PALYNOLOGICAL AND GEOCHEMICAL ANALYSIS OF CARBONIFEROUS BOREHOLE AND OUTCROP SAMPLES FROM THE ISLE OF MAN

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Palynological and geochemical analyses were performed on Namurian (mid-Carboniferous) samples from the Ballavaarkish and Shellag Point boreholes from the north of the Isle of Man, and on Dinantian/Namurian outcrop samples from Black Marble Quarry in the south of the island.

The boreholes yielded a rich and diverse (over 60 species) Namurian B-C (Kinderscoutian-Yeadonian) palynomorph assemblage equivalent to the KV/FR Zones of Clayton et al. (1977). Reworked Brigantian-Namurian A palynomorphs of the NC/TK Zones were recorded in the Shellag Point borehole. Offshore seismic data indicates a period of major fault activity in the early Namurian which may support this concept of early Namurian reworking. Amorphous organic matter indicating anoxic/dysoxic depositional conditions together with prasinophyte algae and goniatites suggesting a marine environment were recorded in the Shellag Point borehole.

Vitrinite reflectance and spore colouration measurements coupled with Tmax data from Rock-Eval pyrolysis indicate that the Namurian shales from the Shellag Point borehole are currently in the oil window. Rock-Eval data and kerogen analyses indicate that these shales represent moderate to good gas-prone source rocks which have yet to attain full maturity. The Namurian samples from Ballavaarkish are mainly in the oil window or late mature zone and have poor gas potential. Extract chromatography indicates a relatively mature product and the possible onset of hydrocarbon biodegradation, particularly in the Ballavaarkish borehole samples.

Outcrop samples from near the top of the succession at Black Marble Quarry underwent thermal alteration as a result of dyke intrusion and subsequent volcanism. Although previously believed to be Brigantian (end-Dinantian) in age based on goniatites, corals

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and conodonts, the samples have produced a sparse palynological assemblage indicating an apparent age no older than Namurian. The samples are late- to post-mature in terms of hydrocarbon generation and have no remaining source potential.

The results indicate that where Namurian sediments are preserved beneath the base-Permian unconformity, for example in the Solway Basin, hydrocarbons are likely to have been generated.

INTRODUCTION

We report here on palynological and geochemical analyses of a series of Carboniferous borehole and outcrop samples from the Isle of Man (Fig. 1). Samples came from the *Shellag Point* and *Ballavaarkish* boreholes, which were drilled in the north of the island by Riofinex in 1985, and from Black Marble Quarry near Poyllvaaish in the south (Fig. 1). The borehole samples represent the unexposed southern portion of the Solway Basin. The Quarry samples are representative of potential source rocks in the Peel and Eubonia Basins to the east and west of the southern end of the Isle of Man. Carboniferous source rocks are well known from the East Irish Sea Basin (the Namurian Hollywell Shale: Armstrong *et al.*, 1997).

The objectives of this study were to date potential Carboniferous source rocks on the Isle of Man using palynology, to assess their maturity and richness, and to briefly assess the reservoir potential of the interbedded sandstones.

CARBONIFEROUS LITHOSTRATIGRAPHY, ONSHORE ISLE OF MAN

The earliest well-dated post-Caledonian sedimentary rocks on the Isle of Man comprise a 350-m thick outlier of Lower Carboniferous (Dinantian) limestones, shales and dolomites assigned to the Castletown Group (Fig. 2). These occur in the south of the island and are believed to range in age from Arundian to Brigantian (Dickson *et al.*, 1987). Shales within this succession are often rich in terrestrial plant material and brackish water bivalves with marine goniatites preserved at some levels (Quirk *et al.*, 1990). Porosity-filling bitumen has been recorded in dark limestones within this Group. Pyrobitumens are also present, and fill a series of NW-SE trending faults/fractures which run broadly parallel to the Tertiary dykes which are common on the Isle of Man and which are often filled with calcite and quartz. Fluid-inclusion analyses of these cements suggest that they formed at 200-220°C, indicating hydrothermal activity associated with Tertiary dyke intrusion (Parnell, 1997).

The mudstone samples from Black Marble Quarry came from the Close-ny-Chollagh Formation in the upper part of the Castletown Group (Fig. 2). This formation is overlain by basaltic volcanic rocks of the Scarlett Volcanic Formation (Dickson *et al.*, 1987).

The *Shellag Point* and *Ballavaarkish* boreholes encountered different Carboniferous successions below a thick Quaternary cover. At *Ballavaarkish*, the Carboniferous succession is divided into two by a fault zone (Fig. 3). The lower part (below sample *IOM8*) comprises Dinantian shallow-water limestones; above the fault, 45m of grey mudstones and sandstones occur, and samples *IOM 4-8* were taken from the middle and lower parts of this interval. Quirk and Kimbell (1997) proposed that these sandstones are of fluvio-deltaic origin and are probably Silesian in age. In general, the mudstones are interpreted to be lacustrine with the exception of a thin marine band containing a single poorly-preserved goniatite (sample *IOM 5:* Quirk and Kimbell, 1997).

The Carboniferous succession at the *Shellag Point* borehole (Fig. 4) includes a 28-m thick interval comprising upper Namurian, grey-dark grey mudstones and silty mudstones deposited in a lacustrine or brackish-water environment (as indicated by the occurrence of lamellibranchs). Samples were taken from the upper part of this interval (*IOM 1-3*).

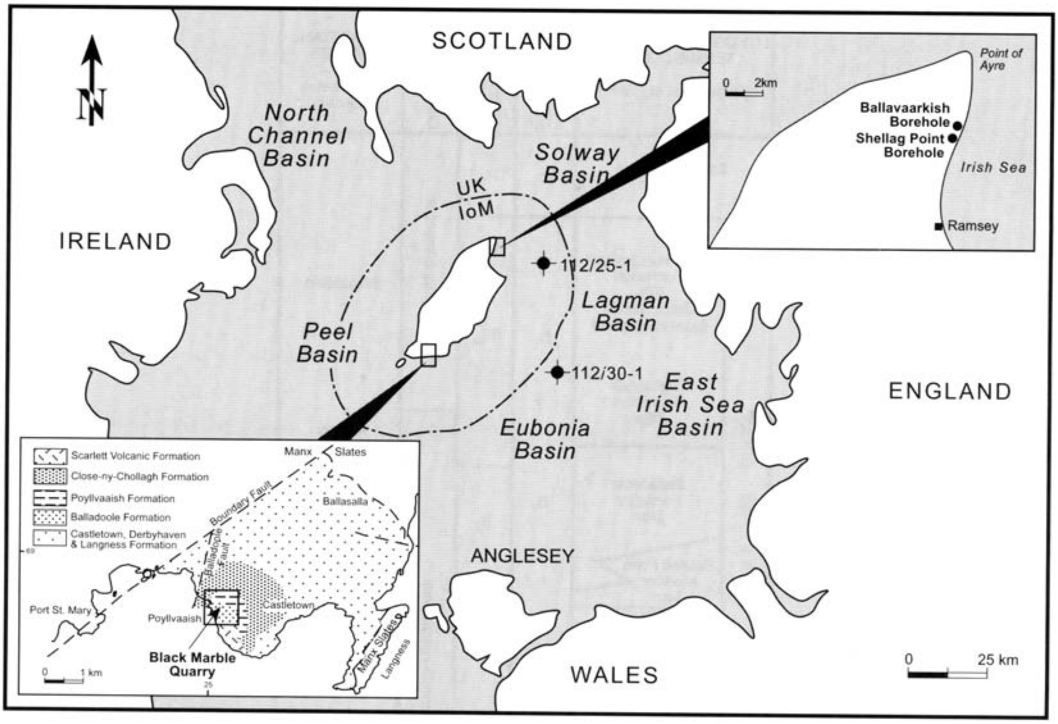


Fig. 1. Location of the Isle of Man in the Central Irish Sea with inset locality maps of borehole and quarry locations (modified from Quirk and Kimbell, 1997).

PALYNOLOGY AND PALYNOFACIES

Analytical Procedures

The samples were acid-digested using HF and HCl and then oxidised using concentrated nitric and fuming nitric acid, with oxidation times varying from one to twenty minutes. The organic residue recovered was sieved through a ten micron mesh and the material was slide mounted. Total counts on the 10+ micron slide were then performed to include all components of the sample i.e. spores and acritarchs.

The Carboniferous zonation used in this paper is that of Clayton *et al.* (1977). Quantitative palynological distribution charts for the three studied sections are given in Tables 1, 2 and 3, and a summary diagram showing the key age diagnostic taxa for the three localities calibrated against the standard palynological zonation for the Carboniferous is given in Fig. 5.

Ballavaarkish borehole samples (Table 1)

Palynological analyses of these samples has yielded a diverse (64 species) assemblage. The presence of *Lycospora pusilla* (Ibrahim) Somers, *Crassispora konsankei* (Potonie & Kremp) plus rarer *Reticulatisporites reticulatus* Ibrahim, *Rugosaspora corporata* Neves & Owens, *Spelaeotriletes arenaceous* Neves & Owens and *Ibrahimispores brevispinosus* Neves is considered to indicate a Namurian B/C (Kinderscoutian-Yeadonian) age for this sequence, equivalent to the KV/FR Zones of Clayton *et al.* (1977). Moreover, the unusual association of *R. reticulatus* and *R. corporata* suggests a most probable age close to the Namurian B/C boundary (i.e. Marsdenian/Yeadonian boundary, arguably FR Zone). The first downhole occurrence of *R. corporata* in samples *IOM7* and *IOM8* is usually taken to indicate a mid-Marsdenian age, although in recent years the stratigraphic

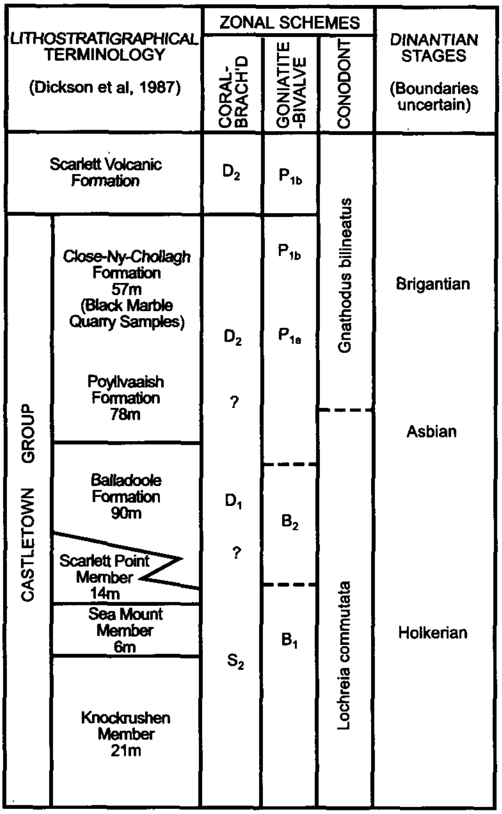


Fig. 2. Stratigraphic subdivision of the Dinantian Castletown Group, southern Isle of Man (modified from Dickson *et al.*, 1987).

Sample Number	*Reticulatisporites spp*	*Auroraspora solisortus*	*Cyclogranisporites*	*Crassispora kosankei*	*Calamospora pallida*	*Spelaeotriletes arenaceous*	*Schulzospora rara*	*Leiotriletes tumidus*	*Raistrickia saetosa*	*Discernisporites micromanifestus*	*Knoxisporites dissidius*	*Knoxisporites spp*	*Schulzospora spp*	*Lycospora pusilla*	*Florinites pumicosus*	*Reticulatisporites reticulatus*	*Apiculatisporites aculeatus*	*Kraeuselisporites echinatus*	*Calamospora spp*	*Anapiculatisporites spp*	*Reinschospora speciosa*	*Ahrensisporites guerickii*	*Verrucosisporites spp*	*Lycospora noctuina*	*Dictyotriletes reticulocingulum*	*Raistrickia spp*	*Spinozonotriletes uncatus*	*Dictyotriletes muricatus*	*Cristatisporites spp*	*Rugospora corporata*	*Proprisporites laevigatus*
IOM4	2	1	1	12	1	6	1	1	1	3	1	1																			
IOM5				3		1							1	1	1																
IOM6				·	1											3															
IOM7				56					1			1	1	123		2	2	1	8	1	1	2	3	5	4	2	1	1	1	2	32
IOM8				7	3	3	1	7	4	1		3	8	47		6												6	9	3	3
IOM19								8	1	2	6	3		45	4	4															

Sample Number	*Auroraspora macra*	*Raistrickia fulva*	*Calamospora parva*	*Savitrisporites nux*	*Florinites spp*	*Convolutispora spp*	*Radiizonates spp*	*Cyclogranisporites aureus*	*Vallatisporites spp*	*Acanthotriletes spp*	*Anaplanisporites baccatus*	*Spencerisporites radiatus*	*Discernisporites irregularis*	*Granulatisporites granulatus*	*Knoxisporites rotatus*	*Spelaeotriletes spp (small)*	*Reticulatisporites polygonalis*	*Lophotriletes spp*	*Lycospora rotunda*	*Raistrickia aculeata*	*Punctatisporites spp*	*Leiotriletes spp*	*Knoxisporites stephanephorus*	*Dictyotriletes spp*	*Laevigatosporites spp*	*Dictyotriletes mediareticulatus*	*Camptotriletes spp*	*Ibrahimispores brevispinosus*	*Punctatisporites sinuatus*	*Secarisporites remotus*	*Trinidulus diamphidios*	Scolecodont
IOM4																																
IOM5																																
IOM6																																
IOM7	1	7	2	36	1	7	43	1	1	2																						
IOM8	3			17	5	4	23		3	1	3	1	1	3	1	4	8	3	65	1	37	16	2	1	5							1
IOM19	1	1	1	4	65	4	3	¼													54	47	4	1	2	1	1	1	1	3	3	

Table 1. Quantitative palynological ditribution chart for the *Ballavaarkish* borehole.

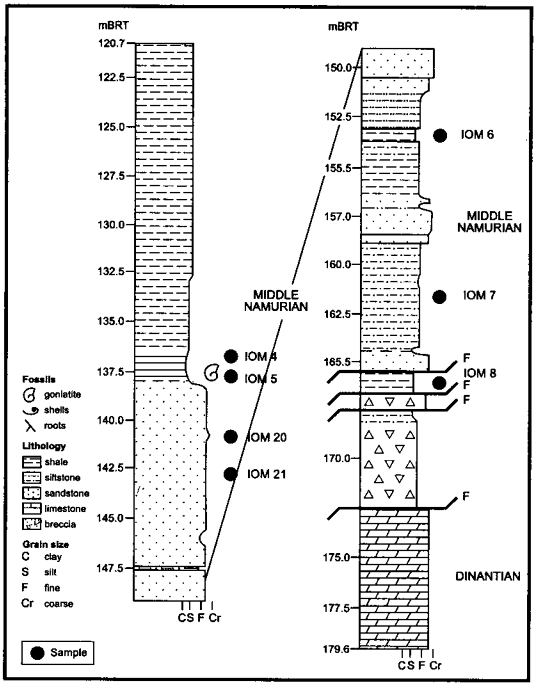
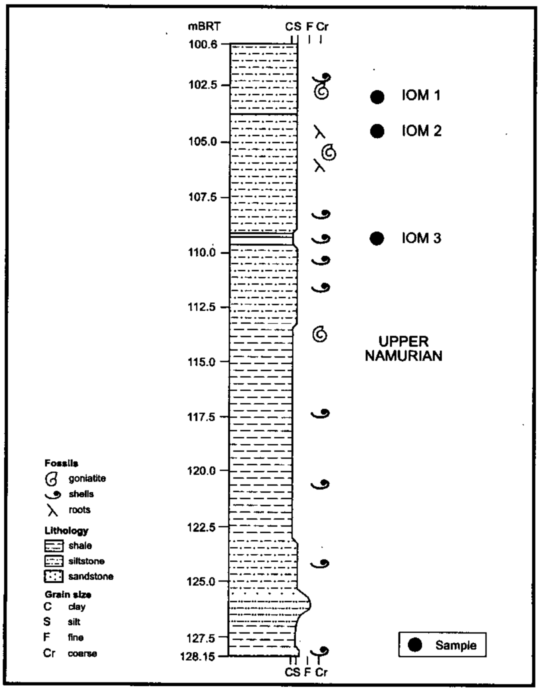


Fig. 3. Sedimentary log of the *Ballavaarkish* borehole (grid reference SC 462 007) (after Quirk and Kimbell, 1997).

Fig. 4. Sedimentary log of the *Shellag Point* borehole (grid reference SC456 996) (after Quirk and Kimbell, 1997).



top of this taxon has crept higher into the mid- to late Yeadonian. *R. reticulatus* present in samples *IOM6-8* and *19* has a stratigraphic base within the mid-Marsdenian, although Clayton *et al.* (1977) put the base of this taxon at the base of the Yeadonian with a range up into Westphalian D. The presence of *Kraeuselisporites echinatus* Owens, Mishell & Marshall in sample *IOM7* and *Raistrickia fulva* Artuz in *IOM7* and *IOM19* suggests an age no younger than mid-Marsdenian and no older than mid-Kinderscoutian. The presence of *Proprisporites laevigatus* indicates an age no younger than top-Marsdenian (Namurian B) within the KV zone. A local abundance of *Raistrikia fulva* may be broadly correlatable with a similar "event" noted in the Maltraeth Bay section on Angelsey to the SE (JGSG, *pers. obs.*). There is a distinct change in assemblage between samples *IOM 7* and *IOM6* where palynomorph abundances decrease up section. This may represent a palaeoenvironmental change, perhaps reflecting greater marine influence and the drowning of a local parent flora in *IOM6*. This potential high-order flooding event is followed by a coarsening-upwards fluvial sandstone which is in turn capped by a second flooding event around *IOM5,* indicated by the presence of a goniatite.

These palynomorphs indicate a strong terrestrial influence with no marine indicators (such as acritarchs) recorded. However, acritarchs are comparatively rare in the Namurian even in clearly marine sediments (such as goniatite-bearing shales), and consequently their absence does not always indicate a non-marine environment of deposition.

Shellag Point borehole samples (Table 2)

These samples produced a moderately diverse assemblage of 27 species. The occurrence of *Laevigatosporites* spp., *C. konsanskei, R. reticulatus,* and *S.arenaceous* indicates an age no older than Namurian B (i.e. Kinderscoutian, KV Zone), while the absence of Westphalian markers indicates a Namurian C (i.e. Yeadonian, FR Zone) age or older. The presence of *Reticulatisporites reticulatus* in *IOM1* and *IOM3* indicates that a Namurian C (i.e. Yeadonian, FR Zone) age is more likely. The occurrence of *Kraeuselisporites echinatus* in *IOM1* suggests a mid-Marsdenian or older age (stratigraphic base in the Asbian) and may be reworked. The occurrence of *Triquitrites triturgidus* (Loose) Potonie & Kremp in *IOM3* indicates reworking of Namurian A, as this species is restricted to the Arnsbergian (TK/SO Zones). The presence of *Rotaspora fracta* in sample *IOM1* may indicate upper Viséan to Namurian A (i.e. Brigantian to Arnsbergian) reworking (VF-TK Zones), possibly related to tectonic activity recorded in the early Namurian by Quirk and Kimbell (1997).

The presence of amorphous organic matter (particularly abundant in *IOM3*) plus prasinophyte algae (*Leiosphere*) in *IOM3* suggests that marine horizons are present, and this is also indicated by the occurrence of the goniatite specimen (Fig. 4). Sample *IOM2* yielded a very vitrinitic (coaly) assemblage suggesting a shallow-water delta-top palaeoenvironment while the abundance of amorphous organic matter suggests a anoxic/dysoxic palaeoenvironment, a feature typical of many marine bands.

Black Marble Quarry (Table 3)

This succession was thought by Dickson *et al.* (1987) to be Dinantian (Brigantian) in age based on a sparse goniatite assemblage. Taxa recorded by Lewis (1930) from the Close-Ny-Chollagh Formation included *Goniatites falcatus* Roemer, *G. straitus* Sowerby and "*G. punctatus*" from the black shales in the upper part of the formation which were assumed to indicate a late Brigantian age.

However, our samples yielded a low diversity (seven taxa) palynomorph assemblage including *Lycospora pusilla, Leiotriletes* spp and *C. konsankei*. The presence of *C. konsanskei* indicates a Namurian-Stephanian age (NC to SS Zones). *L. pusilla* and *Leiotriletes* spp are long ranging and therefore of limited use (latest Tournaisian to lower Permian and Devonian to Recent, respectively). The quarry sequence is overlain by

Sample number	Cingulatizonates spp	Schulzospora spp	Rotaspora fracta	Leiotriletes spp	Krauselisporites echinatus	Densosporites spp	Leiotriletes tumidus	Lycospora pusilla	Punctatisporites spp	Reticulatosporites reticulatus	Crassispora konsankei	Cirratiradites rarus	Calamospora spp	Mooreisporites cf trigallerus	Anapiculatisporites spp	Auroraspora solisortus	Calamospora pallida	Convolutispora spp	Dictyotriletes cf falsus	Discernisporites micromanifestus	Florinites sp	Raistrickia saetosa	Savitrisporites nux	Secarisporites remotus	Spelaeotriletes arenaceous	Triquitrites cf triturgidus	Verrucosisporites spp	Leiosphere
IOM 1	1	1	1	34	1	2	3	67	1	1	16	6																
IOM 2								1					1															
IOM3						1	1	56	5	1	11	2		1	1	9	1	1	2	2	12	1	6	1	3	1	1	2

Table 2. Quantitative palynological distribution chart for the *Shellag Point* borehole.

Sample number	*Anapiculatisporites spp*	*Leiotriletes spp*	*Lycospora pusilla*	*Crassispora kosanskei*	*Schulzospora spp*	*Cingulizonates spp*	*Densosporites spp*	spore indet	scelecodont
IOM9	1	1	3						
IOM11			1	1					3
IOM12								1	
IOM14			3		1				
IOM17			11			1	3		

Table 3. Quantitative palynological distribution chart for Black Marble Quarry.

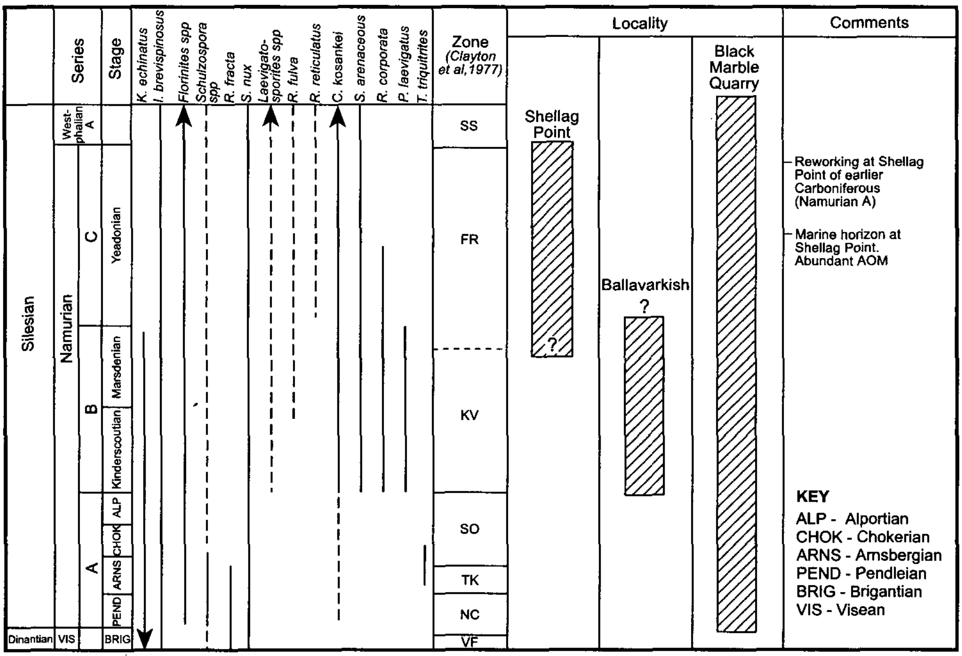


Fig. 5. Distribution chart for key palynomorph taxa in the studied sections. Shaded bars represent probable ages based on taxa present. In the case of Black Marble Quarry, the preferred age is Namurian A (see text for discussion). Zones and stages based on Ramsbottom *et al.* (1978) and Clayton *et al.* (1977).

LOCALITY	TOC	S1	S2	S3	HI	PI	OI	Tmax	Rock-Eval Maturity	H/C Potential
IOM1 Shellag Point	1.72	0.17	1.51	0.23	88	0.1	13	446	oil window	lean
IOM2 Shellag Point	33.3	4.13	60.6	1.29	182	0.06	4	443	oil window	rich
IOM3 Shellag Point	3.08	0.61	5.96	0.49	194	0.09	16	445	oil window	fair/good
IOM4 Ballavarkish	2.73	0.03	0.08	0.5	3	0.27	18	455	late mature	lean
IOM5 Ballavarkish	3.76	0.04	0.12	0.33	3	0.25	9	496	?late mature	lean
IOM6 Ballavarkish	1.41	0.1	0.18	0.22	13	0.36	16	447	oil window	lean
IOM7 Ballavarkish	1.93	0.06	1.05	0.45	54	0.05	23	442	oil window	lean
IOM8 Ballavarkish	1.54	0.07	0.99	0.14	64	0.07	9	443	oil window	lean
IOM9 Black Marble	2.66	0.08	0.08	0.21	3	0.5	8	440	uncertain	very lean
IOM11 Black Marble	3.18	0.05	0.13	0.52	4	0.28	16	460	late mature	lean
IOM12 Black Marble	2.34	0.06	0.1	0.18	4	0.38	8	515	post mature	lean
IOM14 Black Marble	2.05	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
IOM17 Black Marble	1.12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
IOM19 Ballavarkish	2.13	0.05	0.31	0.2	15	0.14	9	431	uncertain	very lean

Table 4. Summary TOC and *Rock-Eval* data for Isle of Man Carboniferous samples.

basalts which may be coincident with the tectonic activity and growth faulting during the early Namurian which has been recorded on offshore seismic lines (Quirk and Kimbell, 1997). It would seem therefore that the Close-Ny-Chollagh Formation samples in the Black Marble Quarry lie approximately at the Dinantian/Namurian boundary.

Dickson *et al.* (1987) noted the presence of the conodonts *Gnathodus homopunctatus* and *Mestognathus beckmani* in brecciated limestones within the Scarlett Volcanic Formation overlying the Close-Ny-Chollagh Formation (Fig. 2). This observation, together with the absence of *Lochreia mononodosa* (a taxon which first appears midway through the Brigantian according to Varker and Sevastopulo, 1985) was taken by Dickson *et al.* (1987) to indicate a pre- *L. mononodosa* Zone age (i.e. early to mid Brigantian) for these formations. However, the conodonts are clearly reworked as they occur in volcaniclastic rocks, and age assignments based on this fauna cannot therefore be relied upon. In the Poyllvaaish Formation which underlies the Close-Ny-Chollagh Formation, the presence of the goniatites *G. crenistra* (Phillips) and *Beyrichoceratoides truncatum* (Phillips) are also taken to indicate an early Brigantian age. The presence of corals including *Dibunophyllum muirheadi* Nicholson & Thompson, *D. turbinatum* M'Coy and *Palaeosimilia murchinsoni* Edwards & Haime, together with the foraminifera *Saccaminopsis* recorded by Lamplugh (1903) and Smith (1911), suggest a D2 coral/brachiopod Zone age (i.e. Brigantian) for the Poyllvaaish Formation (cited in Dickson *et al.*, 1987). However, *D. muirheadi* is considered a zonal species for the upper Brigantian, while *P. murchisoni* is typically an Asbian taxon (ages from Ramsbottom *et al.*, 1978). Therefore, there is some discrepancy in this published age assignation, possibly due to fault activity in the Brigantian (Quirk *et al.*, 1990). Moreover, it is now known that *Dibunophyllum*-bearing limestones within the base of the Yoredale are earliest Namurian in age and not late Dinantian, as was previously assumed (Rosen, *pers. comm.*).

All the quarry samples are strongly carbonised due to their proximity to a dolerite dyke and the overlying Scarlett Volcanics, and consequently the palaeoenvironment cannot be determined from palynofacies. However, the restricted macrofossil assemblage suggests distal brackish-marine depositional conditions.

SOURCE ROCK EVALUATION

A total of 14 Carboniferous core and outcrop samples from the Isle of Man were analysed geochemically to assess their source potential. Analyses included TOC determination, pyrolysis and gas chromatography. Suitable lithologies were also analysed for maturity (vitrinite reflectance, spore coloration (TAI) and kerogen type). A summary of the analytical results is given in Table 4 .

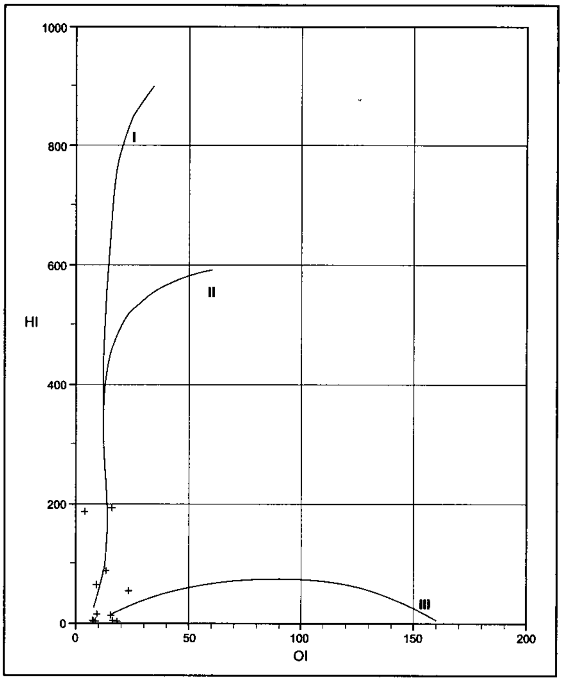


Fig. 6. Van Krevelen diagram for the Isle of Man samples.

Total Organic Carbon

The samples' TOC contents vary widely, but all TOC values were greater than 1%. One sample (*IOM 2*, from a thin coaly horizon) had a TOC of 33%; the others had TOCs of 1.1-3.8%. The mid-Namurian samples from *Ballavaarkish* had TOC values of 1.4-3.8 %, while the upper Namurian samples from *Shellag Point* had TOCs of 1.7-3.1%. Samples from Black Marble Quarry had TOC values of 1.1-3.2%.

Rock-Eval pyrolysis

Of the 14 samples analysed for TOC, 12 were selected for *Rock-Eval* analysis, and analytical results are summarised in Table 4 and plotted on a van Krevelen in Fig.6. The results demonstrate the presence of Type II and Type III kerogens which have little remaining hydrocarbon-generation potential.

Pyrolysis-derived hydrogen indices generally have values less than 90 suggesting the presence of significant proportions of oxidised organic matter (inertinite), the two exceptions being *IOM2* and *IOM3* from *Shellag Point*. The low quality of the organic matter in many of these samples is reflected in the relatively poor S2 yields (Table 4). Some samples (e.g. *Ballavaarkish IOM4-IOM9* and *IOM19* and those from Black Marble Quarry) have very poor remaining source potential (S2 yield <2.0 mg/g).

Rock-Eval Tmax values were used to broadly define the relative maturity of the samples using the following scale (after Barnard *et al.*, 1981):

up to 440° C	Immature to early mature
440 to 460° C	Main generation window (liquids and gas)
460 to 480° C	Late mature (gas condensate/ wet gas)
>480° C	Post-mature

These ranges are typical for the Type II and Type III kerogens which form the database. Tmax values only give a rough guide to maturity and should not be relied on for maturity assessment in isolation especially where *Rock-Eval* results indicate a low hydrocarbon yield. More detailed and accurate maturity measurements were made using vitrinite reflectance and spore colouration (*see below*).

Using the Tmax limits defined above, *Ballavaarkish* sample *IOM19* can be classified as immature to early mature. Samples *Shellag Point IOM1-IOM3 and IOM7*, and *Ballavaarkish* samples *IOM 7* and *8* have entered the main hydrocarbon-generation window. However, hydrogen indices in these samples do not exceed 75 (Table 4, Fig. 5). Progressive maturation reduces hydrogen index values, and consequently in mature samples, HI values may not necessarily signify the presence of oil-prone organic matter. Similarly, bonded hydrocarbon (S2) yields are reduced as generation and hydrocarbon expulsion take place. The original source quality therefore has to be estimated from the free hydrocarbon (S1), residual carbon (TOC) and production index (PI) data in addition to the S2 and HI values. These data allow the "mature" samples to be split into two subgroups:

(i) Samples with low S1 and low TOC have poor source potential; these include samples from *Shellag Point* (*IOM1*) and *Ballavaarkish* (*IOM 6, 7 and 8*). The S1 data shows little evidence of significant generation and hydrocarbon yields are very low. Moreover, the amounts of residual carbon, and particularly the remaining potential indicated by the S2 values (<2.0 mg/g), suggest that these samples have never been likely to yield significant hydrocarbons.

(ii) By contrast, low production indices but relatively high S2 and HI values characterise *Shellag Point* samples *IOM2* and *IOM3*. These samples have a significant residual potential as indicated by their organic carbon contents (33 and 3.1% TOC) and S2 yields (60.6 and 5.96 mg/g). Hydrogen indices of 182 and 194 indicate gas-prone organic matter. This, together with the low PI values (0.06 and 0.09) and the Tmax determinations of 443-445°C, suggest a gas-prone facies which has not attained full maturity for generation.

Ballavaarkish samples *IOM4-IOM6* and Black Marble Quarry samples *IOM9, IOM11* and *IOM12* are considered to have exceeded the range of the main hydrocarbon-generation window. These samples are characterised by very low S2 yields (<0.2 mg/g C) indicating negligible remaining hydrocarbon generation potential. This is further emphasised by the very low HI values which generally fall below 5. By contrast, the amounts of residual carbon are in many cases quite high and often exceed 2%. These signify formerly productive source rocks which now retain only very minor potential for dry gas.

LIQUID AND GAS CHROMATOGRAPHY

Solvent extraction and liquid and gas chromatography was performed on samples *IOM 3* and *IOM 5* (Fig. 7). Sample *IOM3* from *Shellag Point* was selected as a mature source rock which was not thought to have expelled a significant amount of its original potential. Sample *IOM5* from *Ballavaarkish* was selected as a late mature/post mature source with a high level of residual carbon. Extraction data are given in the following table:

Locality	Extract Yield ppm	Saturates %	Aromatics %	Polars %
IOM3 Shellag Point	1,500	0	7.7	92.3
IOM5 Ballavaarkish	222	25	8.4	66.7

The *Ballavaarkish* sample (*IOM5*) produced only 222ppm of extract while the *Shellag Point* sample (*IOM3*) produced 1,500ppm. The compositions of these extracts are different. In general, samples which are more mature and which have generated hydrocarbons contain greater proportions of hydrocarbons (saturates and aromatics) compared to non-hydrocarbons (polars). The sample *IOM3* extract comprised only minor aromatic hydrocarbons with an abundance of polar compounds.

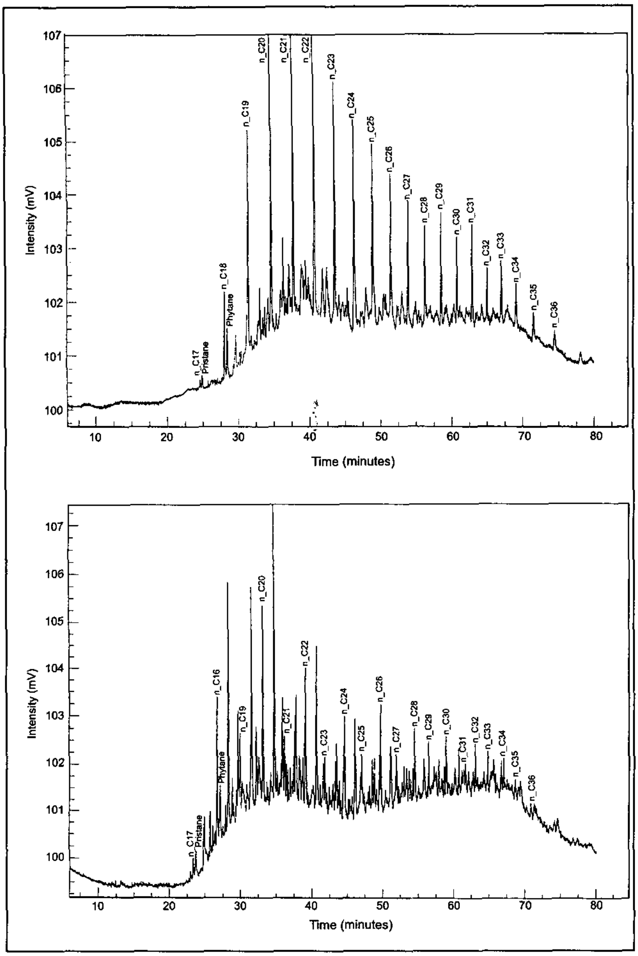


Fig. 7. Gas chromatogrammes (a) of sample *IOM 3* from the *Shellag Point* borehole; and (b) sample *IOM 5* from the *Ballavaarkish* borehole.

The gas chromatogram for *IOM5* (Fig.7b) shows that the *n*-alkane distribution is dominated by a front-end bias favouring the lighter species, which is the normal configuration in a relatively mature product. In both sample *IOM5* and sample *IOM3* (Fig. 7a), pristane and phytane peaks are poorly developed, and humps of unresolved naphthenic matter underlie the main alkane envelope; this is particularly pronounced in *Ballavaarkish* sample *IOM5,* possibly indicating the onset of biodegradation.

Generative capacity

The *Ballavaarkish* borehole penetrated a total of 28m of potential source rock, while the *Shellag Point* borehole penetrated a total of 27.5m of potential source rock. Both boreholes T.D'd within the Namurian. Consequently, the Namurian has a minimum source rock thickness of approximately 60m onshore. However, based on the limited number of samples available for analysis, it is clear that most of these samples have little remaining hydrocarbon generative capacity. Onshore, the Dinantian succession is generally overmature due to its proximity to a Tertiary dyke. However, the relatively high TOC values (2-3%) for most of the samples indicates that these shales may originally have had significant source potential.

LOCALITY	Rm (%)	s.d	No. of grains	TAI (Staplin)	Tmax	Fluoresc	%AOM (Type II)	%Hyalogen (Type III)	%Melanogen (Type IV)	% Phyrogen (Type II)	Comments
IOM1 Shellag Point	0.84	0.13	31	2-	446	pos	30	30	20	20	TAI on Lycospora
IOM2 Shellag Point	0.5	0.05	50	nd	443	pos	0	85	<5	<5	Coaly fragments present
IOM3 Shellag Point	0.62	0.06	9	2-	445	pos	70	10	10	10	TAI on Lycospora
IOM4 Ballavarkish	1.21	0.07	8	3 + to 4-	455	neg	50	<5	40	10	TAI on rare spores
IOM5 Ballavarkish	0.98	0.08	37	3-	496	neg	80	<5	20	<5	TAI on rare spores
IOM6 Ballavarkish	1.04	0.04	19	2+	447	pos	0	30	20	50	TAI on well-preserved spores
IOM7 Ballavarkish	0.73	0.13	30	2	442	pos	30	20	20	30	TAI on well-preserved spores
IOM8 Ballavarkish	0.53	0.07	7	2-	443	pos	10	50	30	10	TAI on well-preserved spores
IOM9 Black Marble	1.72	0.22	40	4	440	neg	70	10	20	<10	Rare indeterminate spores
IOM11 Black Marble	2.26	0.5	50	4	460	neg	40	30	30	<10	Rare indeterminate spores
IOM12 Black Marble	nd	nd	nd	nd	515	nd	60	0	40	0	No vitrinite recorded. TAI on single spore
IOM14 Black Marble	1.88	0.21	39	4	nd	neg	70	10	20	0	TAI on Lycospora
IOM17 Black Marble	1.51	0.14	21	3 + to 4+	nd	neg	80	10	10	0	TAI on Lycospora

Table 5. Maturity and kerogen types for Isle of Man Carboniferous samples. Spore colours are described in terms of the TAI scale of Staplin (1969) together with qualitative fluorescence.

Offshore, where the entire Carboniferous section is preserved below the base-Permian unconformity, a thickness of between 200m and 1,000m of Hollywell Shales is present, together with 500m of upper Namurian shales/siltstones and about 1,200m of Westphalian interbedded coals and shales.

MATURITY ASSESSMENT

The maturity of thirteen Carboniferous core and outcrop samples was assessed through an examination of vitrinite reflectance, Thermal Alteration Index (TAI) and spore fluorescence. Coal samples were processed by washing, crushing and mounting in cold-setting epoxy resin before polishing. For argillaceous samples, 15-20 grams were weighed, treated with HCl to remove carbonates, and then all silica and silicates were removed using 40% HF in a warm water bath. Organic residues were then washed through a 15 micron sieve and mounted on slides for transmitted light and incident blue-light/ UV microscopy. Mean vitrinite reflectance (Rm) was measured using standard techniques on polished organic residues mounted in epoxy resin blocks or on polished thin sections using a *Leitz MPV-1* microscope photometer. Some of the samples were partially disaggregated in HF and the dried residue mounted in epoxy resin for further investigation. Mean random vitrinite reflectance (Rm) measurements were made on all samples where ten or more measurable vitrinite grains were present. Maturity data including Rm, standard deviations and number of grains measured together with kerogen type are given in Table 5.

Vitrinite reflectance values for the upper Namurian samples from *Shellag Point* (*IOM1-IOM3*) vary from 0.5-0.8% Rm, while those for the middle Namurian samples from *Ballavaarkish* (*IOM5-IOM8* but excluding *IOM4*) have values of 0.5-1.0% Rm (Table 5). These values are supported by the TAI values of -2 to +2 for the *Shellag Point* samples, and +2 to +3 for the *Ballavaarkish* samples (excluding sample *IOM4*); and also by the positive fluorescence determinations of the samples (with the exception of samples *IOM4* and *IOM5*, which contain rare, non-fluorescing specimens of *Lycospora* spp with TAIs +3 to +4). The *Shellag Point* samples are interpreted as being in the oil window, while those from *Ballavaarkish* are oil window to late mature. *Ballavaarkish* sample *IOM4* appears to have an anomalously high Rm of 1.21%; however, this was based on only eight measurable grains. Sample *IOM8* from the same borehole has an unusually low Rm of 0.53%, based on only seven measurable grains. If these two samples are discounted, the Rm range narrows to 0.73-1.04% for the *Ballavaarkish* samples.

Dinantian/Namurian samples from Black Marble Quarry (*IOM 9,11, 14* and *17*) are much more mature, with Rm in the range 1.51-2.26% and consistently higher TAIs of +3 to +4. The generally lower Rm values for the Namurian borehole samples suggests either that the area in which the boreholes are located was not buried beneath a significant

Permo-Triassic cover, or that the sampled sequence was not buried significantly during the Carboniferous.

POTENTIAL RESERVOIR ROCKS

Sandstone units in the Carboniferous sequence at the *Ballavaarkish* borehole are up to 13-m thick (Fig. 3). Thin sections show that these sandstones are dominantly fine to medium grained, well-sorted and comprise mainly well-rounded to subrounded grains with only trace amounts of detrital clays. Detrital minerals comprise monocrystalline quartz (98%) with subordinate potassium feldspar (1-2%) and illite boxworks (1%) after alteration of potassium feldspar. Heavy minerals include rare apatite, zircon and magnetite. Feldspar grains are generally fractured and show crenulated margins indicating previous pressure-solution contacts; although syntaxial quartz overgrowths are present, they are relatively rare and only occlude a minor amount of the intergranular volume. Very minor authigenic pyrite, often associated with illite, is also present. The sandstones are texturally and mineralogically very mature suggesting extensive periods of sediment reworking. Modal analyses reveal 10-15% porosity while pore connectivity (permeability) is good due to later cement dissolution. Offshore, oil-stained upper Namurian-lower Westphalian fluvio-deltaic sandstones were encountered in well *112/30-1,* close to the east coast of the Isle of Man (Quirk and Kimbell, 1997).

CONCLUDING REMARKS

Palynological and organic-geochemical analyses were performed on Carboniferous sedimentary rocks from two boreholes in the north of the Isle of Man (*Shellag Point and Ballavaarkish)* and from Black Marble Quarry in the south of the island. The palynological analyses indicated that the borehole successions were Namurian in age, whereas the Quarry samples were dated as Dinantian/Namurian. Other palynological data is consistent with a phase of normal faulting and volcanism at the start of the Namurian, as suggested by Quirk and Kimbell (1997). The results of the organic-geochemical analyses can be summarised as follows:

1. Namurian samples from the *Shellag Point* borehole have fair to moderate source potential (TOC of 1.7-33.3; S2 yields of 1.5-60.6mg/g; and Hydrogen Indices of 88-194). The relatively low HI values suggest that the samples mainly contain gas-prone organic matter; however, other analytical results suggest that this gas-prone facies has not attained full maturity for gas generation.
2. Namurian samples from the *Ballavaarkish* borehole represent poor quality gas-prone source material (TOC of 1.4-3.8%; S2 yields of 0.08-1.05 mg/g, and HI values of 3-64). Maturity assessments indicate that the samples are in the oil window or are late mature.
3. Dinantian/Namurian samples from Black Marble Quarry have no current source potential, possibly due to alteration by nearby intrusions and volcanic rocks. They may originally have possessed moderate source potential (1.12-3.18% TOC). Vitrinite reflectance values of 1.51-2.26% indicate that the samples are post-mature.
4. Gas chromatography of Namurian samples from the *Shellag Point* and *Ballavaarkish* boreholes show an unresolved naphthenic hump underlying the main alkane envelope, which may indicate the onset of biodegradation.

Newman (1999 *this issue*) and Quirk *et al.* (1999 *this issue*) note that a fundamental problem in hydrocarbon exploration around the Isle of Man is the limited occurrence of Silesian source rocks following their removal during uplift and erosion in the Early Permian. The data reported here shows that source rocks of this age are preserved onshore along the margins of the Solway and Eubonia Basins. In addition, potential reservoir-quality sandstones (10-15% porosity) of Namurian age are also present (e.g. at the

Ballavaarkish borehole). It remains to be seen whether older (Devonian-Dinantian) source and reservoir rocks are also preserved

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REFERENCES

ARMSTRONG, J.P., SMITH, J., D'ELIA, V.A.A. and TRUEBLOOD. S.P. 1997. The occurrence and correlation of oils and Namurian source rocks in the Liverpool Bay- North Wales area. In: Meadows, N.S, Trueblood, S.P, Hardman, M and Cowan, G. (eds), Petroleum Geology of the Irish Sea and Adjacent Areas. *Geol. Soc. Spec. Publ.* **124,** 195-211.

BARNARD, P.C., COLLINS, A.G. and COOPER, B.S. 1981. Identification and distribution of kerogen facies in a source horizon: Examples from the North Sea Basin. In: Brooks, J. (ed), Organic Maturation Studies in Fossil Fuel Exploration. Academic Press, London, pp. 271-282.

CLAYTON, G., COQUEL, R., DOUBINGER, K.J.., GUIENN, K.J., LOBOZIAK, S., OWENS, B. and STREEL, M. 1977. Carboniferous miospores of Western Europe: illustration and zonation. *Meded. Rijks. Geol. Dienst.* **29**, 1-71.

DICKSON, J.A.D., FORD, T.D. and SWIFT, A., 1987. The stratigraphy of the Carboniferous rocks around Castletown, Isle of Man. *Proc. Yorks. Geol. Soc.*, **46**, 203-229.

LAMPLUGH, G.W., 1903. The Geology of the Isle of Man. *Memoir of the Geological Survey of England and Wales.*

LEWIS, H.P., 1930. The Avonian succession in the south of the Isle of Man. *Quart. Journ. Geol. Soc. Lond.*, **86**, 234-290.

NEWMAN, P., 1999 *this issue*. The geology and hydrocarbon habitat of the Peel and Solway Basins. *Journ. Petrol. Geol.,* **22**(3), 305-324.

PARNELL, J. 1997. Fluid migration history in the north Irish Sea-North Channel region. In: Meadows, N.S, Trueblood, S.P, Hardman, M and Cowan, G (eds) Petroleum Geology of the Irish Sea and Adjacent Areas. *Geol. Soc. Spec. Publ.* **124,** 213-228.

QUIRK, D.G., FORD, T.D., KING, J.A., ROBERTS, I.L., POSTANCE, R.B. and ODELL, I. 1990. Enigmatic boulders and synsedimentary faulting in the Carboniferous Limestone of the Isle of Man. *Proc. Yorks. Geol Soc.*, **48**, 99-113.

QUIRK, D.G. and KIMBELL, G.S., 1997. Structural evolution of the Isle of Man and central part of the Irish Sea. In: Meadows, N.S, Trueblood, S.P, Hardman, M and Cowan, G (eds), Petroleum Geology of the Irish Sea and Adjacent Areas. *Geol. Soc. Spec. Publ.* **124,** 135-159.

QUIRK, D.G., ROY,S., KNOTT, I. REDFERN,J. and HILL, L. 1999 *this issue*. Petroleum geology and future hydrocarbon potential of the Irish Sea. *Journ. Petrol. Geol.,* **22** (3), 243-260.

RAMSBOTTOM, W.H.C., CALVER, M.A.,EAGER, R.M.C., HODSON, F., HALLIDAY, D.W., STUBBLEFIELD, C.G. and WILSON, R.B., 1978. A correlation of Silesian rocks of the British Isles. *Geol. Soc. Lond. Spec. Rep.* **10**, 1-81.

SMITH, J., 1911. Carboniferous Limestone rocks of the Isle of Man with list of fossils appended. *Trans. Geol. Soc. Glasgow*, **14**, 119-164.

STAPLIN, F.L., 1969. Sedimentary organic matter, organic metamorphism, and oil and gas occurrence. *Bull. Can. Petrol. Geol,* **17**, 47-66.

VARKER, W.J. and SEVASTOPULO, G.D., 1985. The Carboniferous System part 1 - conodonts of the Dinantian subsystem from Great Britain and Ireland. In: HIGGINS, A.C. and AUSTIN, R.L. (Eds) *A Stratigraphical Index of conodonts*, Ellis Horwood, Chichester, British Micropalaeontological Society, pp. 167-209.