PETROLEUM GEOLOGY AND FUTURE HYDROCARBON POTENTIAL OF THE IRISH SEA

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The East Irish Sea Basin is hydrocarbon prolific with ten gasfields, two oilfields and another eight gas or oil discoveries. Production is from a widespread Triassic fluvio-aeolian reservoir (the Ormskirk Sandstone) which is sealed by salt-prone mudstones. Three episodes of hydrocarbon generation occurred from a rich, Namurian-age source rock during deep burial in the Late Carboniferous-Early Permian, in the Early Jurassic and in the Late Cretaceous. All of the discoveries are in structural traps which are controlled to some degree by N-S trending normal faults probably active in the Late Jurassic. Consequently, the third (Cretaceous) phase of hydrocarbon generation is the most important. Another phase of uplift and erosion occurred in the Early Tertiary leading to the almost complete removal of Cretaceous and Jurassic strata. This event led to significant primary and tertiary migration as a result of overpressuring in the source rock and gas expansion within the reservoir. Although similar good quality Triassic reservoir occurs in other basins in the Irish Sea, rift-related uplift and erosion in the Middle Permian caused the widespread removal of potential Carboniferous source rocks in these areas, severely limiting the chance of hydrocarbon charge.

INTRODUCTION

Gas reserves amounting to 7.6 TCF and oil reserves of approximately 200 MM brls have been proven in an area of 3,500 sq. km in the East Irish Sea (Fig. 1). Although , the area did not look highly prospective prior to the discovery of the giant *South Morecambe*

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gasfield in 1974, it is worth noting that to date at least one out of every three exploration wells in this area has discovered hydrocarbons. The reason for this high success ratio is the presence of a rich oil and gas source rock of Namurian age (the Holywell Shale), an excellent fluvio-aeolian reservoir of Triassic age (the Ormskirk Sandstone Formation at the top of the Sherwood Sandstone Group), a salt-prone seal (the Mercia Mudstone Group) (Fig. 2), and a series of normal fault-closed traps. However, the East Irish Sea and similar smaller basins in the northern and western parts of the Irish Sea represent only the remnants of two, formerly much more extensive Carboniferous and Permo-Triassic basins. Both basins are of rift-sag origin but have been reduced in their thickness and extent by two major phases of uplift, the first during the Middle Permian (the Saalian event) and the second during the Early Tertiary (Ziegler, 1987; Green *et al.*, 1997; Quirk and Kimbell, 1997; Cowan *et al.*, 1999). The Tertiary uplift event explains why no rocks younger than the earliest Jurassic are preserved (Fig. 2), other than a thin Quaternary cover. All the fields in the East Irish Sea are relatively shallow and there is evidence of early hydrocarbon fills since lost, as well as oil seeps along the edges of the basin (e.g. Colter, 1978; Bushell, 1986; Francis *et al.*, 1997; Armstrong *et al.*, 1997).

The aim of this paper is to draw attention to some of the highlights of recent work in the Irish Sea, much of which has only been published in the last six years. It is hoped that this helps set the scene for the thematic papers which follow later in this issue.

GEOLOGICAL AND GEOPHYSICAL BACKGROUND

The migration path for hydrocarbons from the Holywell Shale to the Ormskirk Sandstone is relatively simple in the East Irish Sea due to the dominance of sandstone in the intervening Permo-Triassic section (Cowan *et al.*, 1999). The main phases of hydrocarbon generation in the East Irish Sea are thought to be ?Early Jurassic (predominantly oil) and Late Cretaceous (predominantly gas) (Bushell, 1986; Hardman *et al.*, 1993; Cowan and Bradney, 1997; Haig *et al.*, 1997). A pre-Triassic phase of hydrocarbon generation may also have occurred during burial in the Late Carboniferous-Early Permian (Green *et al.*, 1997). The later (Cretaceous) gas charge appears to have displaced earlier hydrocarbons away from the centre of the basin (Greenwood and Habesch, 1997) so that the main oil accumulations now occur up-dip towards the southern and eastern margins of the East Irish Sea (e.g. Haig *et al.*, 1997). An additional factor in trapping oil rather than gas is that halite at the base of the Mercia Mudstone Group dies out in the southern part of the basin to be replaced by mudstone interbedded with anhydrite, dolomite and sandstone (Jackson *et al.*, 1997), a factor which also explains many of the dry wells in the area (Seedhouse and Racey, 1997; Cowan *et al.*, 1999). Where early oil was trapped, diagenesis was inhibited, helping to preserve porosity and permeability (e.g. Cowan and Bradney, 1997), although in some places residual oil has blocked pore throats (e.g. Yaliz, 1997). However, areas where no hydrocarbons have been discovered are typically those where vitrinite reflectance data and burial history modelling indicate that the source rock became over-mature in the Early Jurassic (e.g. Cowan *et al.* 1999).

Fault patterns are complex but the most important in terms of trap development is a N-S (?Late Jurassic) trend. Major NW-SE faults are also present which were active during the Early Tertiary (Quirk and Kimbell, 1997), as well as older E-W and NE-SW trends representing reactivated Palaeozoic lineaments (Jackson and Mulholland, 1993; Quirk *et al.*, 1999; Maingarm *et al.*, 1999 *this issue*). Above the base-Permian unconformity, the oldest sediments are the Collyhurst Sandstone Group, an interval of highly variable thickness (0-800m) and diverse lithology (conglomerate-siltstone), with volcanics occasionally present at the base (Jackson *et al.*, 1997). The Collyhurst Sandstone is interpreted as a late syn-rift package associated with normal faults orientated NNE-SSW to ENE-WSW which were probably active during the Middle Permian. Many authors have suggested that rifting continued throughout the Triassic (e.g. Knipe *et al.* 1993;

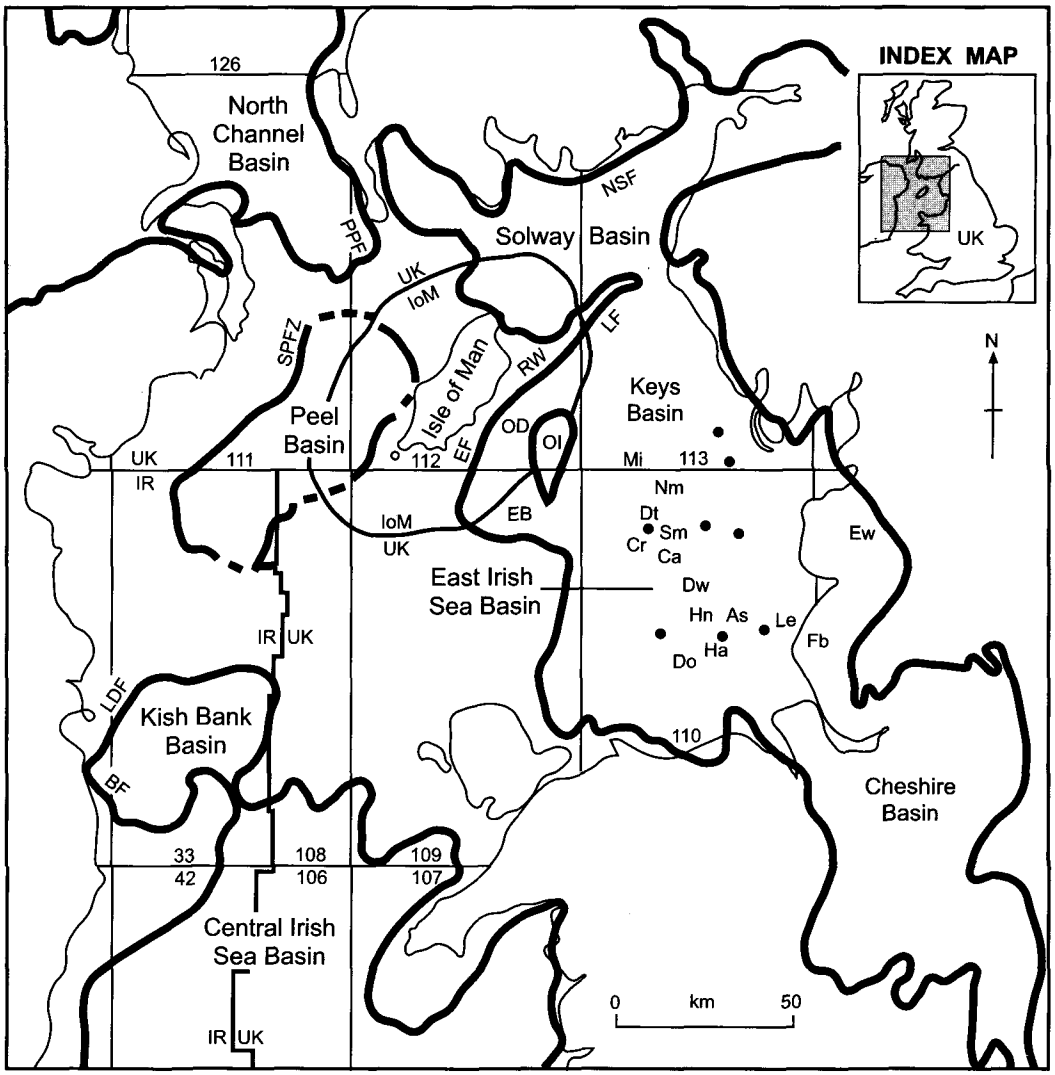


Fig. 1. Location of the main Permo-Triassic basins in the Irish Sea region. Thick black lines indicate the approximate present-day position of the base-Permian unconformity. Coastlines, quadrant divisions and territorial boundaries are also shown (UK = British waters; IoM = Manx waters; IR = Irish waters).

Black dots in the East Irish Sea Basin indicate oil and gas discoveries additional to those named: As = *Asland* gasfield; Ca = *Calder* gasfield; Cr = *Crossans* gasfield; Dt = *Dalton* gasfield; Do = *Douglas* oilfield; Dw = *Darwen* gasfield; Ew = *Elswick* gasfield; Fb = *Formby* oilfield; Ha = *Hamilton* gasfield; Hn = *Hamilton North* gasfield; Le = *Lennox* oil and gasfield; Mi = *Millom* gasfield; Nm = *North Morecambe* gasfield; Sm = *South Morecambe* gasfield.

Structural features and sub-basins referred to in the text are: BF = Bray Fault; EB = Eubonia Basin; EF = Eubonia Fault; LDF = Lambay-Dalkey Fault; LF = Lagman Fault; NSF = North Solway Fault; OD = Onchan Depression; OI = Ogham Inlier; PPF = Portpatrick Fault; RW = Ramsey-Whitehaven Ridge; SPFZ = St. Patrick Fault zone.

The map is based on Naylor *et al.* (1993), Jackson *et al.* (1995), Haig *et al.* (1997), Quirk and Kimbell (1997), Maddox *et al.* (1997), Newman (1999) and unpublished proprietary data.

Meadows and Beach, 1993). However, on the whole the Triassic is a layer-cake succession with regionally predictable lithological trends (Jackson and Mulholland, 1993) quite unlike those of a rift (Prosser, 1993). It seems more likely, therefore, that the Triassic was predominantly a period of thermal sag with only relatively minor movement occurring on normal faults due to isostatic readjustment. A renewed phase of extension began some time after the Triassic (thought to be Late Jurassic), although direct evidence for when this occurred is missing as a result of wholesale uplift and erosion in the Early Tertiary.

In general, two high-amplitude reflections are easily picked on seismic data in the East Irish Sea which correspond with the top of the Ormskirk Sandstone and the top of the Collyhurst Sandstone (Fig. 2). Although the main objective of seismic interpretation is to map the Ormskirk Sandstone, the presence of salt in the Mercia Mudstone and of channel-like features in the Quaternary, may make it necessary to interpret younger horizons to improve time-to-depth conversion (e.g. Blow and Hardman, 1997). On good-quality seismic profiles, a high-amplitude reflection corresponding to the top of the Dinantian (Garwood Group) can often be observed. Beyond the confines of the East Irish Sea Basin, where the risk of no source rock is high, it is important to interpret this reflection in order to identify areas where a Holywell Shale equivalent may be preserved below the base of the Permian. At the reservoir scale, the correlation and lateral prediction of producing zones is not straightforward because most of the Triassic is barren of fossils and seismic quality is variable. However, new techniques such as chemostratigraphy and magnetostratigraphy are helping to improve confidence (e.g. Mange *et al.* 1999 *this issue*).

The Irish Sea is traversed by numerous WNW-ESE Tertiary dykes. These are clearly visible on high resolution aeromagnetic data (e.g. Quirk and Kimbell, 1997; Kimbell and Quirk, 1999) but are rarely more than a few metres wide (cf. Arter and Fagin, 1993). These dykes may, however, be significant in terms of impeding hydrocarbon migration and promoting diagenesis.

HYDROCARBON RESERVES IN THE EAST IRISH SEA BASIN

Morecambe fields

Until recently, the East Irish Sea Basin was best known for containing a single giant gasfield west of Morecambe Bay, operated by Hydrocarbon Resources Limited, a subsidiary of Centrica (formerly British Gas). The main accumulation (the *South Morecambe* gas field, Fig. 1) was officially discovered by UK well *110/2-1* in 1974 after British Gas reinterpreted UK well *110/8-2* as gas-bearing (Colter, 1978). Well *110/8-2* was drilled within the field, down-flank of the culmination and was originally classified (wrongly) as dry by the then-operator Gulf Oil in 1969. The trap consists of a faulted anticline developed in the hanging wall of a large NNW-SSE trending fault (Bushell, 1986).

The *South Morecambe* field is separated from the *North Morecambe* field by a narrow ENE-WSW graben thought to represent a transfer zone linking faults on either side of the structure (Knipe *et al.*, 1993). The *South Morecambe* field has a 410m gas column and initial reserves of 4.2 TCF. The *North Morecambe* gas field was discovered in 1976 by UK well *110/2-3* and has reserves of 1.0 TCF (Cowan, 1996). Although the main gas fill occurred in the Cretaceous, evidence exists for a tilted palaeo-hydrocarbon-water contact of Early Jurassic age below which permeability is significantly reduced due to the presence of platy illite (Macchi *et al.*, 1990; Stuart, 1993; Cowan, 1996).

Liverpool Bay fields

It was a surprise to those who regarded the East Irish Sea Basin as a one-field basin when Hamilton Brothers (now BHP) discovered both the *Hamilton* gasfield and the *Douglas* oilfield in 1990 (Fig. 1), with the first and second wells drilled in UK block 110/13. These fields comprise a set of narrow N-S trending tilted fault blocks that were

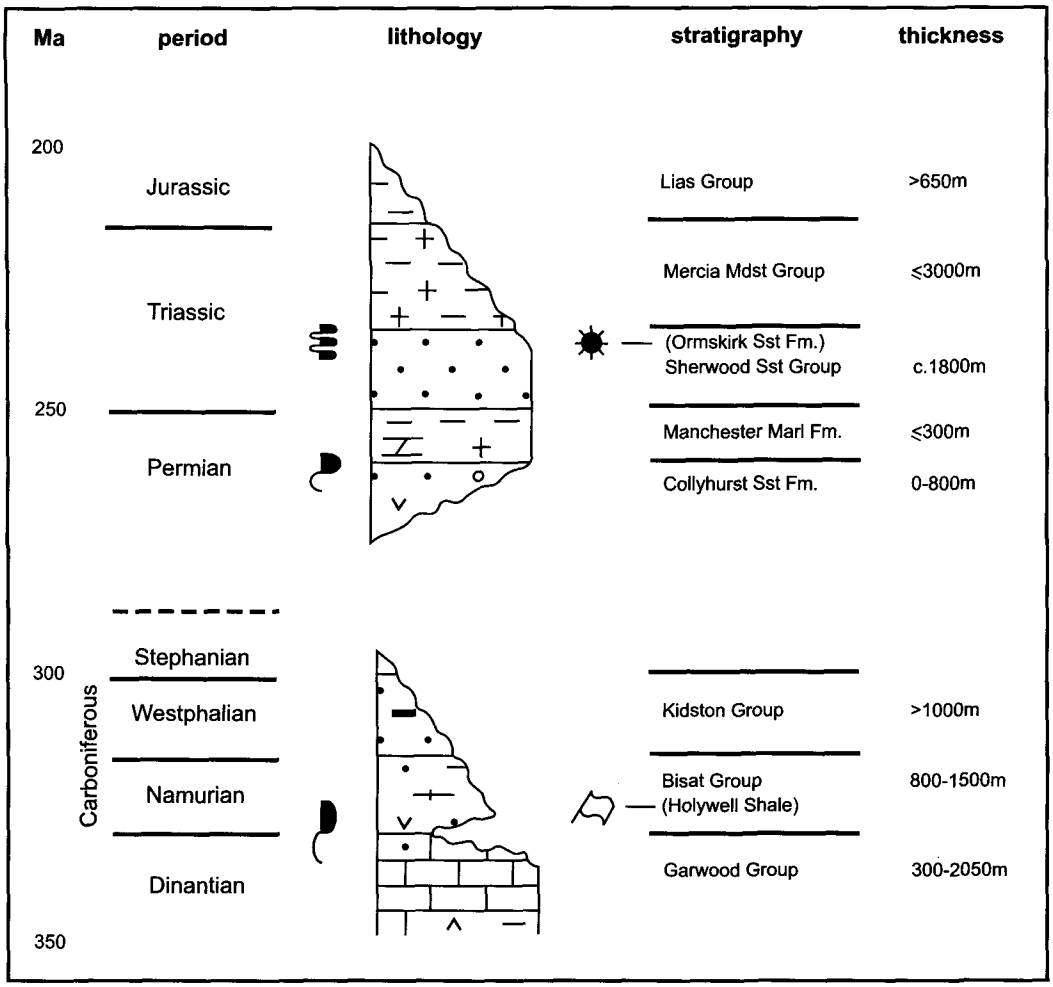


Fig. 2. Simplified stratigraphy for the East Irish Sea Basin using nomenclature formalised by Jackson *et al.* (1997). Thicknesses are those where minimum post-depositional erosion has occurred and are based on information in Jackson and Mulholland (1993), Jackson *et al.* (1997), Quirk and Kimbell (1997) and Cowan *et al.* (1999). Idealised seismic wavelets for key boundaries are also shown. To avoid being constrained by the strict definitions of these lithostratigraphic units, the terms "Formation" (Fm) and "Group" are often omitted in the main text. The suffix "equivalent" is usually applied when discussing similar intervals in areas outside the East Irish Sea.

probably formed during Late Jurassic extension although, in common with the *Morecambe* fields, evidence of an earlier hydrocarbon fill suggest that traps, possibly unfaulted, existed from Early Jurassic times (Yaliz, 1997). The *Hamilton* field together with a related accumulation, *Hamilton North,* contain estimated reserves of 760 BCF gas and *Douglas* contains reserves of approximately 120 MM brls oil (Yaliz, 1997). These fields have been developed by BHP and partners in conjunction with the *Lennox* oil- and gasfield discovered in 1992 by UK well *110/15-6*. The *Lennox* structure consists of a rollover anticline in the hanging wall of the N-S orientated Formby Point Fault and has estimated reserves of 60 MM brls oil and 460 BCF gas (Haig *et al.*, 1997).

A minor onshore accumulation (the *Formby* oilfield, Fig. 1) in the footwall of the Formby Point Fault produced approximately 70,000 brls of oil between 1939 and 1965 when it was abandoned (Colter, 1978). It represents little more than a heavily biodegraded oil seep trapped below Quaternary boulder clay (Falcon and Kent, 1960).

Other discoveries

There are at least six other economic gas discoveries in the East Irish Sea Basin (Fig. 1), four of which are now operated by Burlington Resources. The *Millom, Dalton, Crossans* and *Calder* fields all lie west of and close to the Morecambe Bay development. Unfortunately, the gas in the *Calder* field contains 0.5% H_2S (Blow and Hardman, 1997) and the *Millom* field has poor reservoir properties due to the presence of platy illite and quartz and carbonate cements (Cowan and Bradney, 1997). The platy illite at *Millom* is thought to have been derived from fluids expelled out of the Keys Basin, which lies north and down-dip of the trap, during the Jurassic. The field is a WNW-ESE oriented anticline with a saddle in the middle dividing it into a western and eastern part. The structure is probably younger (?Early Tertiary) than the N-S faults (?Late Jurassic) which define the majority of traps in the East Irish Sea. The *Darwen* and *Asland* discoveries lie closer to the Liverpool Bay development in the south. Another four gas discoveries have been made east of the *Morecambe* fields as well as one gas discovery and three oil discoveries around the Liverpool Bay fields (Fig. 1), but their economic viability is yet to be established.

BEYOND THE EAST IRISH SEA BASIN

A number of smaller basins and related structures lie to the north and west of the East Irish Sea, namely the Keys (or Lagman) Basin, Solway Basin, Peel Basin, Onchan Depression, Ogham Inlier and Eubonia Basin (Fig. 1). Each of these has been tested by one or two wells but none has yet produced hydrocarbons.

A Triassic section remarkably similar to the East Irish Sea is present in the Keys, Solway, Peel and Eubonia Basins (Fig. 2). However, in the Peel and Solway Basins, uplift during the Middle Permian was more severe, at least in part removing potential Upper Carboniferous source rock. Although the Holywell Shale is preserved in the Onchan Depression and Ogham Inlier, the Ormskirk Sandstone is mostly eroded and two wells here have instead tested Permian and Carboniferous levels.

Since 1992, the central part of the Irish Sea has fallen under Manx jurisdiction, with Isle of Man territorial sea extending to 12 miles from the coast of the island (Fig. 1). Manx acreage includes parts of the Solway Basin, Peel Basin, Onchan Depression, Ogham Inlier and Eubonia Basin.

Keys Basin

The Keys Basin represents the northern, deep extension of the East Irish Sea Basin. Seismic mapping indicates that the top of the Carboniferous is buried to a depth of approximately 7,000m in the centre of the basin and is therefore overmature. However, the NW part of the basin, also known as the Lagman Basin (Jackson and Mulholland, 1993), is significantly shallower. Well *112/25-1* (BP in 1982), drilled close to the basin-bounding Lagman Fault in this NW part, encountered gas-bearing Collyhurst Sandstone above the base-Permian unconformity (Fig. 2). It failed to flow during testing, even after fracture stimulation, probably because of a high primary clay matrix. The Manchester Marl overlying the Collyhurst Sandstone is composed largely of halite (equivalent to the St. Bees Evaporites of Jackson and Mulholland, 1993) and seismic data show that minor salt swells are present at this level in the vicinity of the well (Fig. 3). The Ormskirk Sandstone is present but water-bearing and the upper 80m is fairly argillaceous. Although the Ormskirk Sandstone is overlain by a 10-m thick halite layer, the next 60m of Mercia Mudstone is silty with gas shows of up to 11%. The Carboniferous was also encountered

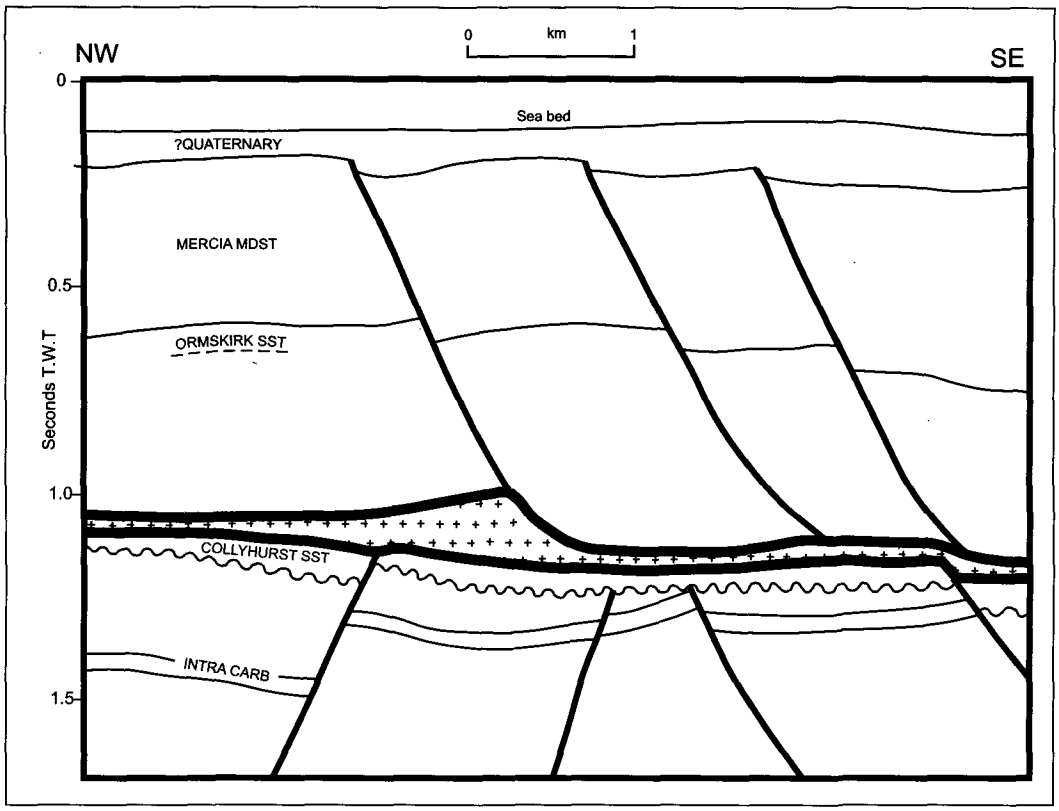


Fig. 3. Simplified 2D geoseismic section of JEBCO line *JS-IOM92-1020* across the NW part of the Keys Basin, close to well *112/25-1*. Note the salt swell (crosses) developed at a level equivalent to the Manchester Marl above the Collyhurst Sandstone and the angular nature of the base-Permian unconformity below the Collyhurst Sandstone. Normal faults affecting the Carboniferous are interpreted to have formed during rifting in the Middle Permian, with the Collyhurst Sandstone deposited as a late syn-rift deposit.

in the well, comprising reddened mudstone in its upper part and Yoredale-type facies of Dinantian age in its lower part (Quirk and Kimbell, 1997). The reddened upper part may represent Holywell Shale oxidised beneath the base-Permian unconformity. The well is now located in Isle of Man territorial sea but it was originally drilled in UK acreage.

Eubonia Basin, Ogham Inlier and Onchan Depression

The Eubonia Basin represents the NW extension of the East Irish Sea Basin and is underlain by a thick Carboniferous section. The top of the Ormskirk Sandstone reaches a depth of a little over 0.35 s two-way-time (TWT) (c. 650m) in several places. UK well *109/5-1* (Esso in 1996) tested a NW-SE trending tilted fault block but is rumoured to be dry.

The Ogham Inlier lies immediately north of the Eubonia Basin (Fig. 1). It comprises a post-Triassic horst block centred on a pre-existing Variscan (end-Carboniferous) inversion structure (Fig. 4) with the base-Permian unconformity lying at or close to the sea bed (Quirk and Kimbell, 1997). Oil shows were encountered in Upper Carboniferous fluvio-deltaic sandstones in UK well *112/30-1* (Cluff Oil in 1975/76), drilled on the flank of the Variscan structure.

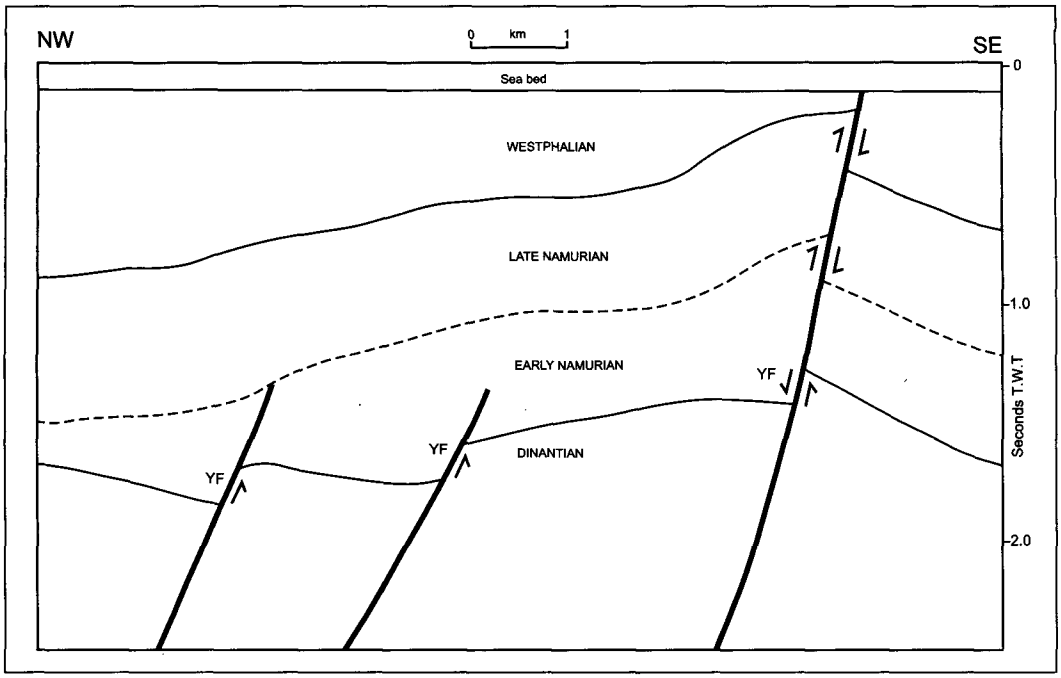


Fig. 4. Simplified 2D geoseismic section of JEBCO line *JS-MANX-128* across part of the Ogham Inlier. The section shows a major Variscan (end-Carboniferous) inversion structure which developed by reactivation of an Early Namurian growth fault. The Early Namurian section is interpreted to contain Holywell Shale as well as possible Yoredale-type facies (YF) in the hanging-walls of this and other syn-sedimentary normal faults. See text for discussion.

The Onchan Depression represents a sub-basin on the western side of the Ogham Inlier located in Manx territorial waters (Fig. 1). Permo-Triassic strata dip west towards the intersection of the NNE-SSW Eubonia Fault with a NW-SE structural lineament which bisects the Isle of Man (Quirk and Kimbell, 1997). From seismic data, it appears that the Ormskirk Sandstone lies close to the sea bed or is entirely eroded due to the effects of post-Triassic uplift. The base-Permian unconformity reaches a maximum depth of 0.75s TWT (c. 1,400m) close to the Eubonia Fault. Seismic facies analysis suggests that the unconformity is overlain by Collyhurst Sandstone and is sub-cropped by an unusually young Carboniferous section. These ?Late Westphalian-Stephanian strata may represent molasse-type sediments deposited during growth of the Variscan inversion structure which forms the core of the Ogham Inlier to the east (Quirk and Kimbell, 1997). The down-dip end of a narrow NNW-SSE trending horst was tested without success by Manx well *112/29-1* (Marathon in 1996) where the risks of poor reservoir (?Collyhurst Sandstone) and unreliable seal (?Manchester Marl) were high.

Peel Basin

The Peel Basin lies to the west of the Isle of Man and represents a complex half-graben defined at its NW end by the N-S trending St. Patrick Fault zone (Fig. 5). Permo-Triassic strata dip towards this set of faults and away from a series of north-dipping normal faults which connect with the Isle of Man (Fig. 6). The eastern side of the basin pinches out towards the Manx coast, where Permo-Triassic strata are truncated at the sea bed. The southern margin of the basin is difficult to map on seismic data. The Ormskirk Sandstone

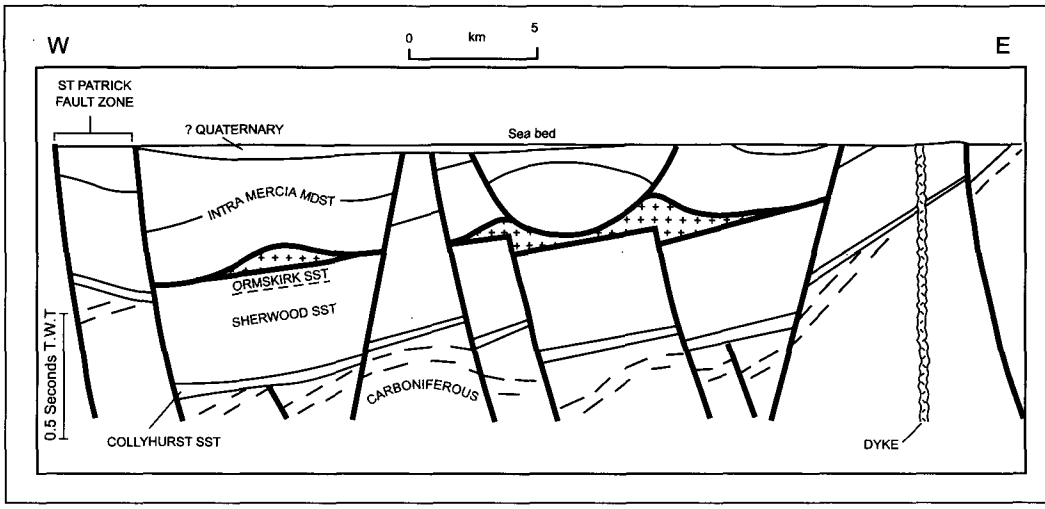


Fig. 5. Idealised geoseismic section across the Peel Basin based on a composite of NW-SE and NE-SW orientated 2D seismic lines owned by JEBCO.

equivalent reaches a maximum depth of 0.75 s TWT (c. 1,350m) close to the St. Patrick Fault zone. The basin contains many dolerite dykes and sills of Tertiary age.

Salt is present in the Mercia Mudstone and Manchester Marl equivalents. This salt plays an important role in the type of structures developed in the Peel Basin in that faults sole-out onto it, often in association with minor halokinetic swells (Figs. 5 and 7). As a consequence, the Sherwood Sandstone equivalent above the Manchester Marl is more highly faulted than the Collyhurst Sandstone equivalent underlying it. Furthermore, faults in the Mercia Mudstone commonly dip in a direction opposite to those in the Sherwood Sandstone (Fig. 7).

The basin has been tested dry by Elf in UK wells *111/29-1* and *111/25-1* (Figs. 6 and 8) drilled in 1994 and 1996, respectively (Newman, 1999 *this issue*). Both wells are relatively shallow but their failure can be explained by the absence of Holywell Shale equivalent source rock. Instead, shallow-water Dinantian carbonates were found directly in contact with the base-Permian unconformity (Fig. 8). Limited gas shows were encountered in the Permian in UK well *111/25-1* indicating that there may be limited source rock potential within the Dinantian or older.

Solway Basin

In common with the Peel Basin, the Solway Basin represents a complex half-graben, in this case dipping NW, away from the up-thrown foot wall of the Lagman Fault (the Ramsey-Whitehaven Ridge) and towards the North Solway Fault (Fig. 1). The western and eastern margins of the basin are partly controlled by a number of N-S oriented normal faults. The top of the Ormskirk Sandstone equivalent reaches a maximum depth of a little over 1.0 s TWT (c. 1,750m) near the centre of the basin where the strata have a synclinal form (Newman, 1999 *this issue*).

Again, salt has influenced Triassic structures with domino faulting in the Sherwood Sandstone accommodated by pinch and swell of halite in the Manchester Marl equivalent. Evidence of halokinesis and dissolutional collapse is also seen on seismic profiles within the Mercia Mudstone equivalent.

In a similar story to the Peel Basin, neither UK well *112/15-1* (Esso in 1996) nor Manx well *112/19-1* (Elf in 1996/97) in the Solway Basin have discovered hydrocarbons in the

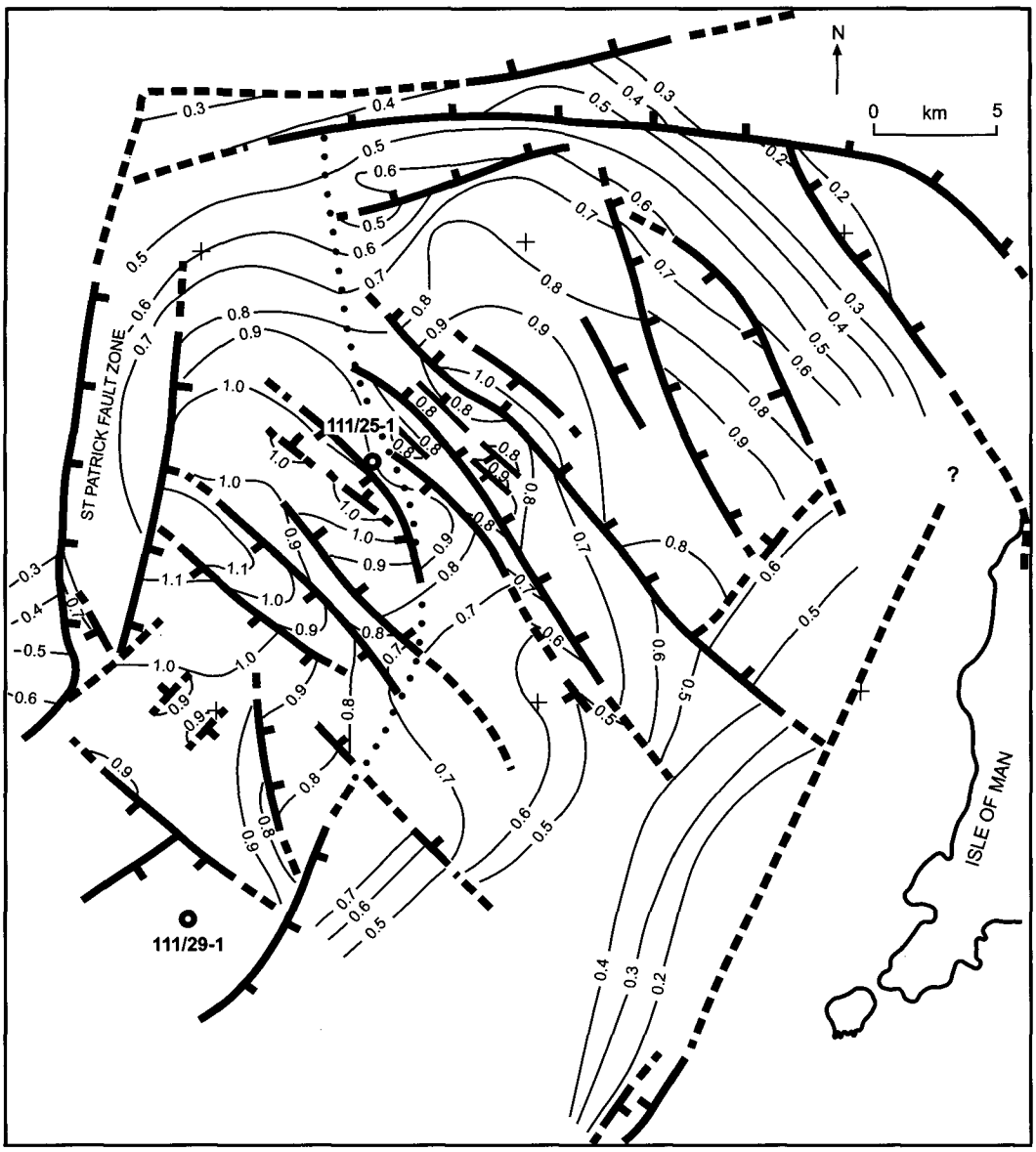


Fig. 6. Simplified structure map of the northern half of the Peel Basin in seconds two-way-time at the top of the Collyhurst Sandstone equivalent based on an interpretation of 2D seismic data owned by JEBCO. Dashed lines indicate uncertainty in fault interpretation in areas of limited seismic coverage. Dotted line shows the position of a possible structural divide below the base-Permian unconformity.

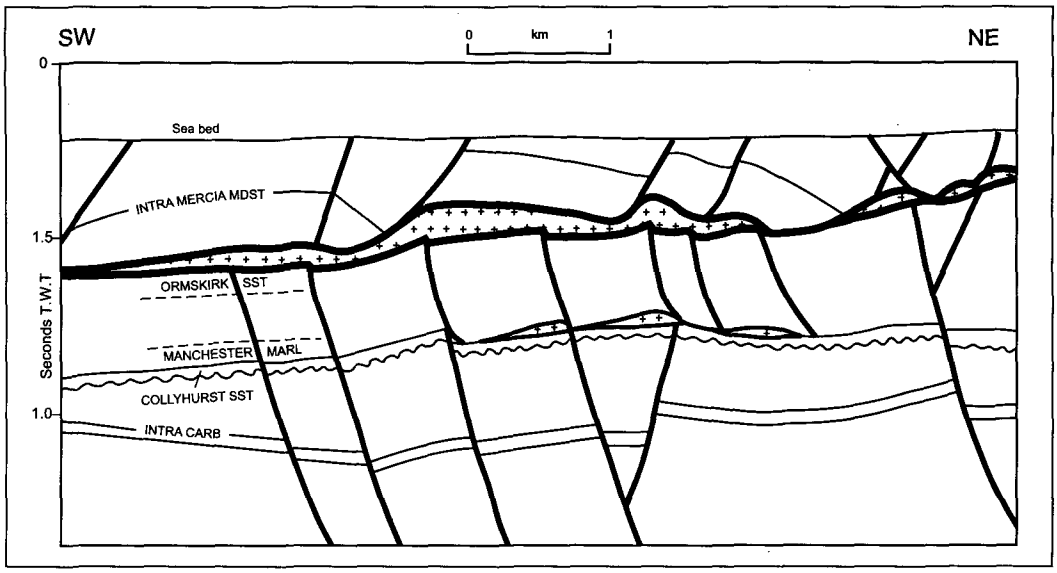


Fig. 7. Simplified 2D geoseismic section of JEBCO line *JSM-92-37* across part of the Peel Basin. The section illustrates the effect that salt (indicated by crosses), through which faults do not propagate, has on structural styles.

Ormskirk Sandstone equivalent. Dinantian-Early Namurian Yoredale-type facies rather than source rock sub-crop the base-Permian unconformity in well *112/19-1* although traces of oil were encountered in the Triassic (Newman, 1999 *this issue*). Two onshore wells at the SW margin of the Solway Basin on the Isle of Man do, however, contain Namurian shales with TOCs of 1-4% and low-moderate gas-generating potential (Quirk and Kimbell, 1997; Racey *et al.*, 1999 *this issue*). In addition, the Cumbrian coal field on the eastern side of the Solway Basin contains significant amounts of gas-prone source rock as well as fluvial sandstones with reservoir potential within the Westphalian (Quirk and Kimbell, 1997). Porous fluvio-deltaic sandstones of Late Namurian age are also present in the two onshore boreholes on the Isle of Man.

In addition to questions about the source rock, the problem of charging the Ormskirk Sandstone is compounded by the presence of halite in the Manchester Marl (e.g. Fig. 9), which is likely to impede secondary migration. Instead, similar to well *112/25-1* in the NW part of the Keys Basin, it is possible that hydrocarbons will be preferentially trapped within the Collyhurst Sandstone equivalent.

The Ramsey-Whitehaven Ridge represents the uplifted footwall of the Lagman Fault, defining the NW margin of the Keys Basin (Fig. 1). As much as 4km of vertical offset is recorded on this fault. A significant part of this fault movement is thought to be post-Triassic, probably Late Jurassic in age (Quirk and Kimbell, 1997). However, seismic data show that towards the crest of the ridge, increasingly older Carboniferous strata are truncated below the base-Permian unconformity in the footwall of the Lagman Fault suggesting that it first developed as a tilted fault block during rifting in Middle Permian times. The Ramsey-Whitehaven Ridge represents a structural extension of the Isle of Man and therefore the island itself may have been formed at this time. By how much it was buried in the Triassic and Cretaceous is poorly constrained but is nonetheless of scientific interest (cf. Green *et al.*, 1997; Racey *et al.*, 1999 *this issue*).

UK well *Easton-1* was drilled onshore at the eastern end of the Solway Basin by Edinburgh Oil and Gas in 1990. The well encountered non-commercial gas in the Dinantian with an unexpectedly thick succession of mixed anhydrite-carbonate-siliciclastic sediments (Ward, 1997).

Related basins bordering the Irish Sea

The Kish Bank Basin lies between the Peel Basin and the Central Irish Sea Basin in Irish territorial waters. It is controlled by two faults trending NE-SW and NW-SE on the western side of the basin (the Lambay-Dalkey and Bray Faults, respectively: Fig. 1) (Naylor *et al.*, 1993). Stratigraphically, it is similar to other Permo-Triassic basins in the Irish Sea region with good reservoir quality Ormskirk- and Collyhurst-equivalent sandstones (Naylor and Shannon, 1999 *this issue*). It has been tested by four dry wells, the last of which (*33/17-2*) was drilled in 1997/98 by Enterprise. Unlike the Peel Basin, Upper Carboniferous rocks (including coal-bearing Westphalian strata) have been encountered and show present-day maturity, but the distribution of these and the timing of trap formation is apparently less favourable than the East Irish Sea Basin (Corcoran and Clayton, 1999 *this issue*; Naylor and Shannon, 1999 *this issue*). However, shallow gas accumulations are known to be present in thin Eocene-Recent sediments (Croker, 1998) and a fifth exploration well is planned by Enterprise in 1999.

The North Channel Basin lies to the NW of the Irish Sea. At its southern end, the Portpatrick Sub-Basin dips ENE towards the Portpatrick Fault (Fig. 1, Maddox *et al.*, 1997) and was tested by UK well *111/15-1* (BG, 1995) where the Ormskirk Sandstone equivalent was reported to be water-bearing.

Onshore, a small gasfield has been developed at *Elswick* on the eastern margin of the Irish Sea (Evans, 1998). The reservoir is the Collyhurst Sandstone with production from a single well. A number of coal-bed methane tests have also been made in Westphalian strata in north Wales and Cheshire on the SE side of the Irish Sea.

FUTURE HYDROCARBON POTENTIAL

In summary, the East Irish Sea Basin is particularly hydrocarbon prolific due to the following factors: (i) the presence of thick Holywell Shale source rock; (ii) an optimum geothermal history; (iii) a relatively simple migration path from source to reservoir; (iv) the excellent reservoir properties of the Ormskirk Sandstone; (v) a salt-prone seal; and (vi) fault-related structuration. Current well and seismic data indicate that beyond the Morecambe and Liverpool Bay areas, a number of these elements are absent. The critical factor, however, at least in the Peel and Solway Basins, remains the apparent lack of source rocks (Newman, 1999 *this issue*; Naylor and Shannon, 1999 *this issue*). Except where Upper Carboniferous strata can be mapped on seismic outside areas already drilled (e.g. Fig. 9), or until the presence of older source rocks in, for example, the Dinantian can confidently be predicted, it seems likely that these basins will remain fairly unprospective. A number of exploration commitments still exist in the Solway, North Channel and Kish Bank basins but due to the perceived charge problems, it seems sensible to carry out a seep detection survey before any future wells are drilled.

Of course, by analogy with the Southern North Sea, additional prospectivity still exists in the East Irish Sea Basin. For example, it may be worth looking for potential stratigraphic traps in the Triassic, either at Ormskirk Sandstone level, where up-dip migration may be impeded by areas of severe diagenesis or the presence of Tertiary dykes, or at other levels, where laterally impersistent sandstone bodies might exist, particularly towards the margins of the basins. The identification of amplitude anomalies on seismic may help in this search (e.g. Francis *et al.*, 1997) although this sort of study needs careful integration with high-resolution aeromagnetic data to avoid mistaking igneous bodies for direct hydrocarbon indications (cf. Arter and Fagin, 1993).

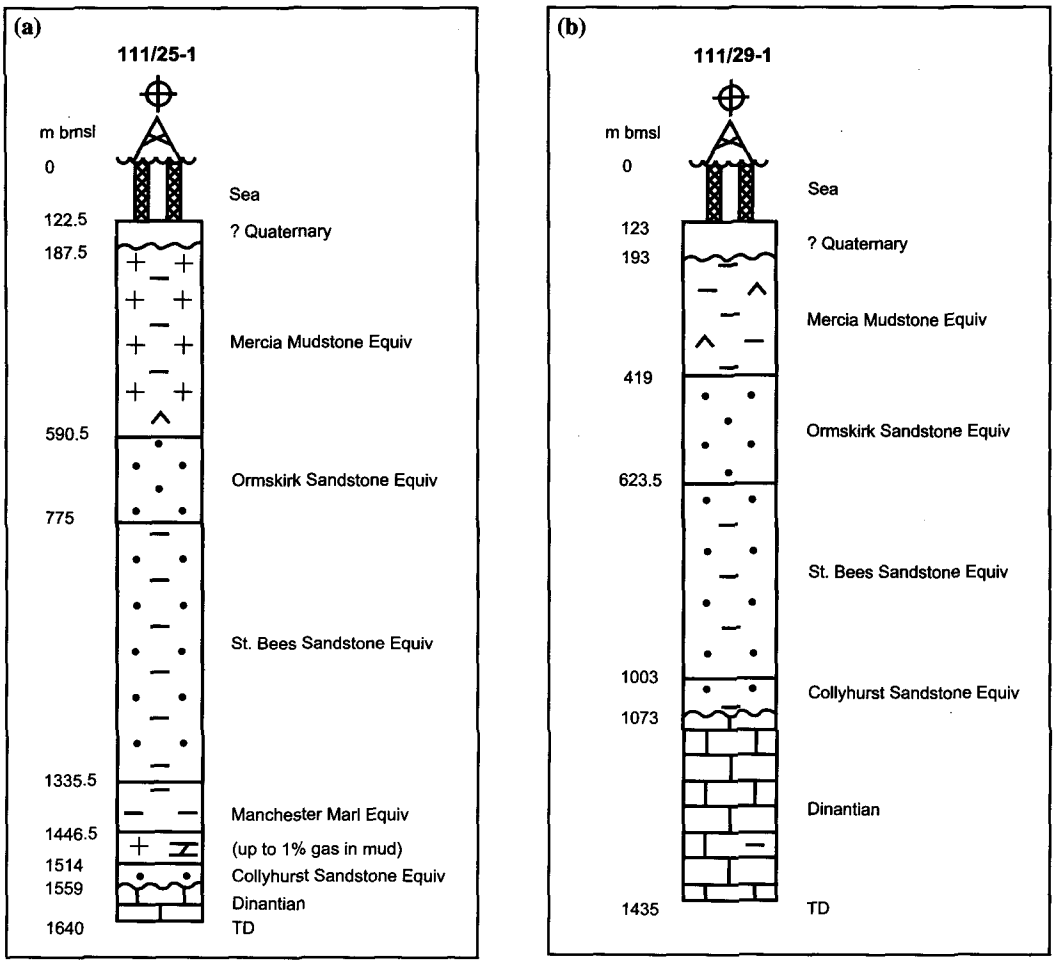


Fig. 8. Simplified stratigraphic log of (a) UK well *111/25-1* and (b) UK well *111/29-1*, both drilled in the Peel Basin. See Fig. 6 for locations.

So far, the potential of the Collyhurst Sandstone as a secondary target has proved disappointing. It is largely aeolian, but its distribution, thickness and reservoir quality have proved fairly unpredictable. However, deeper reservoirs may also exist. Quirk and Kimbell (1997) and Racey *et al.* (1999 *this issue*) point out that porous Upper Carboniferous sandstones have been encountered in well *112/30-1* and onshore Isle of Man and Cumbria. Furthermore, Quirk and Kimbell (1997) observed thickening and brightening of seismic reflections on the down-thrown side of normal faults active during the Early Namurian (Fig. 4). They suggest that such intervals may comprise fluvio-deltaic Yoredale-type facies (cyclic sandstones, shallow-marine carbonates, coals and shales) with both reservoir and source potential. There is the additional possibility of a fractured basement play, for example along the Ramsey-Whitehaven Ridge, an idea which is lent support by evidence of oil migration through veins in metamorphic rocks exposed onshore (e.g. Parnell, 1997).

Remaining questions

Although exploration in the East Irish Sea can be regarded as having entered the mature stage, many geological uncertainties still exist, some of which have direct bearing on the future hydrocarbon prospectivity of this area and related basins.

Of particular interest is the burial history. This is hard to constrain because of the existence of two regional unconformities, at base-Permian level and close to the sea bed. The base-Permian unconformity is highly angular due to the combined effects of Variscan compression in the Late Carboniferous and thermal doming in the Middle Permian associated with the Saalian rifting event (Quirk and Kimbell, 1997). Evidence for very high heat flows during the Early-Middle Permian is now emerging (e.g. Corcoran and Clayton, 1999 *this issue*) implying that Carboniferous source rocks may have reached higher maturity than previously thought prior to burial in the Permo-Triassic (cf. Green *et al.*, 1997).

Although evidence of variations in the thickness of the Sherwood Sandstone and Mercia Mudstone have previously been interpreted as indicating that rifting continued during the Triassic (e.g. Knipe *et al.*, 1993), it is more likely that the Triassic was in fact a time of passive continental subsidence with isostatic readjustment on faults rather than active extension (Quirk and Kimbell, 1997; Herries and Cowan, 1997). This fits with a model of thermal sag following Permian rifting and helps to explain the remarkable lateral continuity of the main lithostratigraphic units (cf. Jackson and Mulholland, 1993). Nevertheless, Triassic strata are affected by post-depositional normal faults displaying offset of hundreds to thousands of metres close to the sea bed, interpreted by the present authors as either Late Jurassic (probably those orientated N-S to NE-SW) or Early Tertiary (probably those orientated NW-SE) in age (cf. Bushell, 1986; Quirk and Kimbell, 1997).

The amount of uplift and erosion that occurred during the Middle Permian may be as much as 3km in places where Stephanian, Westphalian and Namurian strata have been removed. Estimates ranging between 1 and 3km for uplift during the Early Tertiary have been made on the basis of apatite fission-track analysis (e.g. Lewis *et al.* 1992; Holliday, 1993), vitrinite values (e.g. Lenehan, 1998), compaction calculations (e.g. Colter, 1978), and reconstructed Cretaceous thicknesses (e.g. Cope, 1997). In fact, assuming that the interpretation of Late Jurassic tectonism is correct, then two post-Triassic uplift events may have occurred. The nature of the Early Tertiary event is still debatable, but it is probably related to the brief establishment of a mantle hot-spot some 65-60 Ma ago causing intrusion of swarms of dolerite dykes (e.g. Arter and Fagin, 1993), elevated geothermal temperatures (e.g. Hardman *et al.* 1993; Green *et al.* 1997) and hydrothermal fluid flow (e.g. Green *et al.* 1993; Greenwood and Habesch, 1997). It is perhaps surprising that with this amount of uplift and associated effects that any hydrocarbons have been preserved in the East Irish Sea Basin at all. This not only vouches for the integrity of the Mercia Mudstone seal during gas expansion and tertiary migration, but hints at the possibility that inversion facilitates primary migration by over-pressuring the source rock. One way of better constraining models of hydrocarbon charge would be to integrate existing and additional burial history data with diagenetic information on a regional rather than local scale (cf. Bushell, 1986; Macchi *et al.* 1990; Greenwood and Habesch, 1997; Cowan and Bradney, 1997).

Other parameters which require further investigation by regional studies are differences in hydrocarbon type and quality and the prediction of seal capacity. Problems also exist in seismic time to depth conversion because of the presence of large faults and salt in the Triassic and variations in the thickness and velocity of Quaternary sediments at the sea bed. However, even if new discoveries are made, significant development challenges still exist. For example, deciding on the optimum recovery method is not straightforward due to the shallow depth and structural complexity of traps, diagenetic problems within

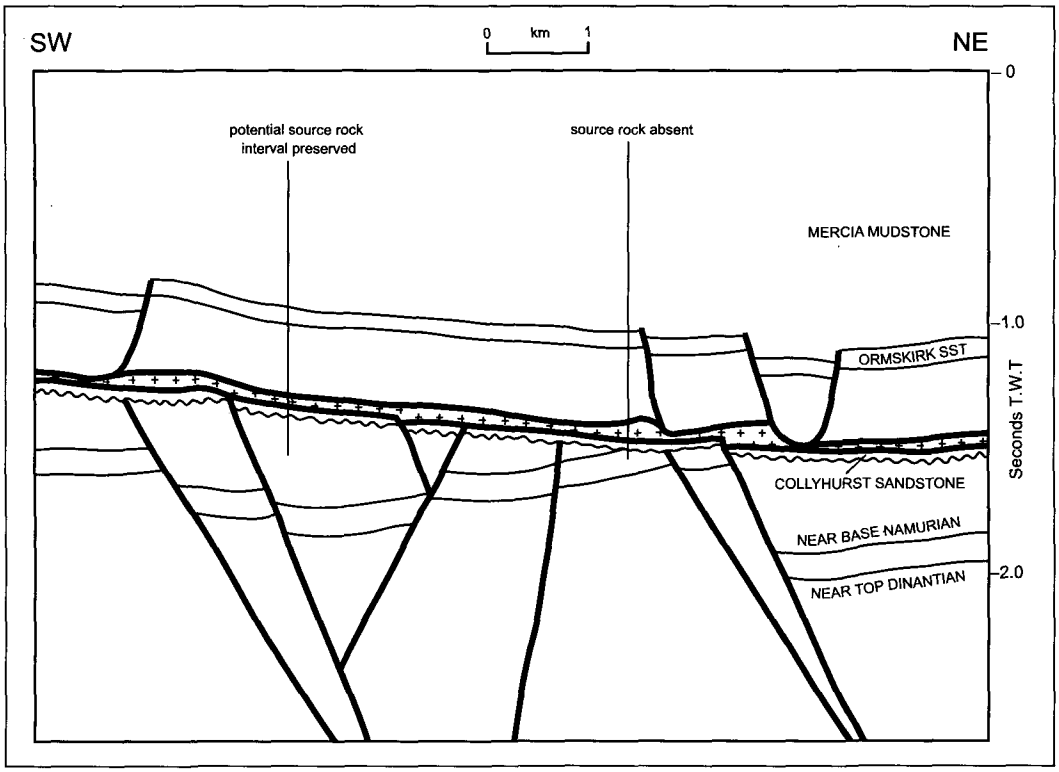


Fig. 9. Simplified 2D geoseismic section of JEBCO line *JS-IOM92-27* from the Solway Basin. Even where erosional truncation is severe, Namurian source rocks are more likely to be preserved below the base-Permian unconformity on the down-thrown side of normal faults active during the Middle Permian. Salt in the Manchester Marl equivalent is indicated with crosses.

the reservoir and difficulties in maintaining fluid pressure over time. Nonetheless, the *Dalton* and *Millom* gasfields are now under development, a number of smaller field developments are planned, and the exploration potential remains high.

CONCLUSIONS

The Irish Sea region contains a superb reservoir-seal pair of Triassic age – the Ormskirk Sandstone and Mercia Mudstone and their lateral equivalents. In the Peel and Solway Basins, hydrocarbon charge is problematic due to the widespread absence of Upper Carboniferous source rock and possible difficulties in migration through the Permian. The low chance of exploration success beyond the known oil and gas trend in the East Irish Sea Basin will only improve if direct hydrocarbon indications in the form of seeps or seismic amplitude anomalies are observed. Although additional plays may exist at Permian and Carboniferous levels, these are regarded as of much higher risk than traditional Triassic fault-block targets in the East Irish Sea. The potential for stratigraphic traps is so far untested. In addition, the effect that uplift in the ?Late Jurassic and in the Early Tertiary has had on charge and trap integrity is still not fully understood.

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