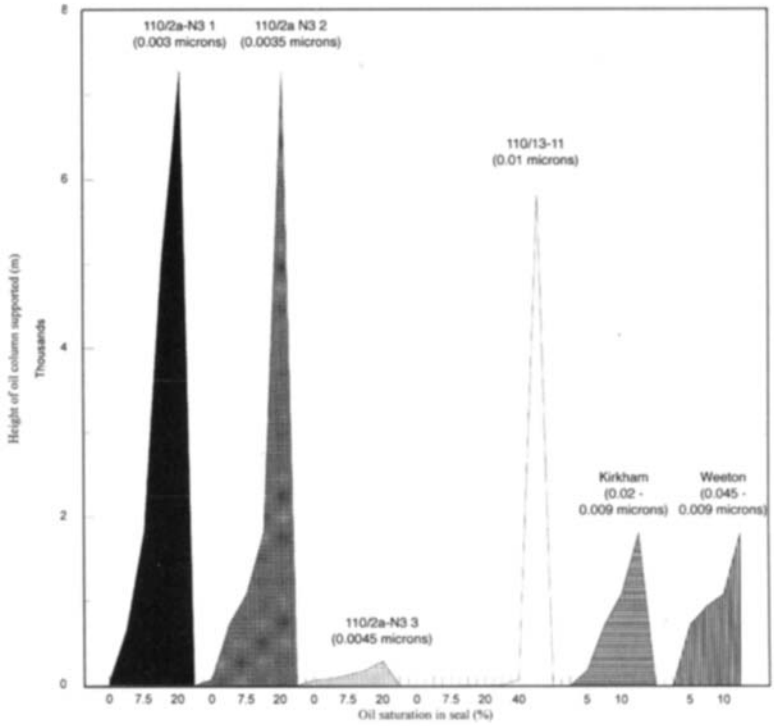

Fig. 9. Plot of oil-column height supported by Mercia Mudstone Group samples for a variety of oil saturations.

Faults and fractures

Evidence exists in the East Irish Sea Basin for both fracturing and faulting of the Mercia Mudstone Group, both of which produce weaknesses in the top-seal and may cause leakage of hydrocarbons.

Hydrofractures are partings formed when fluid pressure exceeds the tensile strength of the host strata (Phillips, 1972). In sedimentary basins, the conditions under which hydrofractures form are met only if pore fluids are overpressured (Dewers and Ortoleva, 1994). When dilatant, hydrofractures are sites of seal failure in sedimentary basins (Dewers and Ortoleva, *ibid.*) and become sites of very enhanced fluid flow (Bredehoeft *et al.*, 1994). The presence of hydrofractures has a major effect upon the migration of fluids (including hydrocarbons) from lower to higher stratigraphic and structural levels, and thereby reduce seal potential. Hydrofracturing has also been proposed as a possible mechanism to facilitate the migration of hydrocarbons from impermeable source rocks to permeable reservoirs (Capuano, 1993).

The presence of hydrofractures in some parts of the East Irish Sea basin indicates that, at the time of fracture propagation, the sediments were overpressured (Bredehoeft *et al.*, 1994). Whatever the cause of pressure generation in the East Irish Sea Basin, it seems therefore that overpressures were once present and resulted in the formation of hydrofractures. Petrographic evidence (Figs. 7d and 7e) shows that liquid hydrocarbons were present during fracturing, and filled inter- and intra-grain fractures. There are no signs of authigenic minerals precipitating as fracture-fills from aqueous solutions.

One important difference between the hydrofractures seen in well *110/13-11* and those reported elsewhere (e.g. Rowe, 1994) is their orientation. Hydrofractures are usually vertical or sub-vertical features associated with vertical pressure release along preferred lines of weakness. In this case the fractures are horizontal indicating a horizontal line of weakness. In order to fracture a rock in this orientation, the pore-fluid pressure must have been sufficient to exceed the weight of the overburden and allow horizontal fluid migration. The pressure regime under which this could happen requires maximum stress to be horizontal (as in a compressive tectonic regime), and for minimum stress to be vertical. The former is difficult to envisage in the East Irish Sea Basin, which is dominantly extensional; however, minimum vertical stress occurs during uplift and erosion, which took place 65 MM (million) yrs ago (Roberts, 1989). The extent of uplift in the basin has been estimated using a variety of techniques (1-D basin modelling; AFTA; maturity modelling; shale velocities), producing values between 300 m and 3,000m (Hardman *et al.*, 1993).

All these estimates provide for basin inversion on a scale which would aid hydrofracturing by causing pore pressures in well-sealed compartments to approach the pressures needed to fracture the overburden by overpressuring (Fig. 10). If well-sealed and overpressured reservoir was uplifted, and this uplift was sufficiently rapid so that pressures could not re-equilibrate, then pore pressures may approach the fracture gradient (0.8 of lithostatic) lifting the overburden to form hydrofractures (Fig. 10).

Hydrofractures have been reported in the East Irish Sea Basin in both the Sherwood Sandstone Group (Rowe, 1994) and the Mercia Mudstone Group (Shearman *et al.*, 1972). Fractures in the MMG in shallow, onshore boreholes are thought to have been produced by the volume increase (63%) associated with the hydration of anhydrite to gypsum. The hydrofractures associated with the hydration described by Shearman *et al.* (1972) are similar to those seen in the *Weeton Camp* and *Kirkham* boreholes and are near-surface phenomena. Rowe (1994) invoked an uplift-related mechanism as the causative process, forcing mildly overpressured rocks at depth to rise to a depth where that pressure approaches lithostatic, resulting in hydraulic fracturing (Fig.10).

Jackson *et al.* (1987) showed faulting and flexure of the Mercia Mudstone Group in a number of seismic sections. Salt movement will also influence the flexure of the Mercia Mudstones, thus further complicating the factors that need to be considered when estimating seal quality in the East Irish Sea Basin.

The key to the effect that these faults may have on the sealing integrity of the Mercia Mudstone Group is the ductility of the rocks, and their capacity to bend without brittle failure. The ductility will be controlled by the lithology, rate of flexure, overburden thickness and temperature.

Mann and Mackenzie (1990) suggest that one of the key factors controlling pressure distribution at burial depths greater than two km is the existence of high-permeability connections (along faults, fractures or sandy intervals) with the surface, or with the shallowest 2km of sediments (which tend to be in pressure connectivity with the surface). In the East Irish Sea Basin, the lateral extent of the halites could cut off vertical connections with the shallowest sediments (except towards the basin margins). However, faulting and halokinesis may have provided pathways for pressure dissipation, unless the traps were bounded by lateral sealing faults.

Hydrocarbon saturation in pores in the mudstones

The data presented in this paper demonstrate that the hydrocarbon column height (HCH) of a sampled lithology is linked directly to the percentage oil saturation. This is consistent with the work of Noble *et al.* (1993), who showed that oil saturation in shales correlates with HCH. These workers have taken this a step further and used geochemical analyses (*Rock-Eval* pyrolysis, and Extractable Organic Matter assessment) to estimate oil saturation, and hence seal capacity.

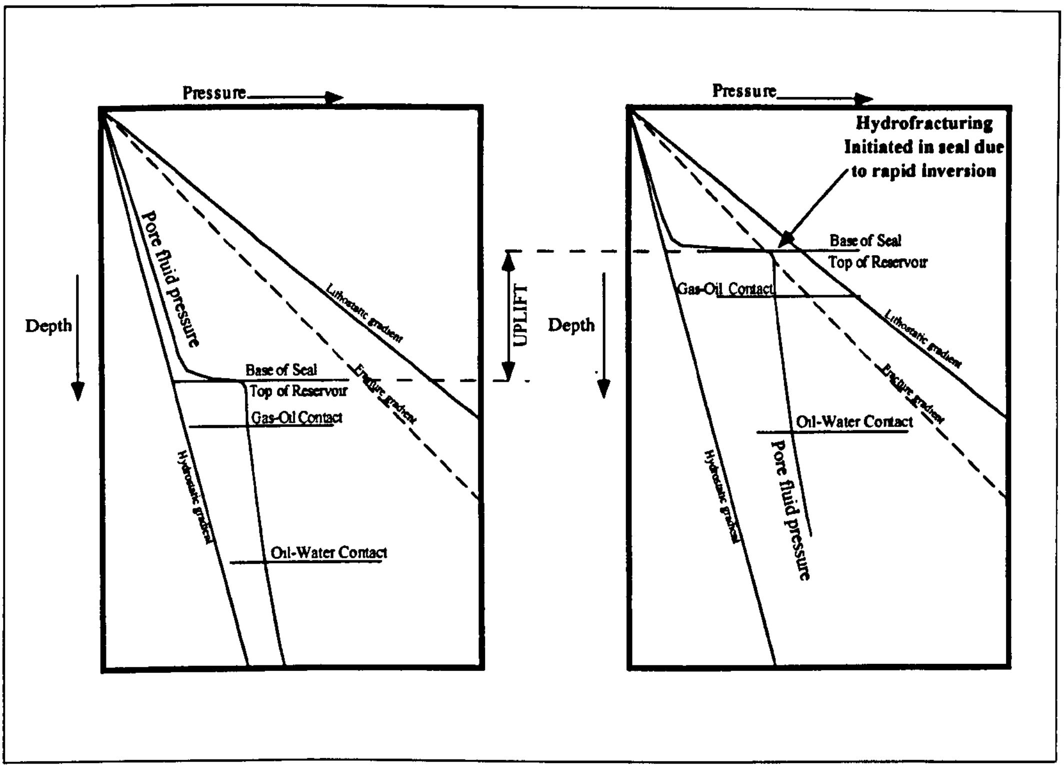

Fig. 10. Mechanism for initiating hydrofracturing in top seal by inversion. Uplift results in overpressure approaching the regional fracture gradient (80% of lithostatic pressure), such that hydrofractures may be initiated by lifting the overburden as pressure re-equilibrates.

In the East Irish Sea Basin, gas generation and migration follows an earlier phase of oil generation and migration. This "early" oil may have infiltrated the Ansdell Mudstone to produce the observed bitumen staining. Early oil migration could also be related to the presence of hydrofractures, as is indicated by the presence of bitumen in many of the horizontal fractures. As discussed above, hydrofracturing was possibly triggered by a change in lithostatic pressure associated with uplift and erosion of the overburden. However, any hydrocarbon accumulations present prior to inversion could have produced some degree of palaeo-overpressure, which, given sufficient inversion, could have resulted in hydrofracturing and invasion of the fractures by hydrocarbons. The pervasive "dead" hydrocarbons within interstices and fractures in the Ansdell Mudstones in well *110/13-11* appear to have enhanced the ability of the Mudstones to support hydrocarbons by plugging the pore network and forming a diagenetic cement.

Pore-fluid pressures are in a continual state of flux as they attempt to reach equilibrium with their surroundings at hydrostatic pressures. Any pressures generated by hydrocarbon buoyancy will attempt to dissipate to the surroundings, and can only be stopped by an effective seal. Moreover, the present-day pressure gradient may not be representative of past pressures.

Current downhole pressure trends in both aqueous and hydrocarbon "legs" in wells from the East Irish Sea Basin display only slight overpressure compared with hydrostatic gradients (Fig. 4). These pressures are insufficient to overcome the capillary entry pressure of the Mercia Mudstone Group, and are certainly too low to produce hydraulic fracturing in the mudstones at their current depths. In order to produce the distribution of hydrocarbons observed in the seals (i.e. interstitial bitumen and bitumen-filled fractures), palaeo-pressures in the reservoir rocks must have exceeded those currently observed; alternatively, the reservoirs must have been present at much shallower depths.

Maximum burial depths

As mentioned above, estimates of basin inversion in the East Irish Sea Basin are very variable, and range from 300 to 3,000m. However, there is no doubt that inversion has taken place, and present-day burial depths are much less than they were prior to 65 MM yrs ago. This may alter seal capacity in several ways; as discussed above, fracturing may take place due to a palaeo-overpressuring; also, a decrease in temperature may lead to a decrease in mudstone ductility.

Seal thickness

The importance of seal thickness has been emphasised by several workers (Leonard, 1993; Mann and Mackenzie, 1990) in other basins. It is also thought to play an important role in the East Irish Sea Basin, where only one hydrocarbon discovery has been made where the seal thickness is less than 610m (the Clyde Petroleum discovery at 365m). In this context, the work of Mann and Mackenzie (1990) is relevant — in particular their idea of high-permeability connections with the surface at less than 2km.

The present-day thickness of the Mercia Mudstone Group in the East Irish Sea Basin is largely controlled by Early Cretaceous and Cenozoic inversion (Ziegler, 1987), which in turn was controlled by the basement structure. Locally, this has resulted in the Sherwood Sandstone Group subcropping at the sea bed (e.g. the Deemster Platform in the southern part of the basin). Originally, the Mercia Mudstones were therefore much thicker, and now constitute a weaker seal due to inversion-related thinning. As the seal sequence becomes thinner, there is a greater chance of hydrocarbons migrating to a high-permeability pathway which connects to the surface.

The overall thickness of a seal is of less importance than other factors, but could be crucial if the lithology overlying the reservoir is of dubious sealing character. If the seal directly in contact with the top of the reservoir has a high capillary entry pressure (e.g. halite), then its depth is of relatively minor importance. However, if the top of the reservoir is overlain by a poorer-quality seal such as silty mudstone, then its depth will by more important, as depth will aid compaction of the pore network within the seal.

Summary

We have discussed the factors which control hydrocarbon distribution in structural traps in the East Irish Sea Basin. A schematic model showing the factors that influence hydrocarbon distribution in the Ansdell Mudstone is illustrated in Fig. 11. A certain height of hydrocarbon column must be present in order to overcome the capillary entry pressures of the Mercia Mudstones by buoyancy, and thus breach the seal. Hydrocarbons may then percolate upwards in the Mercia Mudstones until they meet an impermeable seal (in this case, the lowermost halite unit in the MMG). Hydrocarbon staining in the MMG will only therefore occur beneath this halite. If the Ansdell Mudstone is sufficiently permeable, then some variation in the distribution of hydrocarbons (or bitumen staining) within the zone of low permeability mudstones in the MMG may develop.

CONCLUSIONS

(i) The most important factor in determining the sealing capacity of the Mercia Mudstone Group in the East Irish Sea Basin is the lithology directly overlying the Sherwood Sandstone reservoir. Where evaporites overlie the Sherwood Sandstones, then top seal integrity is likely to be excellent. However, where mudstones overlie the Sherwood Sandstones, then the seal integrity will be controlled by the capillary entry pressure of the mudstones.

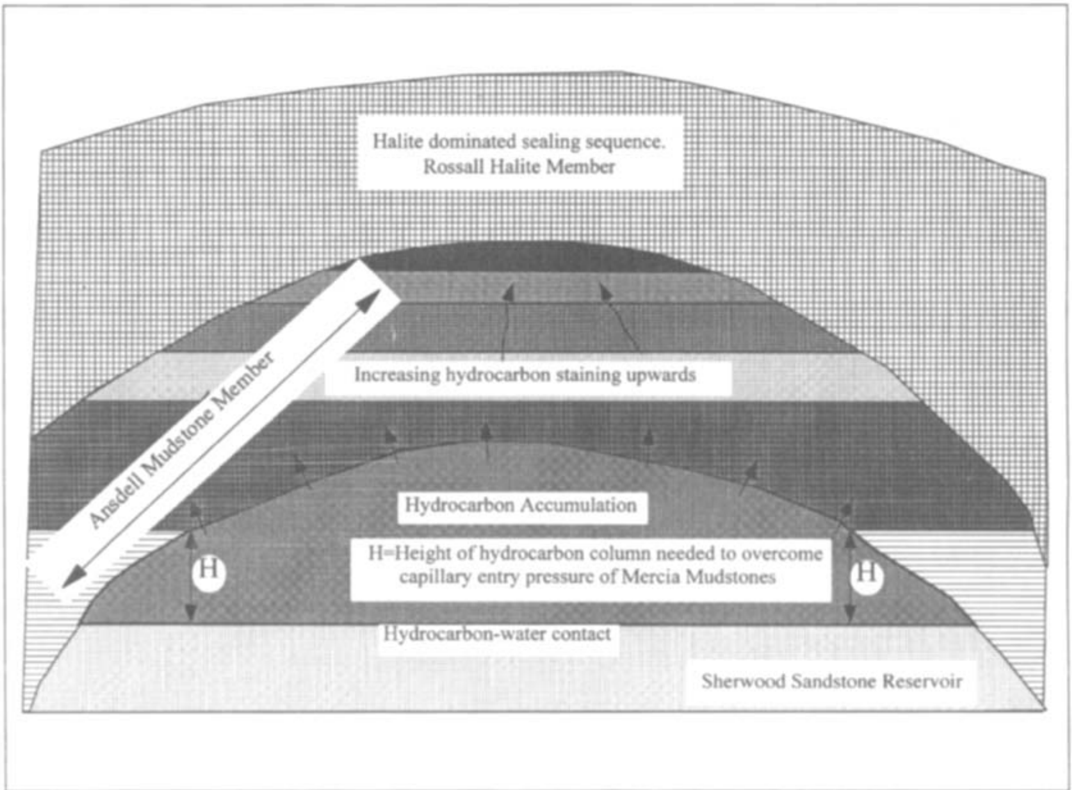

Fig. 11. Schematic model showing distribution of hydrocarbons in the Sherwood Sandstone and Mercia Mudstone Groups. Arrows denote direction of hydrocarbon migration driven by buoyancy. Hydrocarbon staining in the Ansdell Mudstone will vary with time as more fluids are pushed from the reservoir into the overlying, low-permeability mudstones.

(ii) The seal potential of the Mercia Mudstones increases if bitumen plugging of interstitial pore space has taken place. The seal potential also increases as the pore network becomes more saturated with hydrocarbons.

(iii) Horizontal, bitumen-filled hydrofractures were observed in the Ansdell Mudstone Member, and may have acted as high-permeability conduits for hydrocarbon flow within the seal. The hydrofractures are caused by high overpressures which may have been the result of basin inversion.

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