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EXPLORATION FOR GAS IN THE IRISH SEA

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ABSTRACT

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Exploration for gas between the Isle of Man and the mainland has confirmed the presence of a Permo-Triassic basin, with sediment thicknesses in excess of 3,000 m. The section can be correlated with the onshore succession and consists of the following:
'Keuper' Marl + Saliferous series (eroded)
'Keuper' Waterstones
'Keuper' Sandstone
St. Bees Sandstone
Manchester Marl and equivalent halite
Collyhurst Sandstone and equivalent shales.

Drilling and seismic work have shown abrupt thickness changes across some faults, which may show reversals of throw at different times. Sonic velocities in shales at the base of the 'Keuper' Marl suggest depths of burial of more than 4000 m, pointing to the possibility that a thick younger Mesozoic section was once present. Diagenesis of the sandstones includes calcite and quartz cementation and the development of platy illite.

Gas has been found by Hydrocarbons Great Britain Limited, a subsidiary of British Gas Corporation, in sandstones of the 'Keuper' Waterstones, 'Keuper' Sandstone and top part of the St. Bees Sandstone.

INTRODUCTION

The Permo-Triassic Northern Irish Sea Basin, as here defined, is that basin lying between the Isle of Man and the mainland of England and Wales (Figs. 1 and 2). It has also been referred to as the Manx-Furness Basin (KENT, 1975; WHITBREAD, 1975), although this name seems a little confusing, as it suggests a restriction to the northern end of the basin. It also suffers from the grammatical disadvantage of combining an adjective and a noun.

This Permo-Triassic basin is linked with, and inseparable from, a similar onshore basin, the Cheshire Basin. Although this discussion chiefly concerns the results of successful exploration in the Irish Sea, it is necessary to refer to the results of drilling in the Cheshire Basin, as well as to outcrop studies there, in order to paint the full geological picture.

Some early interpretations of the results of exploration were published in 1975 (COLTER & BARR, 1975), and more recently work on the relationships between reservoir properties and depositional and diagenetic fabrics of some Triassic sandstones has been presented (COLTER & EBBERN, 1978).

The present paper will show details of the log correlations on which the original work was based, and will extend and/or modify the views expressed earlier in the light of more recent drilling.

Where thicknesses, depths, velocities and geothermal gradients are given, metric units are used, with the Imperial equivalents in brackets. Since, however, most of the measurements were originally made in Imperial units a certain amount of approximation may be apparent.

HISTORY OF EXPLORATION

The presence of Permo-Trias sediments in the northern Irish Sea was apparent from onshore geology, including the Formby wells drilled by BP, and in the 1960's Professor Bott and others confirmed by geophysical means the presence of a sedimentary basin (BOTT, 1964, 1965, 1968; BOTT & YOUNG, 1971).

The opportunity to explore in this basin came in 1965 when blocks were offered by the British Government in the Second Licencing Round, and five blocks were awarded to a group

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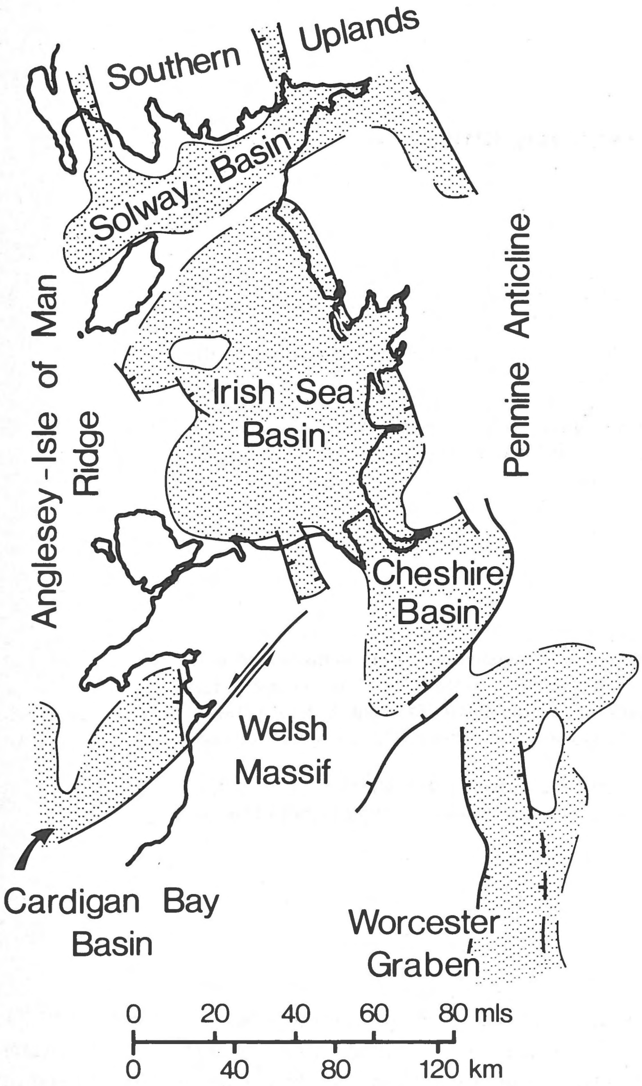


Fig. 1
Schematic relationships of Permo-Triassic basins around the Irish Sea.

consisting of Gulf Oil Corporation and the National Coal Board. Two wells (110/8-1 and 110/8-2) were drilled in 1969 and abandoned.

Also in 1969, it was announced that blocks would again be offered in the Irish Sea, in the 1970 Third Round of licencing. At this time, the Geology Section of the, then, Gas Council became interested in the basin, seismic work was carried out, and a licence application was formulated in the name of a wholly owned subsidiary company, Hydrocarbons Great Britain Ltd.

This interest was based on the view that the Irish Sea Basin could be a small-scale analogue of the southern North Sea Basin. Onshore, a basal Permian sandstone, more or less equivalent to the Rotliegendes, was known (the Collyhurst Sandstone), which is capped by an argillaceous formation roughly equivalent to the Zechstein (the Manchester Marl). Overlying these two formations was known to be a thick Triassic sandstone sequence ('Bunter'/St. Bees and 'Keuper' Sandstones), itself capped by 'Keuper' Marls and Saliferous Beds. These younger sandstones were thought likely to constitute a secondary target. A potential gas source, in the form of the Carboniferous Coal Measures, was known onshore, and natural gas had been fed for many years into the local gas-works from the Point of Air Colliery in North Wales (not to be confused with Point of Ayre, Isle of Man, Fig. 4). Similarly, the coal mines at the other end of the basin, at Whitehaven in Cumbria, were notoriously gassy. Moreover, BP had produced oil from Triassic sandstones just beneath the glacial drift at Formby. Attempts to find a deeper source for this recently re-migrated oil had been unsuccessful, but the thought that any such source might be offshore, deeper in the basin, was an encouragement to Irish Sea exploration.

With this background in mind, Hydrocarbons Great Britain Ltd. applied for, and was ultimately awarded, 4 blocks (110/6, 7, 12 and 14). At the same time, other companies were awarded licences covering a large part of the prospective basin. Again in 1971, in the Fourth Round of licencing, blocks were offered, and HGB acquired Block 110/2.

At or about the same time, another gas-industry subsidiary, Gas Council (Exploration) Ltd., in partnership with British Petroleum, had acquired two Production Licences at the northern end of the linked and related onshore Cheshire Basin, with a precisely similar exploration play in mind, i.e. Carboniferous gas structurally trapped in Permo-Triassic sandstones.

In 1974, HGB drilled its first offshore test 110/2-1. This well found gas in Triassic sandstones, in which it was terminated, a data exchange arrangement with Gulf/NCB having shown that in this part of the basin the originally envisaged Basal Permian sandstone reservoir had been replaced by shale (see below). Meanwhile, onshore, the GC(E)/BP Knutsford No. 1 well had been abandoned as dry early in 1974, after reaching the Carboniferous, apparently for lack of caprock at Permian sandstone level and lack of structure at top Triassic sandstone level. Trend Exploration Ltd. drilled the dry hole Prees No. 1 at the southern end of the Cheshire Basin in 1972-3.

Subsequently, HGB has drilled 7 delineation wells on the original gas discovery, now called the Morecambe Field, as well as 4 wildcats on separate structures. In 1976, Cluff Oil drilled the 112/30-1 dry hole.

HGB has in the meantime acquired the previously unlicenced block 110/9, as well as blocks relinquished by other companies (110/8 & 113/26). At present, Cluff Oil is the only other licencee in this area.

Exploration has been by seismic reflection work and drilling. The results of seismic work cannot be described as other than mediocre. Two events have been followed: a 'top Triassic Sandstone' and a 'Permian event'. Depth conversion and actual identification of the more significant 'top Triassic Sandstone' event have been influenced by unpredictable salt

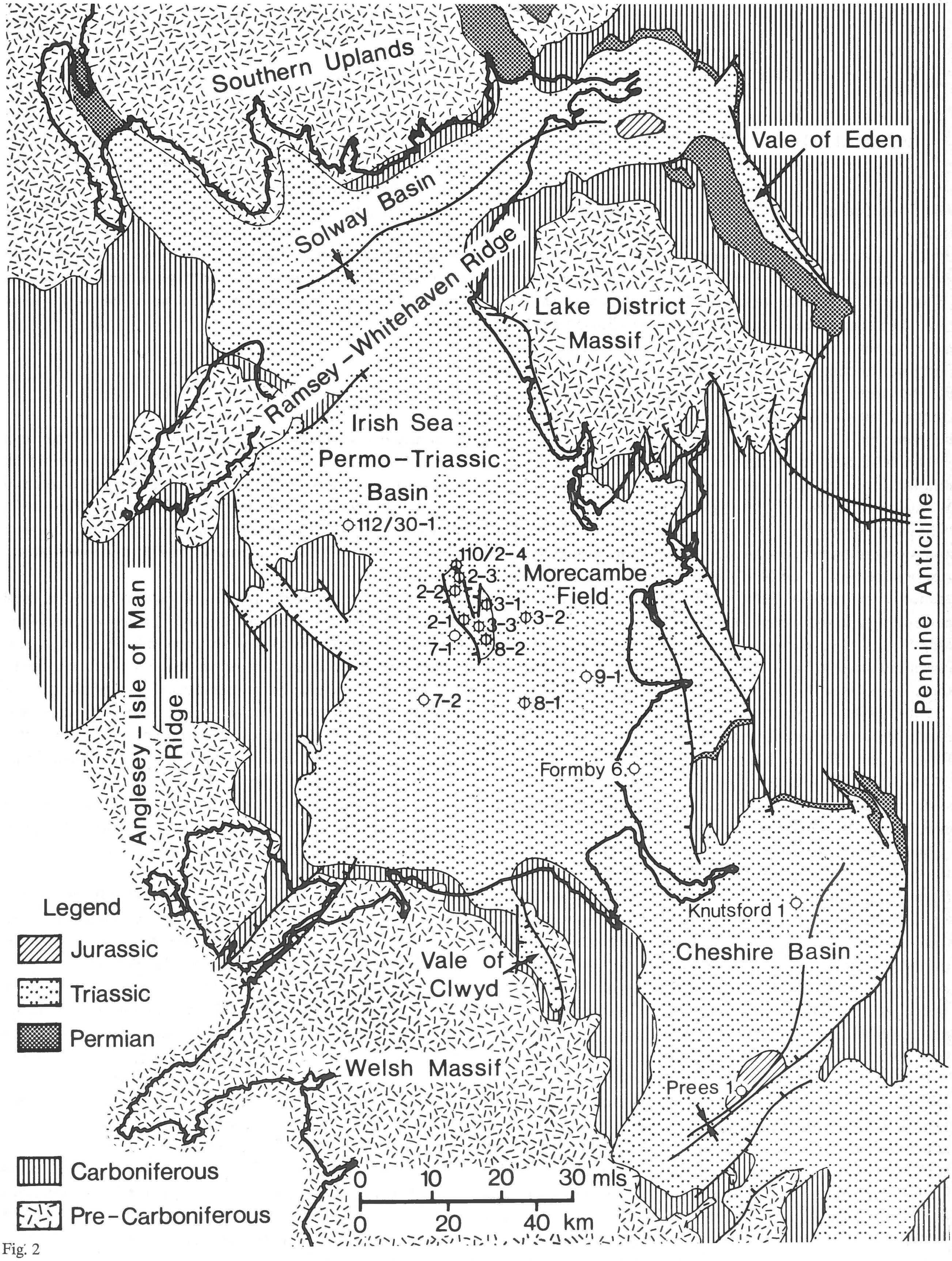


Fig. 2

Geological map of the Irish Sea (Based on I.G.S. 'Ten-mile' map of Great Britain, and unpublished data from the I.G.S. Continental Shelf Unit, Leeds).

horizons in the overlying 'Keuper' Marls and Saliferous Series.

The distribution of wells drilled is shown on figure 2.

REGIONAL GEOLOGICAL FRAMEWORK AND STRUCTURE

The Irish Sea and Cheshire Basins are half-grabens, controlled on their eastern sides by down-to-the-west faults, which throw the Permo-Triassic sediments against rocks ranging in age from Early Ordovician to Late Carboniferous (Figs. 1 and 2). On the western side, in both cases, the sediments dip eastwards off the Precambrian to Palaeozoic basement. In the case of the Irish Sea, considerable small-scale faulting, affecting the outcrop feather edge, has been mapped by the Institute of Geological Science (G. Rhys, pers. comm.), but this does not appear to invalidate the half-graben concept.

The Irish Sea and Cheshire Basins have an en-echelon relationship with each other and with the more southerly Worcester Graben (Fig. 1). This trend has been called the 'Cheshire-Severn Graben' by W. H. ZIEGLER (1975, Fig. 6), and seems to have been initiated by the same tensional forces responsible for other N.W. European Triassic basins and grabens (P. A. ZIEGLER, 1975, p. 136). The directions of faulting controlling the individual shapes of the Irish Sea and Cheshire Basins have apparently been influenced by local deep basement structures, so that the arrangement of the axes of these basins is a zig-zag pattern.

Thus, whilst the Worcester Graben trends essentially N-S along Malvernoid trends, the eastern side of the Cheshire Basin is controlled by a major NE-SW fault of Caledonoid trend, which is en-echelon with the Church Stretton fault-system emerging from the Welsh Massif. At its north-easterly end, this fault swings round to a N-S (Pennine) or NW-SE (Charnoid) trend, which is reflected in the faults cutting the Lancashire coal field and the northern edge of the Cheshire Basin. This combination of N-S and NW-SE trends is seen again in the faults controlling the eastern side of the Irish Sea Basin, as well as within the basin itself. The N-S and NW-SE trending faults controlling the eastern edge of the Irish Sea Basin cut across Caledonian structures in the Lake District and inherited Caledonian folding in the Carboniferous rocks of the Ribblesdale Fold Belt. The Morecambe gas accumulation is controlled by NW-SE and N-S faults (Fig. 2).

The NW-SE, Charnoid trend is of great interest, since it appears to be traceable from the Tornquist Line and the Danish-Polish Trough, through the British Southern North Sea and the Charnwood Forest Precambrian outcrop. In the Irish Sea and environs, not only is it reflected in part by the form of the basin and its structures, but it is also seen in a number of adjacent long, narrow Permo-Trias grabens such as the Vale of Clwyd, the Vale of Eden and Loch Ryan.

At the northern end of the Irish Sea Basin, the Caledonoid trend reasserts itself, and this basin is separated from the NE-SW Solway Basin by the similarly trending Ramsey-Whitehaven Ridge.

Although the faulting described above corresponds to these three old trends, it appears to have been initiated during a Permo-Trias period of tension. Movements were certainly taking place during the Permo-Trias, to judge from the abnormal stratigraphic sections encountered on some fault blocks, and persisted until some time after the deposition of the youngest Triassic rocks preserved (see below). The general absence of still younger beds makes it impossible to date the last movements on these faults, although there is some evidence for deep burial of the basin and more recent uplift.

STRATIGRAPHY

Stratigraphic correlation within the Permo-Trias of the Irish Sea and adjacent land areas is hampered by the general lack of faunas and floras, consequent upon the largely terrestrial or restricted marine environments of deposition of the sediments concerned. This problem has been ventilated by KENT (1970), AGER (1970), PATTISON ET AL. (1973) and SMITH ET AL. (1974).

Accordingly, lithostratigraphic correlation has been used in the subsurface, based on cores, drill cuttings and wire-line logs and a comparison with established outcrop stratigraphy. Another problem at the time of writing is the lack of modern detailed lithostratigraphic nomenclature, so that the old names are retained here. The use of the names 'Bunter' and 'Keuper' implies no exact time-stratigraphic equivalence with the continental subdivisions. These terms have, however, the virtue of familiarity. The lithostratigraphic units recognized on log characteristics can in some cases be traced over considerable distances, and one suspects with AGER (1970, p. 8) that diachronism may have been over-emphasised in the past.

The Permo-Trias boundary is conventionally put at the base of the Bunter Pebble Beds, but in the absence of these beds even this expedient is impossible. No attempt is made, therefore, in this paper to separate the Permian from the Trias in the Irish Sea. The actual top of the Carboniferous is hard to pick as a result of extensive reddening at the old land surface and lack of floras in the reddened rocks. Recognition of unaltered Carboniferous sediments has, however, generally not been difficult in those wells penetrating these beds, as a result of lithological contrasts, and the presence of some palyno-floras. Even here though, spores tend to be blackened as a result of former deep burial.

Well control is insufficient for the drawing of meaningful isopach maps of the various units described, but representative thicknesses can be derived from the sections in figures 3 and 4, as well as from COLTER & BARR (1975, Fig. 3).

Pre-Permo-Trias

An interpreted subcrop map of the pre-Permo-Triassic rocks of the Irish Sea area was published by COLTER & BARR (1975, Fig. 2). More recent information suggests that the extent of the Namurian Millstone Grit may be larger than was then mapped, but since some wells have been drilled on isolated fault blocks, it is difficult to be sure of their regional significance.

The Namurian beds penetrated generally consist of shales with subordinate, low-porosity sandstones.

Permo-Trias

Figure 2 shows the outcrop of Permo-Trias rocks round the Irish Sea. Figure 3 is based on 5 wells, and shows the wire-line log picks on which the subsurface correlations are made. The Permo-Trias boundary is conventionally placed at the base of the Bunter Pebble Bed.

One feature that is seen over the whole of the Irish Sea and Cheshire Basins, has been correlated with the Hardegsen Unconformity (COLTER & BARR, 1975), and the stratigraphy can conveniently be discussed in terms of those beds below it and those above.

The Permo-Triassic beds beneath the Hardegsen Unconformity can be regarded as a thick package of sandstones, interrupted by an incursion of restricted marine sediments from the northwest (Manchester Marl/St. Bees Shales and Evaporites) and a higher conglomeratic episode from the south (Bunter Pebble Beds). Neither of these deposits reached all parts of the Irish Sea and Cheshire Basins, and their presence or absence in various places has resulted in the apparent use of different names for higher, lower and equivalent sandstones in different places (Fig. 3). COLTER & BARR (1975, Fig. 3) show some of the names used in other adjacent areas.

The beds above the unconformity are as a whole less variable laterally, and may reflect a re-organisation of patterns of sedimentation following the movements responsible for this period of uplift.

Collyhurst Sandstone/Bunter Lower Mottled Sandstones – These sandstones, which occur above, below and lateral to the Manchester Marl and its equivalents, and below the Bunter Pebble Beds, are described at the outcrop as being of continental aspect, with intervals of dune bedding and 'millet-seed' sandstone (WILLS, 1951, Plate XII, B).

The Collyhurst Sandstone, which crops out intermittently around the northern side of the Cheshire Basin and the eastern side of the Irish Sea Basin, is highly variable in thickness. This condition which is attributed to deposition on an uneven surface and/or to depositional control by active faults, persists into the subsurface at Formby on the eastern flank of the Irish Sea Basin, where thicknesses ranging from 0-720 m are recorded (KENT, 1948; FALCON & KENT, 1960). The sandstones are generally light coloured, and often have dune bedding, 'millet-seed' sand grains and conglomeratic or pebbly horizons. Similar sandstones are seen at Knutsford No. 1 in the Cheshire Basin. The Collyhurst Sandstone rests unconformably on beds ranging from Upper Coal Measures to Millstone Grit, a fact that testifies to the great uplift and erosion that took place as a result of the Hercynian earth movements.

At the southern end of the Cheshire Basin where no Manchester Marl is seen at the outcrop, no separate Collyhurst Sandstone can be distinguished, and all beds beneath the Bunter Pebble Bed are assigned to the Bunter Lower Mottled Sandstone. This situation is seen also in the Prees No. 1 well, and correlations between this well and Knutsford No. 1 of higher horizons, such as the Bunter Pebble Bed and the top of a widespread, more agillaceous silicified zone in the overlying Upper Mottled Sandstone, suggest that the absence of Manchester Marl is by lateral facies change into Lower Mottled Sandstone.

In the Irish Sea, the Collyhurst Sandstone of Formby appears to pass through alternating sandstones and shales in the Gulf/NCB 110/8-1 well, into mudstones in 110/8-2. Some uncertainty surrounds the exact thickness of the mudstones to be attributed to Collyhurst Sandstones equivalent in these wells, owing to the lack of good floras and faunas and the general presence of a reddened weathered zone at the top of the Carboniferous. The picks given on figure 3 are those of Gulf Oil Corporation.

In the north of the Irish Sea, at Whitehaven in Cumbria, the Collyhurst Sandstone facies is replaced by thin breccias, the Brockrams, resting on eroded Carboniferous Millstone Grit and Coal Measures. In the Vale of Eden and Solway Basins, the Collyhurst Sandstone is represented by the lithologically similar Penrith Sandstone.

COLTER & BARR (1975, Fig. 5a) showed a suggested facies map for the Collyhurst Sandstone and its equivalents. More recent, still confidential, drilling has changed but little the basic pattern of the shale-out line shown at that time. The chief change might be to push this line further into the basin, from the North Welsh coast, and to bring the pinchout of these basal Permian clastics further into the basin on the western flank.

Manchester Marl and St. Bees Evaporites – The Manchester Marl of the outcrop, which conformably overlies the Collyhurst Sandstone, consists of shales, mudstones and marls with calcareous silty and sandy layers. Some of the latter have an impoverished *Bakevellia* fauna of Late Permian age (PATTISON ET AL., 1973).

To judge from the very sandy section in Knutsford No. 1, the Manchester Marl is rapidly replaced by sands to the south, and its absence in Prees No. 1 is here attributed to this process (Fig. 3). As was mentioned above, this view is based additionally on the parallelism of the base and top of the Bunter Pebble Beds and the Silicified Zone with the top of the Carboniferous in Knutsford No. 1 and Prees No. 1. It seems unlikely from these observations that the Manchester

Marl is cut out to the south by onlap by the Lower Mottled Sandstone, or by erosion at the base of the Bunter Pebble Bed.

From the rather sandy development in the Formby boreholes, the Manchester Marl passes into mudstones with anhydrite in Gulf/NCB 110/8-1 and rapidly into a largely salty section in 110/8-2. The presence of halite in the middle of the Irish Sea Basin is not surprising, since near Whitehaven in Cumbria at an apparently equivalent stratigraphic position, intertidal anhydrites and dolomites of the St. Bees Evaporites overlie the clastic Brockrams and underlie the St. Bees Shales (ARTHURTON & HEMINGWAY, 1972). The salt of 110/8-2 is accordingly assigned here to the St. Bees Evaporites, and the mudstones of 110/8-1 to the Manchester Marl/St. Bees Shale. A similar succession to that at Whitehaven is known from the Vale of Eden overlying the Penrith Sandstone (ARTHURTON, 1971). The Eden Shales have a basal plant bed (Hilton Plant Bed), interbeds of anhydrite and/or gypsum and a 6 m dolomite (Belah Dolomite).

More recent, still confidential, drilling has not materially changed the facies picture drawn by COLTER & BARR (1975, Fig. 5b). The change from shale to salt appears, however, to take place further into the basin on the southern side, and these beds may pinch out earlier on the western flank than was then interpreted.

Bunter Pebble Beds – Beyond the southern end of the Cheshire Basin, the Bunter Pebble Beds rest unconformably on the Bridgnorth Sandstone, which has been assigned to the Permian (SMITH ET AL., 1974, p. 26), apparently on lithological character. Elsewhere in this region, the Pebble Beds onlap onto Carboniferous rocks. On this basis, the bottom of the Pebble Beds has generally been regarded as marking the Permo-Trias boundary, although there seems to be no very compelling reason for this assumption. The unconformity at the base of the Pebble Bed has been tentatively extended into North Cheshire and South Lancashire (PATTISON ET AL., 1973, Table 2). FITCH ET AL. (1966) have described the Pebble Beds in terms of the deposits of a large, subaerial alluvial fan. Rock types represented include a range from sandstones, through pebbly sandstones to conglomerates. Particularly characteristic are abundant pebbles of a liver-coloured quartzite. These, together with some other constituents, have a supposed Breton origin, which is in agreement with indications of current direction showing a southerly source for these deposits.

In the subsurface of the Cheshire Basin, precise definition of the top and bottom of the Pebble Beds is difficult, because of the difficulty of recognizing pebbles in drill cuttings, especially in view of the tightly cemented nature of the matrix. In both wells, the base is here picked at a sharp upwards decrease in porosity and increase in shaliness seen on the sonic and gamma-ray logs respectively (Fig. 3). Both the shaliness and apparently associated cementation persist into the overlying sandstones. The top of the Pebble Beds is picked on the highest appearance of pebbles in Knutsford No. 1, and on a slight change of log character in Prees No. 1. Milky quartz pebbles are recorded from both wells, and liver-coloured quartzite pebbles occur in Knutsford No. 1.

Pebble Beds are also recorded from Formby Nos. 4 and 5 wells, but were not figured in Formby No. 6 by FALCON & KENT (1960, Fig. 18). Neither was the unit picked on the geologist's log for this well. A perusal of the lithological log shows, however, that below 3965 feet, 'white quartz' fragments and 'rare pink quartz or quartzite fragments' occur. This depth is accordingly taken as the tentative top of the Pebble Bed in Formby No. 6 (Fig. 3). Coincidentally or otherwise, this pick gives a very similar thickness of sediment down to the Manchester Marl to that in Knutsford No. 1.

Pebble Beds have not been recorded from 110/8-2 and other still confidential wells to the northwest of Formby in the Irish Sea. Here the absence may be real, since the formation is known to be absent onshore at Garstang in Lancashire at a similar latitude, and from the Solway and Vale of Eden Basins. The disappearance northwards is consistent with a southerly derivation for the pebbles.

Bunter Upper Mottled Sandstones/St. Bees Sandstones – The Bunter Upper Mottled Sandstones consist of the beds between the top of the Bunter Pebble Beds and the Hardegsen Unconformity or base of the 'Keuper' Sandstone. In the absence of the Pebble Beds, as in the Irish Sea Basin, all beds above the Manchester Marls and their equivalents are grouped in the St. Bees Sandstones (Fig. 3).

The environments of deposition of these sandstones are discussed by FITCH ET AL. (1966) and AUDLEY-CHARLES (1970). In general, at the outcrop they are said to be of fluviatile and lacustrine origin, although Fitch et al. recorded evidence of aeolian influence near the top in Cheshire.

Evidence from the subsurface supports the view that the environment was dominantly fluviatile (COLTER & EBBERN, 1978), but some apparently wind-rounded sand grains have been found in more porous beds in Knutsford No. 1. The St. Bees Sandstones from Irish Sea wells are uniformly more argillaceous than their onshore equivalents, as is the case also in the section in an Isle of Man borehole (Point of Ayre No. 3, Fig. 4). This may be related to distance from a southerly source and be a continuing manifestation of the northwards fining that causes the Bunter Pebble Beds to pass northwards into the lower part of the St. Bees Sandstone.

The argillaceous nature of much of the St. Bees Sandstone has been invoked to explain the low permeabilities of some reservoir rocks for a range of porosities from 4-20% (COLTER & EBBERN, 1978, p. 60 and Plate 3). Availability of more extensive core data since the initial study has shown that clean sandstones with better permeabilities exist, but the St. Bees Sandstone is, nevertheless, not generally a very attractive reservoir (see gamma-ray/sonic log for 110/8-2, Figs. 3 and 4).

Occurring towards the bottom of the St. Bees and Upper Mottled Sandstone, and including the Bunter Pebble Bed where present, is a tight, silicified zone, which is seen on sonic and other logs from Prees to 110/8-2, a distance of about 120 km, although not well developed in the shallow 110/8-1 well. That depth of burial alone is not the primary controlling factor is seen from the fact that in both Knutsford No. 1 and Prees No. 1 the silicified zone is underlain by the more porous sandstones of the Bunter Lower Mottled Sandstone, easily seen on the sonic logs in figure 3.

One factor common to all the sections of the silicified zone figured is, however, a greater amount of argillaceous and/or micaceous material, as seen on the gamma-ray log, compared with the under- and overlying less cemented beds. The contrast in gamma-ray response between the porous Lower Mottled Sandstones and the tight beds above is easily seen in figure 3. This suggests that original lithology is the primary factor controlling cementation. Although no sonic log is available from Formby No. 6, silicification appears to decrease below the point picked on the resistivity log as the top of the Pebble Bed. The full-scale gamma-ray log shows this part of the section to be marginally less radioactive. Wellsite geological reports, however, describe all of this section as 'well-cemented'.

The well 110/8-1 spudded into an eroded Triassic sandstone section, having been located on a high fault block. The silicified zone does not appear to be well represented, but above a point appropriate in thickness terms to the top of the silicified zone elsewhere, the gamma-ray response appears to decrease. The higher part of the log, not shown on figure 3, was run through casing, so that it is not possible to see how valid this correlation would be in younger beds. The apparent lack of a good silicified zone in the structurally high block drilled by 110/8-1 may be an indication that although primary lithology controlled susceptibility to silicification, depth of burial also played a part. As is shown below, however, reconstruction of the burial histories of fault blocks in this basin is not easy.

The upwards decrease in argillaceous content in the Upper Mottled Sandstone may be related to changes in the environment of deposition that were reflected in the observation that wind-rounded sand grains are seen higher in the section.

The top of the St. Bees/Upper Mottled Sandstone is here taken in wells at a marked change in gamma-ray log character interpreted to reflect the change into the cleaner lower part of the Keuper Sandstone. This change is also seen in an unlogged, but cored borehole in the Isle of Man (Fig. 4).

The parallelism of horizons from the top of the silicified zone down to the base of the Permian in figure 3, and the discordance between these and horizons from the base of Keuper Sandstone upwards is in agreement with the observation at the outcrop of an unconformity at the top of the Upper Mottled Sandstone, equated with the Hardegsen Unconformity by WARRINGTON (1970).

More detailed correlations within the upper part of the St. Bees/Upper Mottled Sandstone, to demonstrate more precisely the amount of possible erosion at this unconformity, have suffered from lack of laterally persistent log markers in this fluviatile series. Some markers have been correlated between wells on the Morecambe Field, but over short distances the amount of differential erosion seems to be slight.

An interesting observation is that at this time the northern end of the Cheshire Basin was structurally lower than the southern end, to judge from the sections in Knutsford No. 1 and Prees No. 1. At the present day, the situation is reversed.

Keuper Sandstone – The Keuper Sandstone of the outcrop in Cheshire has been studied by THOMPSON (1970-a, b), who recognized three members in ascending order:

(1) A lower partly aeolian, partly fluviatile series, the *Thurstaston Member.*

(2) A middle fluviatile unit with red pebbly sandstones and interbedded shales and silts, the *Delamere Member*.

(3) An upper predominantly aeolian unit, the *Frodsham Member.* This unit includes in the type area some dramatic dune-bedding, although fluviatile conditions also existed from time to time.

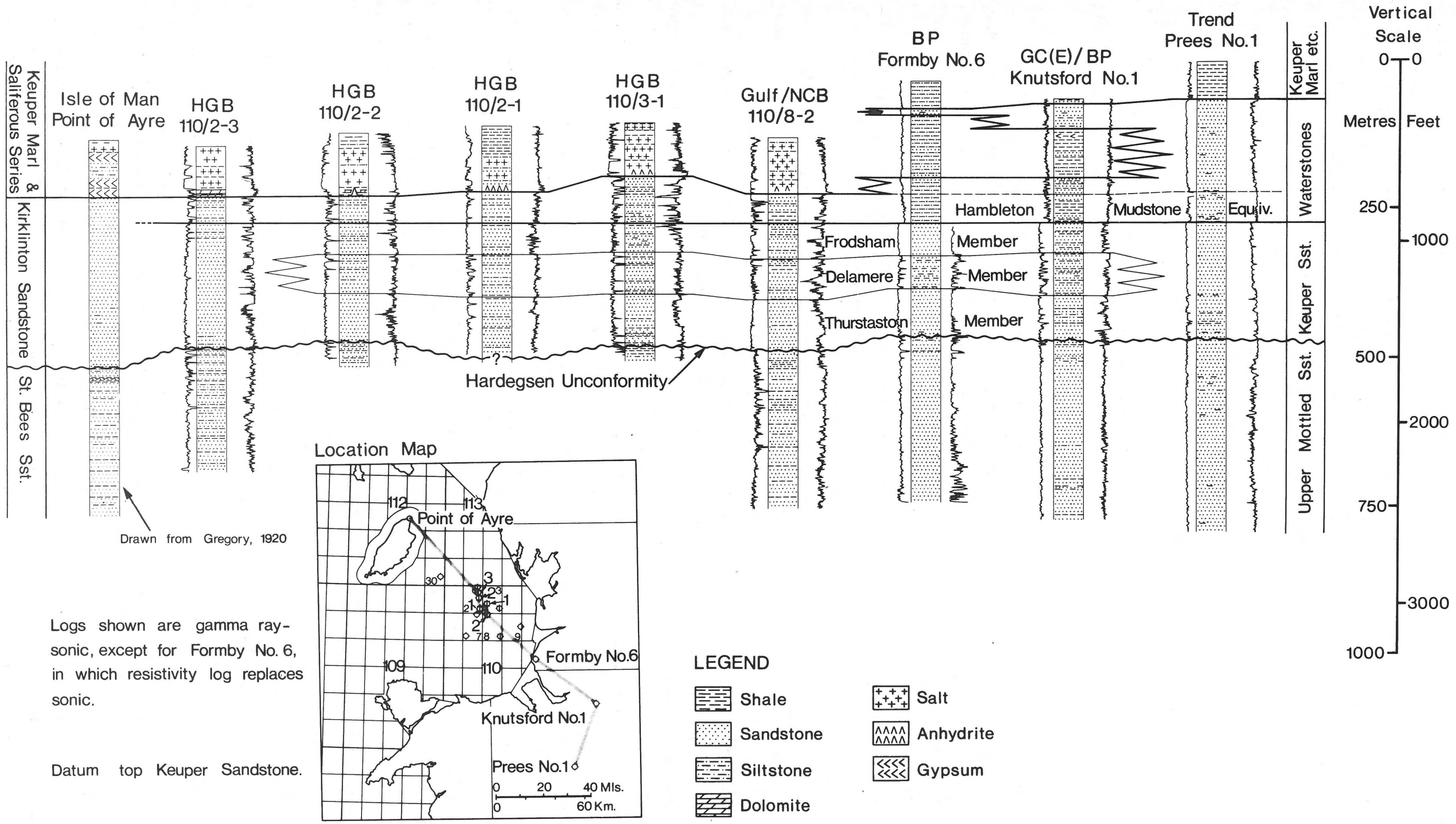
This threefold subdivision was not recognized by Thompson at the outcrop of the southern end of the Cheshire Basin.

In the subsurface, in Knutsford No. 1 at the northern end of the basin, a threefold subdivision of the Keuper Sandstone was recognized originally on gamma-ray/sonic logs (Fig. 4). The lowest unit is a cleaner sand than the underlying Upper Mottled Sandstones, with some wind-rounded sand grains in more porous rocks. Above this is a less porous unit, with argillaceous and silty interbeds, which is followed by another cleaner unit, with aeolian grains and some zones of good porosity. These three members were correlated with Thompson's subdivisions (COLTER & BARR, 1975; and Fig. 4 in this paper).

To the south, in Prees No. 1, the subdivision is not apparent, at least on log data available, which is consistent with Thompson's observation at that end of the basin.

A subdivision similar to that in Knutsford No. 1 was also seen on the gamma-ray log of Formby No. 6, the only well in that area in which this tool was run. From Formby No. 6, the correlation was followed to Gulf/NCB 110/8-2, and thence to the other Morecambe Field wells. A detailed correlation of these intervals is shown in figure 4.

The exact boundaries of the units recognized are picked somewhat arbitrarily, since the subtle interplay of aeolian and fluviatile influence on which the members are based is only approximately discernible from cuttings descriptions and wire-line logs. Grain shapes by themselves are unreliable indicators of environments of deposition, as wind-rounded grains can and do occur in water-laid deposits. COLTER & EBBERN (1978) have published data on petrography and reservoir properties of some cores which tend to support the correlation. In general, the sonic logs of figure 4 show that the interpreted Thurstaston and Frodsham Members have



Logs shown are gamma ray-sonic, except for Formby No. 6, in which resistivity log replaces sonic.

Datum top Keuper Sandstone.

Fig. 4
Detailed correlation of higher Triassic Sandstones, Point of Ayre to Trend Prees No. 1.

better porosity than do the interpreted Delamere Member and underlying St. Bees Sandstones, as might be expected from their environments of deposition. Core material from the Delamere Member has shown a porosity field with low permeabilities similar to that described earlier for the fluviatile St. Bees Sandstone (COLTER & EBBERN, 1978, Plate 5). Diagenesis has modified much of the original porosity in the two other units, but zones with excellent porosity remain (COLTER & EBBERN, 1978, Plates 4 and 6; see also below).

It seems from the correlations in figure 4, that the Delamere Member may become less argillaceous and disappear as a unit recognizable on gamma-ray logs in wells to the north. This observation may be consistent with the lack of subdivision in the core descriptions of the Kirklinton Sandstone in the Isle of Man borehole (GREGORY, 1920, pp. 3-5).

Keuper Waterstones – Lying conformably on the Keuper Sandstones at the outcrop in Cheshire is a more argillaceous, generally thinly bedded unit called the Waterstones. These beds have recently been the subject of a detailed study by IRELAND ET AL. (1978) who illustrate a coarsening upwards sequence of shales, siltstones and fine sandstones. From these beds were recorded in addition to the long-known *Chirotherium* footprints, trace fossils such as *Diplocraterion luniforme* and *Arenicolites* sp., which together indicate that the environment of deposition was in part intertidal.

In Knutsford No. 1, above the Keuper Sandstone is a series of beds beginning with about 40 m of quite radioactive shale and siltstone (Figs. 3 and 4), which pass upwards into somewhat coarser sediments giving a total of about 75 m. These beds are similar in thickness, and as far as can be judged from logs and cuttings in general sequence, to the Waterstones of IRELAND ET AL. (op. cit., Plate 13).

To the south in Prees No. 1, the more highly radioactive unit just above the Keuper Sandstone can still be made out on the gamma-ray log, but it is followed by a much thicker sandstone layer, tongues of which seem to persist into the beds above the Waterstones proper of Knutsford No. 1.

The radioactive unit has also been seen in Formby No. 6, and in a well drilled by Northwest Gas at Kirkham where it appears to correlate with a local unit called the Hambleton Mudstones. In both of these cases, the amount of sandy material just above it seems to be less than in Knutsford. The widespread nature of this gamma-ray log-marker and its persistence through the facies changes seen from Prees to Kirkham give one some confidence in regarding it, as often seems to be the case with such markers, as having some time-stratigraphic significance. The top of the Waterstones might, thus, be diachronous, but the base not.

Passing from Formby No. 6 into the Irish Sea, a more argillaceous unit was recognized above the interpreted Frodsham Member of the Keuper Sandstone in the well 110/8-2, and subsequently in other wells drilled in that basin (Fig. 4). This unit is generally coarser than its interpreted onshore equivalents, but does show, on log characteristics, a general coarsening upwards. It is capped in most wells by a thin anhydritic and/or dolomitic bed, which is quite characteristic and the first indication during drilling of proximity to the top of the Triassic Sandstones (see below, *Keuper Marls and Saliferous Beds*).

Significantly, perhaps, at the top of the Kirklinton Sandstone in the borehole from the Isle of Man in figure 4, there is a gypsum layer here interpreted as being the equivalent of the anhydrite of the offshore area. The Kirklinton Sandstone of this borehole seems, then, to include the Keuper Sandstone and the interpreted Waterstones equivalents of the offshore area. These appears from the core descriptions of this borehole, however, to be no recognizable subdivision based on argillaceous content corresponding to the threefold breakdown of the Keuper Sandstone, and the Waterstones. If this apparent general increase in sandiness northwards through the Irish Sea is real, then it appears to represent a modification of the predominantly southern derivation of the beds laid down before the Hardegsen unconformity, and may point to a fundamental reorganisation of patterns of deposition after this episode. More drilling further north will be needed to test this possibility.

Keuper Marl and Saliferous Beds – Overlying the Keuper Waterstones, and apparently interdigitating with them in North Cheshire (Figs. 3 and 4), is a series of red, brown and greenish mudstones and shales, sometimes calcareous or dolomitic. In Cheshire, two distinct halitic horizons occur, the Upper and Lower Saliferous Beds. Salts occur commonly in the Irish Sea equivalents, but the amounts and distribution are completely unpredictable. Correlations even from well to well in the Morecambe Field have proved impossible. It is not known whether this variability is primary, or whether it is due in part to solution of salts. Some loss of drilling mud has been experienced in drilling through this otherwise tight series, which may suggest the presence of collapse breccias.

Whatever the cause of the variability, it results in problems with seismic mapping as the variations in the amount of high velocity salt in the section can affect the conversion of seismic times to depths. Another consequence is that the task of the well-site geologist in recognizing proximity to the top the reservoir sand is rendered difficult by the uncertainty in the seismically calculated depths and by the lack of useful stratigraphic markers until the anhydrite immediately over the sandstone is reached.

Rhaetic

Thin Rhaetic shales, siltstones and limestone stringers are known from the outcrop in the south of the Cheshire Basin and 20 m (68 ft) of similar beds were found in Prees No. 1. No Rhaetic sediments have been found to date in the Irish Sea, but any representative beds are likely to be confined to undrilled synclinal areas.

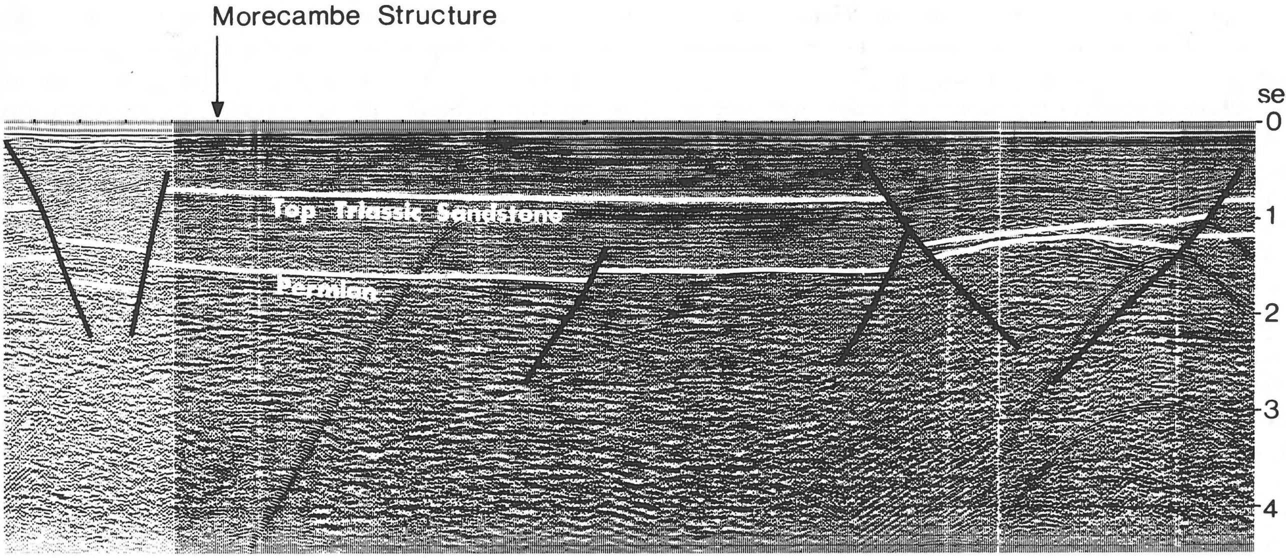


Fig. 5
Seismic section, showing formation thickness changes caused by differential fault movement (Interpretation by R. Young).

Jurassic

The outcrops of Rhaetic beds mentioned from the southern end of the Cheshire Basin are overlain by Early Jurassic Shales, and 600 m (1968 ft) of Liassic shales were penetrated in Prees No. 1. The preservation of complete Keuper and Rhaetic sections and a considerable thickness of Early Jurrassic sediments is a result of the shift southwards of the deepest part of the basin since the movements responsible for the Hardegsen Unconformity (Fig. 3).

No Jurassic beds have been identified in the Irish Sea, although a smaller outlier lies to the North in the onshore part of the Solway Basin.

STRATIGRAPHIC CONSEQUENCES OF DIFFERENTIAL FAULT MOVEMENT AND REGIONAL UPLIFT

The stratigraphy described in the previous section suggests a certain uniformity of rates of sedimentation, with a logical lateral succession of facies from the southern end of the Cheshire Basin into the Irish Sea.

Seismic surveys, however, revealed some fault blocks with sections of sediments radically different from those demonstrated in figure 3. One such, tested by the drill, is shown on the right of figure 5. The well proved a very abbreviated lower section, including the probable Collyhurst Sandstone equivalent, the St. Bees Evaporites and a very much reduced St. Bees Sandstone/Keuper Sandstone. On top of this succession, extending to the sea-bed, was found nearly 2300 m (7500 ft) of Keuper Marl and Saliferous Beds, including one largely salt horizon of about 600 m.

It appears that the fault block on which the well was located was at first a positive feature, but that after the deposition of the Triassic sandstones it became strongly negative, and accumulated the thickest Keuper Marl and Saliferous Beds section known from this or adjacent basins.

It is obvious that the representation of faulting in figure 5 is rather schematic, and that either reversal took place on some faults or complex fault zones exist that are not apparent on seismic sections.

This kind of rapid change from positive to negative and vice-versa on some fault blocks, resulting in abrupt changes in Permo-Triassic sediment thicknesses, was noticed in the Midlands basins of England by Professor L. J. WILLS (1965). To describe this phenomenon of differential fault block movement, Wills coined the expression 'block jostling'.

The movements so far described for this particular Irish Sea fault block were not, however, the last to affect it. It was noticed that the velocities for mudstones in the Keuper Marls, as seen on the sonic logs, increase downwards until at the base of this series they exceed the velocities in the salt, reaching around 4800 m/sec (16000 ft/sec). These unusually high velocities were immediately suggestive of still deeper burial at some time in the past.

In order to investigate this possibility further, selected velocities from mudstones in the Keuper Marl were plotted against depth, and compared with the 'normal burial' curve constructed for the Bröckelschiefer of the southern North Sea by MARIE (1975, Fig. 1D, and Fig. 6 of this paper). Whilst Marie's curve is for a different Triassic shale, in a different basin, this was the closest available for comparison, since no idea of normal burial history in the Irish Sea was available in view of the incomplete stratigraphic section preserved. Despite the fact that original compositional differences could affect the comparison, it appears that the lowest mudstones in this

Irish Sea well might at one time have been buried to more than 4000 m, i.e. 2000 m + deeper than at present.

As a check on this estimate, spore colouration and vitrinite reflectance measurements were commissioned from Robertson Research International Ltd. for Carboniferous material from the same well, assuming a geothermal gradient of 2.55 °C/100 m (1.4 °F/100 ft).

These studies independently came up with a similar original depth of burial (± 4,500 m) to those estimated from the sonic velocities, supporting the view that this fault block has lost some thousands of metres of section.

As a further comparison, spore colouration and vitrinite reflectance measurements were carried out on Carboniferous material from another well about 20 km away on a different fault block, with an apparently 'normal' Permo-Trias succession. These studies suggest original depths of burial of 5,000 + m, with corresponding amounts of more recent uplift and erosion in the vicinity of this well.

The likelihood exists, then, that the whole Irish Sea Basin was once the site of a much thicker Mesozoic section, including probably Jurassic and maybe Cretaceous sediments. The only remnants of such a regional sedimentary cover appear to be the Jurassic outliers in the Solway and Cheshire Basins.

AGES OF PERMO-TRIASSIC LITHOSTRATIGRAPHIC UNITS

As was stated earlier, correlations of the Permian and Triassic rocks of the Irish Sea and Cheshire Basin with sections in other basins and with established time-stratigraphy, on anything but the broadest of lines, is difficult on account of the generally unfossiliferous nature of the beds.

Permian

The apparent equivalence between the Collyhurst Sandstone- Manchester Marl sedimentary cycle and the Rotliegendes-Zechstein megacycle of the North Sea and elsewhere has some faunal and floral support. The *Bakevellia* fauna of the Manchester Marl, named after the bivalve *Bakevellia bicarinata,* has Zechstein affinities (PATTISON ET AL., 1973). ARTHURTON & HEMINGWAY (1972) suggest a ZI – ZII age for the St. Bees Evaporites, and note that similar floras have been recorded in these beds and in the Hilton Plant Bed of the Vale of Eden graben. On the other hand, BENNISON & WRIGHT (1969) state that the dolomite in this basin has affinities with the Upper Magnesian Limestone, of ZIII age. The same dolomite has also yielded the alga *Calcinema*, which is normally characteristic of the Upper Magnesian Limestone (Dr. J. C. M. Taylor, pers. comm.; TAYLOR & COLTER, 1975, Plate 1A).

In the subsurface of the Irish Sea, Permian palynofloras have been recorded by Robertson Research International palynologists from the Manchester Marl in some HGB wells.

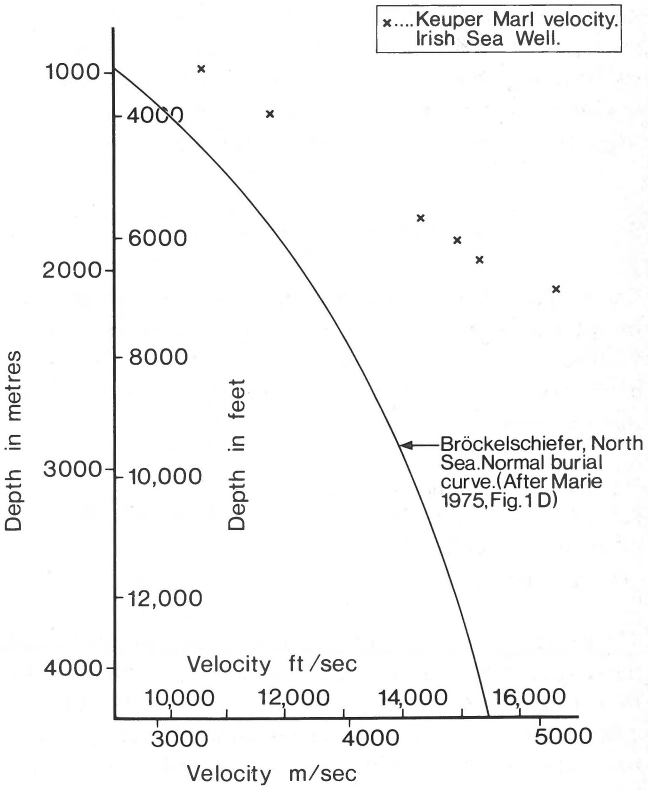


Fig. 6
Sonic velocities of shales versus present depth of burial for an Irish Sea well drilled on the fault block with reduced Permian-Triassic Sandstone section in figure 5, and the Bröckelschiefer of the southern North Sea.

No sign is apparent in the Irish Sea and environs of the four or five Zechstein cycles that are such a characteristic feature of the Zechstein of the southern North Sea (TAYLOR & COLTER, 1975), which may mean that the eustatic sea-level changes causing these cycles did not penetrate into this Permian cul-de-sac. On the other hand, these cycles are not everywhere obvious in the northern North Sea Zechstein either. If the base of the Trias is really to be put at the base of the Bunter Pebble Bed, then the upper part of the Zechstein in the Irish Sea and Cheshire Basin would be represented by the clastics of the Lower Mottled Sandstone, and the St. Bees Evaporites and associated beds would be equivalent to only the lower cycles of the Zechstein of the southern North Sea.

Trias

The interpretation of Triassic chronostratigraphy is fraught with similar problems to those affecting the subdivision of the Permian. PATTISON ET AL. (1973) reviewed the early part of the Trias, and WARRINGTON (1970-a) discussed Keuper stratigraphy. The results of exploration have brought no new light to bear on these problems. Using palynology, Warrington (1970-b) concluded that the Waterstones become older northwards from the Midlands, through Cheshire into the Irish Sea. The correlations in figures 3 and 4 suggest that the top of this formation becomes older northwards, but the widespread gamma-ray marker at the base, conformable as it is with the underlying units of the Keuper Sandstone, is not suggestive of strong diachronism at that level.

SANDSTONE DIAGENESIS

The results of work on the diagenesis of sandstones in cores from the St. Bees Sandstone, the Keuper Sandstone and the Waterstones from wells in the Irish Sea have been published by COLTER & EBBERN (1978). The types of diagenesis seen at that time were:

(1) tangential illite rims;
(2) calcite cementation;
(3) quartz cementation;
(4) platy illite.

The earliest diagenesis seems to have been the formation of the tangential illite skins, which was followed chronologically by calcite cementation. Quartz diagenesis in the form of syntaxial overgrowths and pressure solution seems to have been later than most calcite cementation, and has been inhibited by the presence of this mineral.

The tangential illite probably only materially affects reservoir properties of the finer rocks. Calcite and quartz cementation, on the other hand, have been effective in reducing both porosity and permeability, although the latter property has suffered less for a given porosity reduction in sandstones of greater initial grain size. Reduction of porosity below about 10% results in disproportionately large decreases in permeability, presumably as a result of increased tortuosity consequent on complete blocking of some pore-throats.

In one set of cores from a highly porous band in the equivalent of the Thurstaston Member of the Keuper Sandstone in 110/2-3 (Fig. 4), low permeabilities were attributed to the presence of platy illite, which here, as in many other areas, has reduced permeability by acting as a baffle, without greatly affecting porosity (TAYLOR, 1978, p. 4). High porosity, relatively low permeability values have since been recorded in cores from a zone correlative with that in 110/2-3 in another well, 110/2-5, and scanning electron microscope examination has revealed the abundant presence of platy illite (Fig. 7).

Predicting patterns of diagenesis within the basin is difficult, and, indeed, the variability both vertical and horizontal within the Morecambe Field is not easily explained. Superimposed on this are the known differences of behaviour of individual fault blocks.

The original depths of burial that have emerged in the study of subsidence and uplift are not encouraging for the hope that good reservoir properties will exist in sandstones low in the succession.

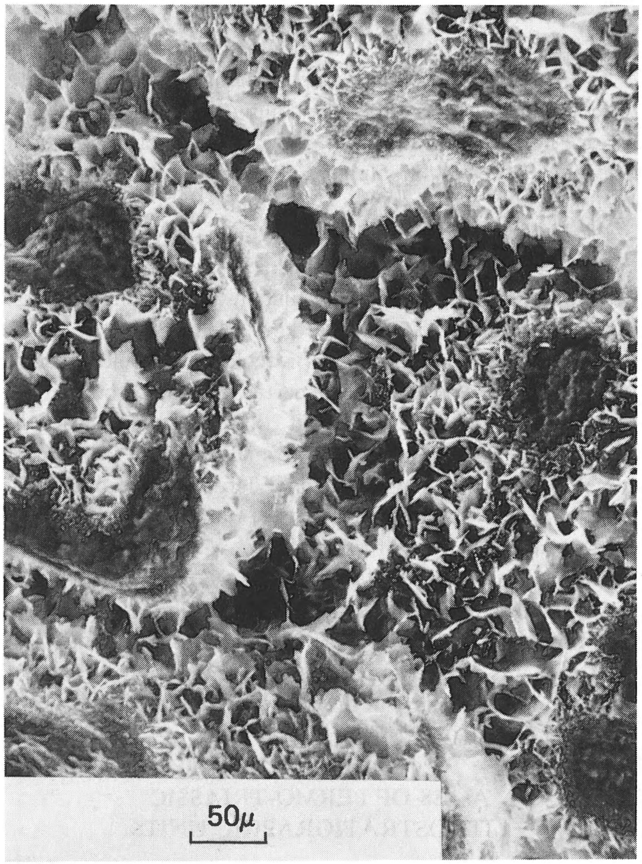


Fig. 7
Scanning electron photomicrograph of sandstone from the Thurstaston Member of the Keuper Sandstone in well 110/2-5. Porosity 22.5%, horizontal permeability 28.2 millidarcies. (Photomicrograph by J. Ebbern and R. Sinha).

HYDROCARBONS

The original incentive for exploration in the Irish Sea and Cheshire Basins was the prospect of finding gas of Coal Measures origin, such as was known from the coal mines onshore. The possibility also existed of finding oil similar to that at Formby, of presumed marine origin. The discovery of the Morecambe Field has confirmed this basin as a gas-prone area.

The composition of the gas is similar to that from the British Sector of the Southern North Sea. One difference is that the nitrogen content in the Irish Sea gas is greater, although less than in the case of the Groningen gas. Likely depths of burial in the basin in excess of 5000 m, estimated from sonic velocities in the Keuper Marl and by vitrinite reflectance, appear to have been adequate for gas generation either from coal or from any marine rocks that might be present in the Namurian or older Carboniferous beds. The time of gas generation is not known, but the maximum depth of burial seems likely to have been reached in the late Mesozoic.

The presence of oil at Formby on the edge of the basin points to a marine source rock, which may be in the Namurian Bowland Shales, and which has evidently not been buried so deeply as in the case of the rocks investigated in the deeper part of the basin. The fact that this oil was apparently trapped beneath Pleistocene Boulder Clay indicates very recent migration or re-migration.

CONCLUSIONS

The original supposition that the northern Irish Sea Basin might be an analogue of the gas-bearing southern North Sea Basin has been justified inasmuch as gas of presumed Carboniferous origin has been found in Triassic sandstones. So far, however, the exact analogy with the North Sea, where the bulk of the gas is in basal Permian sandstones, has eluded the efforts of those exploring in the area.

During the course of this exploration, knowledge of the stratigraphy and structure of the subsurface of this basin and of the neighbouring Cheshire Basin have been extended by seismic work, and by exploration and delineation wells.

The major stratigraphic units of the Permo-Trias are recognized in the subsurface, with some notable facies changes that can be related to distance from a predominantly southern source of clastic sediments. Faulting controlling the Morecambe gas field conforms to the NW-SE and N-S inherited trends seen onshore. Some fault blocks show a history of differential movement, picturesquely described from elsewhere as 'block jostling' by WILLS (1956). There is evidence that the whole basin has been much more deeply buried presumably beneath younger Mesozoic sediments, and has since undergone several thousand feet of uplift followed by erosion. This great depth of burial must be responsible for the generation of gas from Carboniferous sources, either marine or terrestrial, and is probably a contributory factor to the diagenesis of some of the sandstones in the succession.

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Additionally, sea-bed sampling and shallow seismic work carried out by the Institute of Geological Sciences has led to the better definition of the western edge of the Irish Sea Basin, and permission to modify the simple basin outline map in figure 1, in the light of these results, is gratefully acknowledged.

REFERENCES

Ager, D. V. 1970 The Triassic system in Britain and its stratigraphical nomenclature – Q. J. geol. Soc. London 126: 3-13.

Arthurton, R. S. 1971 The Permian evaporites of the Langwathby Borehole, Cumberland – Rep. Inst. Geol. Sci. 71/17: 18 pp.

Arthurton, R. S. & J. E. Hemingway 1972 The St. Bees Evaporites – a carbonate-evaporite formation of Upper Permian age in West Cumberland, England – Proc. Yorks. geol. Soc. 38: 565-592.

Audley-Charles, M. G. 1970 Triassic palaeogeography of the British Isles – Q. J. geol. Soc. London 126: 50-81.

Bennison, G. M. & A. E. Wright 1969 The geological history of the British Isles – Edward Arnold (London): 406 pp.

Bott, M. H. P. 1964 Gravity measurements in the north eastern part of the Irish Sea – Q. J. geol. Soc. London 120: 369-396.

—— 1965 The deep structure of the northern Irish Sea, a problem of crustal dynamics – Colston Pap. 17: 179-201.

—— 1968 The geological structure of the Irish Sea Basin. In: D. T. Donovan (ed.): Geology of Shelf Seas – Oliver & Boyd (Edinburgh): 93-113.

Bott, M. H. P. & D. G. G. Young 1971 Gravity measurements in the north Irish Sea – Q. J. geol. Soc. London 126: 413-432.

Colter, V. S. & K. W. Barr 1975 Recent developments in the geology of the Irish Sea and Cheshire Basins. In: A. W. Woodland (ed.): Petroleum & the Continental Shelf of North West Europe, 1, Geology – Applied Science Publ. (Barking): 61-75.

Colter, V. S. & J. Ebbern 1978 The petrography and reservoir properties of some Triassic sandstones of the Northern Irish Sea Basin – J. geol. Soc. London 135: 57-62.

Falcon, N. L. & P. E. Kent 1960 Geological results of petroleum exploration in Britain, 1945-57 – Geol. Soc. London Mem. 2: 56 pp.

Fitch, F. J., J. A. Miller & D. B. Thompson 1966 The palaeogeographic significance of isotopic age determinations on detrital micas from the Triassic of the Stockport-Macclesfield district, Cheshire – Palaeogeogr. Palaeoclimatol. Palaeoecol. 2: 281-313.

Gregory, J. W. 1920 The red rocks of a deep bore at the north end of the Isle of Man – Trans. Inst. Min. Engineers 59: 156-168.

Ireland, R. J., J. E. Pollard, R. J. Steel & D. B. Thompson 1978 Intertidal sediments and trace fossils from the Waterstones (Scythian-Anisian?) at Daresbury, Cheshire – Proc. Yorks. geol. Soc. 41: 399-436.

Kent, P. E. 1948 A deep borehole at Formby, Lancashire – Geol. Mag. 84: 2-18.

—— 1970 Triassic rocks of the British Isles: Introductory remarks – Q. J. geol. Soc. London 126: 1.

—— 1975 The tectonic development of Great Britain and the surrounding seas. In: A. W. Woodland (ed.): Petroleum & the Continental Shelf of North West Europe, I. Geology – Applied Science Publ. (Barking): 3-28.

Marie, J. P. P. 1975 Rotliegendes stratigraphy & diagenesis. In: A. W. Woodland (ed.): Petroleum & the Continental Shelf of North West Europe, I. Geology – Applied Science Publ. (Barking): 205-210.

Pattison, J., D. B. Smith & G. Warrington 1973 A review of late Permian and early Triassic biostratigraphy in the British Isles. In: A. Logan & L. V. Hills: The Permian & Triassic systems and their mutual boundary – Can. Soc. Petrol. Geol. Mem. 2: 220-260.

Smith, D. B., R. G. W. Brunstrom, P. I. Manning, S. Simpson & F. W. Shotton 1974 Permian: a correlation of Permian rocks in the British Isles – Geol. Soc. London Sp. Rept. 6: 45 pp.

Taylor, J. C. M. 1978 Sandstone diagenesis, State of the art, 1977 – J. geol. Soc. London 135: 3-5.

Taylor, J. C. M. & V. S. Colter 1975 Zechstein of the English Sector of the Southern North Sea Basin. In: A. W. Woodland (ed.): Petroleum & the Continental Shelf of North West Europe, I. Geology – Applied Science Publ. (Barking): 249-263.

Thompson, D. B. 1970-a Sedimentation in the Triassic Red Pebbly Sandstones in the Cheshire Basin and its margins, – Geol. J. 7: 183-216.

—— 1970-b The stratigraphy of the so-called Keuper Sandstone Formation – Q. J. geol. Soc. London 126: 151-179.

Warrington, G. 1970-a The stratigraphy and palaeontology of the Keuper Series of the central Midlands of England – Q. J. geol. Soc. London 126: 183-217.

—— 1970-b The 'Keuper' Series of the British Trias in the northern Irish Sea and neighbouring areas – Nature 226: 254-256.

Whitbread, D. R. 1975 Geology and petroleum possibilities west of the United Kingdom. In: A. W. Woodland (ed.): Petroleum & the Continental Shelf of North West Europe I Geology – Applied Science Publ. (Barking): 45-59.

Wills, L. J. 1951 Palaeogeographical Atlas – Blackie & Son Ltd. (London): 64 pp.

—— 1956 Concealed Coalfields (A palaeogeographical study of the stratigraphy and tectonics of Mid-England in relation to coal reserves) – Blackie & Son Ltd. (London): 208 pp.

Ziegler, P. A. 1975 North Sea basin history in the tectonic framework of North-Western Europe. In: A. W. Woodland (ed.): Petroleum & the Continental Shelf of North West Europe I Geology – Applied Science Publ. (Barking): 131-149.

Ziegler, W. H. 1975 Outline of the geological history of the North Sea. In: A. W. Woodland (ed.): Petroleum & the Continental Shelf of North West Europe I Geology – Applied Science Publ. (Barking): 165-190.