Hydrocarbon and Aqueous Fluid Migration in the Porcupine Basin, Offshore Ireland: Evidence from Fluid Inclusion Studies

ISPSG Project IS05/01
NUIG fluid inclusion studies of Irish Shelf

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Contents

1. Summary and Conclusions

ISPSG project IS05/01 (NUIG fluid inclusion studies of the Irish Shelf) studied fluid inclusions in 33 samples from 13 wells located in the Porcupine Basin, offshore western Ireland (Feely et al. 2006; Feely and Conliffe 2007). This report summarises the fluid inclusion data from these samples. It also integrates fluid inclusion data (41 samples; 12 wells) from the earlier Porcupine Basin study PSG project P00/16 (Feely and Parnell 2001, 2003). The combined datasets are used to help elucidate more fully the history of migration and trapping of aqueous and hydrocarbon bearing fluids during the evolution of the basin. The format of the report is as follows:

- Geological setting of the Porcupine Basin
- Methodology used in this study
- Summary of fluid inclusion data from Jurassic and Cretaceous horizons
- Discussion of fluid inclusion data and implications for fluid migration during the evolution of the Porcupine Basin

The main findings are:

- Hydrocarbon bearing fluid inclusions (HCFI) have been recorded in 23 sandstone samples (i.e. 22 Jurassic and 1 Cretaceous). The HCFI occur in inter- and intragranular trails. HCFI trapped in cements were recorded in samples from wells 26/27-1B and 26/28-2 located in the Northern Porcupine Basin. Hydrocarbon migration in the Porcupine Basin is a feature of Jurassic sandstone horizons and occurred after cementation. This is consistent with published diagenetic sequences which suggest that hydrocarbon migration occurred late in the diagenetic history of these sandstones (Robinson and Canham 2001).
- Two-main types of HCFI have been recorded, reflecting at least two hydrocarbon migration events. Blue-white fluorescing HCFI (Type 1; API gravity = 40-50°) are commonly encountered in wells throughout the Porcupine Basin. Yellow-green fluorescing HCFI (Type 2; API gravity = 25-35°) inclusions are more common in the North Porcupine Basin. Comparisons between fluid inclusion data and geochemical studies of potential source rocks and oils recovered from Lower and Middle Jurassic horizons in the Porcupine Basin (Scotchman, 2001) suggest

that Type 1 HCFI represent light oils sourced in marine shales, while Type 2 HCFI originate in non-marine lacustrine rocks.

- Primary aqueous inclusions hosted in the cements (Type 3 inclusions) of Jurassic and Cretaceous sandstones provide evidence of variations in the timing of cementation in these horizons. Type 3 inclusions in Jurassic sandstones were trapped at temperatures ranging from 70 to 120°C. In Cretaceous sandstones however, Type 3 inclusions were trapped at relatively low temperatures (< 50°C). Cementation here was likely to have occurred at shallow levels in contrast to Jurassic sandstones where higher trapping temperatures indicate cementation occurred at deeper levels.
- The occurrence of intergranular trails of aqueous inclusions in Jurassic and Cretaceous sandstones provides evidence for post-cementation migration of aqueous fluids in the basin. These inclusions were trapped at temperatures ranging from ~ 57 to 175°C and may reflect hydrothermal fluid migration events similar to those recorded from other sedimentary basins along the North Atlantic margin. They may represent plume-related activity during the opening of the North Atlantic.

2. Introduction

Fluid inclusion studies of North Atlantic oil bearing sedimentary basins play a key role in helping to elucidate the histories of hydrocarbon and aqueous fluid movements, during basin evolution (e.g. the Jeanne D'Arc Basin (Parnell *et al.* 2001); West of Shetland (Parnell *et al.* 1999, Baron *et al.* 2007); the Rathlin Basin (Middleton *et al.* 2001)). Fluid inclusions are micron scale samples of basin fluids (oil ± water) trapped during cementation and annealing of microfractures (i.e. crack and seal events). Fluid inclusions can be studied using a variety of techniques, including fluid inclusion petrography, ultraviolet light microscopy and fluid inclusion microthermometry. These techniques help build a fluid profile that reflects fluid salinities, trapping temperatures and pressures thus facilitating the reconstruction of fluid flow histories on both regional and local scales. This report integrates the results of ISPSG project IS05/01 (Feely et al. 2006; Feely and Conliffe 2007) with those from PSG project P00/16 (Feely and Parnell 2001) to generate a regional perspective of aqueous and hydrocarbon fluid flow in the Porcupine Basin.

3. Geological setting

The Porcupine Basin is located in deep waters (200 to 3500m water depths) on the continental shelf to the WSW of Ireland (Fig. 1). The basin reflects a series of rift events with intervening periods of thermal subsidence and contains up to 13 km of Upper Palaeozoic to Cenozoic sediments (Figure 2; Shannon, 1991 and Shannon and Naylor, 1998). The sedimentary history of the Porcupine Basin began with a pre-rift Upper Carboniferous deltaic to shallow marine succession (comprising of sandstones, shales and thin coals). Following initial Permo-Triassic rifting which led to the generation of small rift basins the basin experienced a major E-W extension in the Middle to Upper Jurassic (Shannon, 1991). This rifting was accompanied by deposition of deltaic sandstones during the Middle Jurassic. Submarine fan sandstones with occasional lacustrine siltstones and mudstones formed as a northward-progressing marine transgression occurred during the Upper Jurassic. Cretaceous and Tertiary sediments (that lie unconformably on Jurassic strata) include shales, chalky limestones and deltaic sandstones deposited during significant thermal subsidence following the end of crustal extension (Moore and Shannon, 1995). Potential reservoir sandstone intervals which were targeted for fluid inclusion studies are of Carboniferous, Jurassic, Cretaceous and Palaeocene-Eocene age.

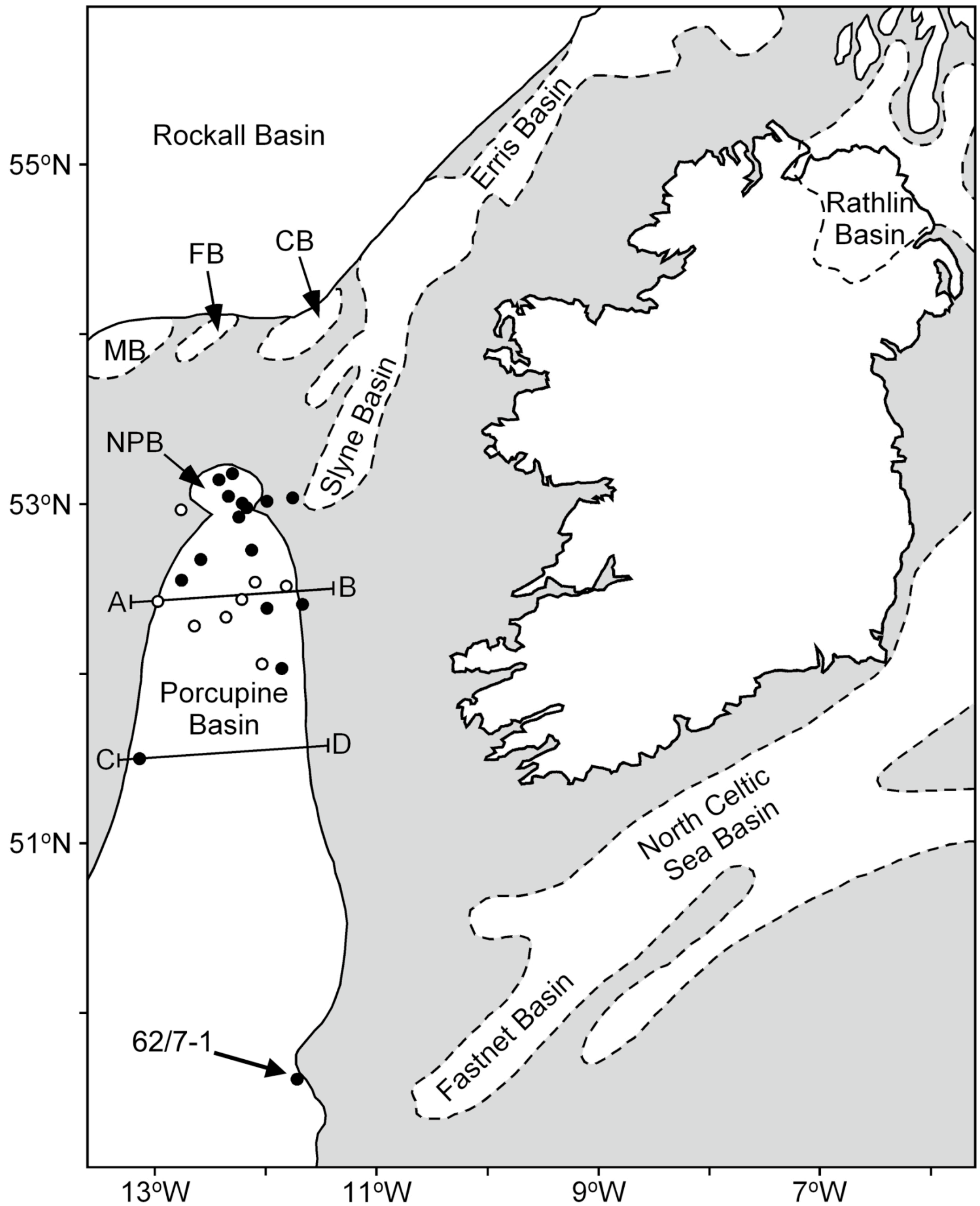

Fig. 1. Map of sedimentary basins in the Irish offshore massif showing the distribution of wells sampled in this study (open circles). Filled circles represent wells in which Cretaceous and/or Jurassic horizons were encountered. NPB = North Porcupine Basin; MB = Macdara Basin; FB = Fursa Basin; CB = Colm Basin. Basin distribution from Shannon *et al*. (2001).

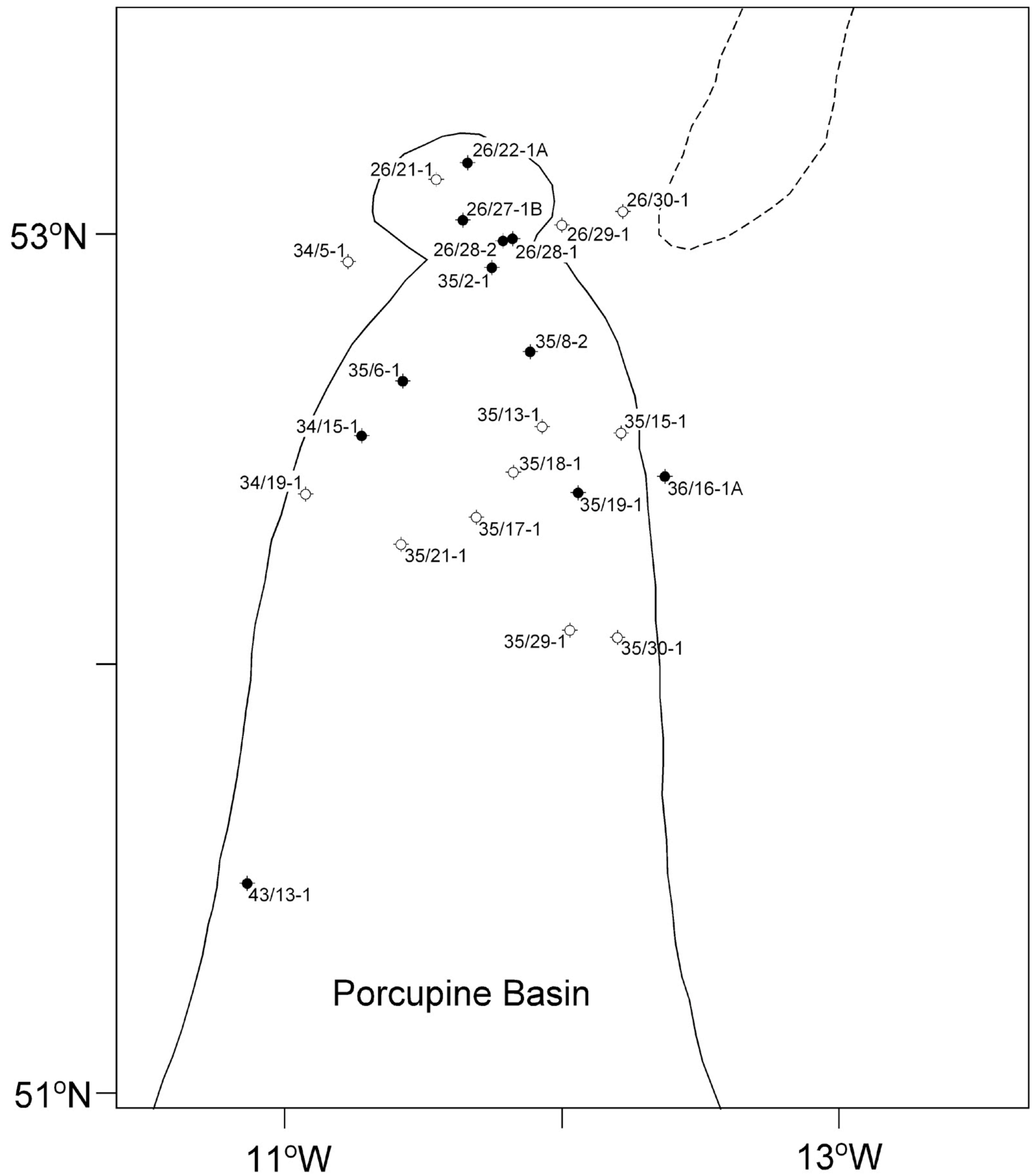

Fig. 2. Map of the Porcupine area showing the distribution of the wells studied during ISPSG project IS05/01 (open circles) and those from PSG project P00/16 (closed circles). Location of well 62/7-1 shown on Fig. 1.

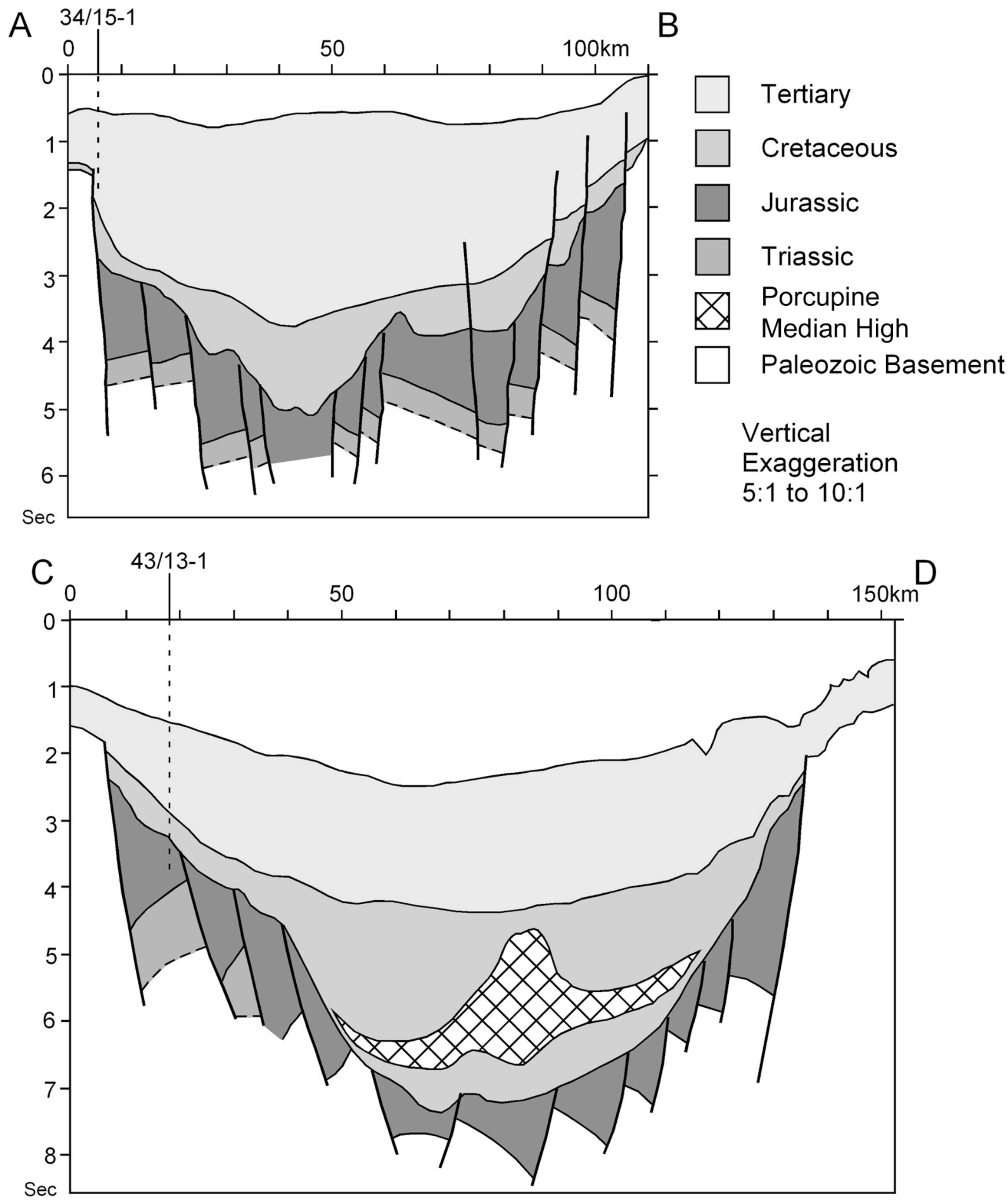

Fig. 3. Cross sections through the Porcupine Basin (located in Fig. 1). Based on Spencer and MacTiernan (2001).

Table 1. Sandstone horizons sampled during ISPSG project IS05/01

Well	Sample Depth	Horizon
26/21-1	1100m	Upper Cretaceous
26/21-1	1260m	Lower Cretaceous
26/21-1	1719.5m	Lower Cretaceous
26/21-1	1788m	Lower Jurassic
26/21-1	1841m	Lower Jurassic
26/21-1	1856m	Lower Jurassic
26/21-1	1901m	Triassic
26/29-1	800-810m	Upper Cretaceous
26/29-1	1330m	Middle Jurassic
26/29-1	1610-1615m	Middle Jurassic
26/29-1	1773.5m	Middle Jurassic
26/30-1	3130ft	Upper Jurassic
34/19-1	2339m	Upper Cretaceous
34/19-1	2640m	Lower Cretaceous
34/5-1	730m	Cretaceous
34/5-1	770m	Cretaceous
34/5-1	830m	Carboniferous
35/13-1	3350m	Lower Cretaceous
35/13-1	4139m	Lower Cretaceous
35/15-1	8300ft	Carboniferous
35/15-1	8450ft	Carboniferous
35/17-1	4050m	Eocene
35/18-1	3575m	Paleocene
35/21-1	3550m	Eocene
35/29-1	2650m	Eocene
35/30-1	15010ft	Upper Jurassic
35/30-1	15220ft	Upper Jurassic
35/30-1	15910ft	Middle Jurassic
35/30-1	16270ft	Middle Jurassic
35/30-1	16970ft	Middle Jurassic
62/7-1	7690-7700ft	Lower Cretaceous
62/7-1	8530-8560ft	Lower Cretaceous
62/7-1	10240.4ft	Middle Jurassic

Table 2. Sandstone horizons sampled during PSG project P00/16

Well	Sample Depth	Horizon
26/22-1a	2007.05m	Jurassic
26/22-1a	2020.34m	Jurassic
26/27-1b	7100ft	Jurassic
26/27-1b	7540ft	Jurassic
26/28-1	900-930m	Eocene
26/28-1	1100-111m	Upper Cretaceous
26/28-1	1195m	Upper Cretaceous
26/28-1	1325m	Upper Cretaceous
26/28-1	2256.8m	Jurassic
26/28-1	2410m	Jurassic
26/28-1	3255m	Carboniferous
26/28-1	3298m	Devonian
26/28-2	2185m	Jurassic
34/15-1	1740m	Tertiary
34/15-1	2020m	Tertiary
34/15-1	3415m	Jurassic
34/15-1	3790-3810m	Jurassic
34/15-1	4390m	Carboniferous
34/15-1	4440.1m	Carboniferous
35/19-1	16444ft	Cretaceous
35/2-1	3225m	Jurassic
35/2-1	3620m	Jurassic
35/6-1	3710m	Jurassic
35/6-1	3953.6m	Jurassic
35/8-2	6775-6800ft	Tertiary
35/8-2	9960-10000ft	Upper Cretaceous
35/8-2	10240-10250ft	Upper Cretaceous
35/8-2	13103ft	Jurassic
35/8-2	13147ft	Jurassic
36/16-1	3810-3840ft	Paleocene
36/16-1	3984ft	Paleocene
36/16-1	5400-5410ft	Carboniferous
36/16-1	8280-8290ft	Carboniferous
43/13-1	3255m	Jurassic
43/13-1	3265m	Jurassic
43/13-1	3505m	Jurassic
43/13-1	3570m	Jurassic
62/7-1	9340ft	Cretaceous
62/7-1	9390ft	Cretaceous
62/7-1	10235ft	Jurassic
62/7-1	10251.3ft	Jurassic

4. Methodology

Samples of core and cuttings were prepared as doubly polished wafers. During ISPSG project IS05/01 33 sandstone horizons were subject to fluid inclusion studies (Table 1). 41 sandstone samples were analysed during the course of PSG project P00/16 (Feely and Parnell 2001; Table 2). A total of 33 Jurassic and 15 Cretaceous sandstone samples from 15 wells in the Porcupine Basin were studied. During the course of both projects samples were first examined under transmitted plain polarized light using a Nikon Labophot microscope with a digital camera attached. Petrographic studies helped establish fluid inclusion classification schemes and paragenetic relationships (Fig. 4, Table 3). Ultra-violet (UV) light microscopy, using a Nikon Eclipse microscope with an Epi-Fluorescence attachment, determined the presence of HCFI. Fluid inclusion microthermometry was conducted using a calibrated (using synthetic H_2O and CO_2 standards; precision of ± 0.2^o C at –56.6^o C and ± 0.5^{o}C at 300^{o}C) Linkam THMS600 heating and freezing stage. Fluid salinities in aqueous inclusions were calculated using temperatures of last ice melting (Bodnar 1993).

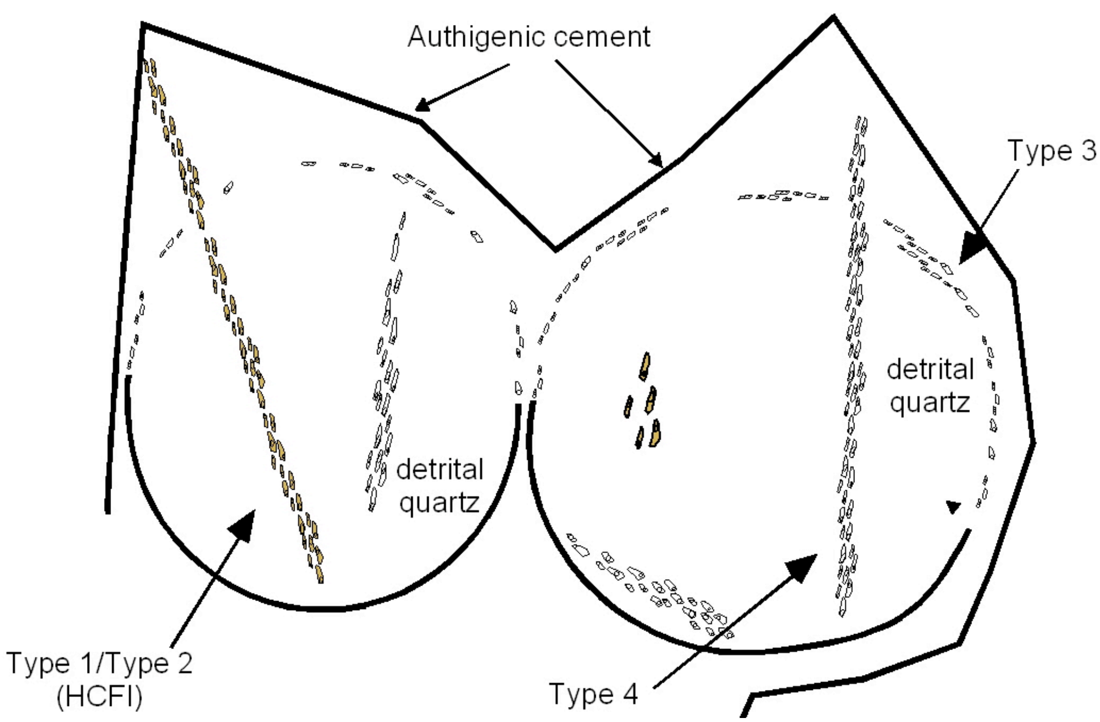

Fig 4: Schematic representation of the distribution of Type 1, 2, 3 and 4 inclusions

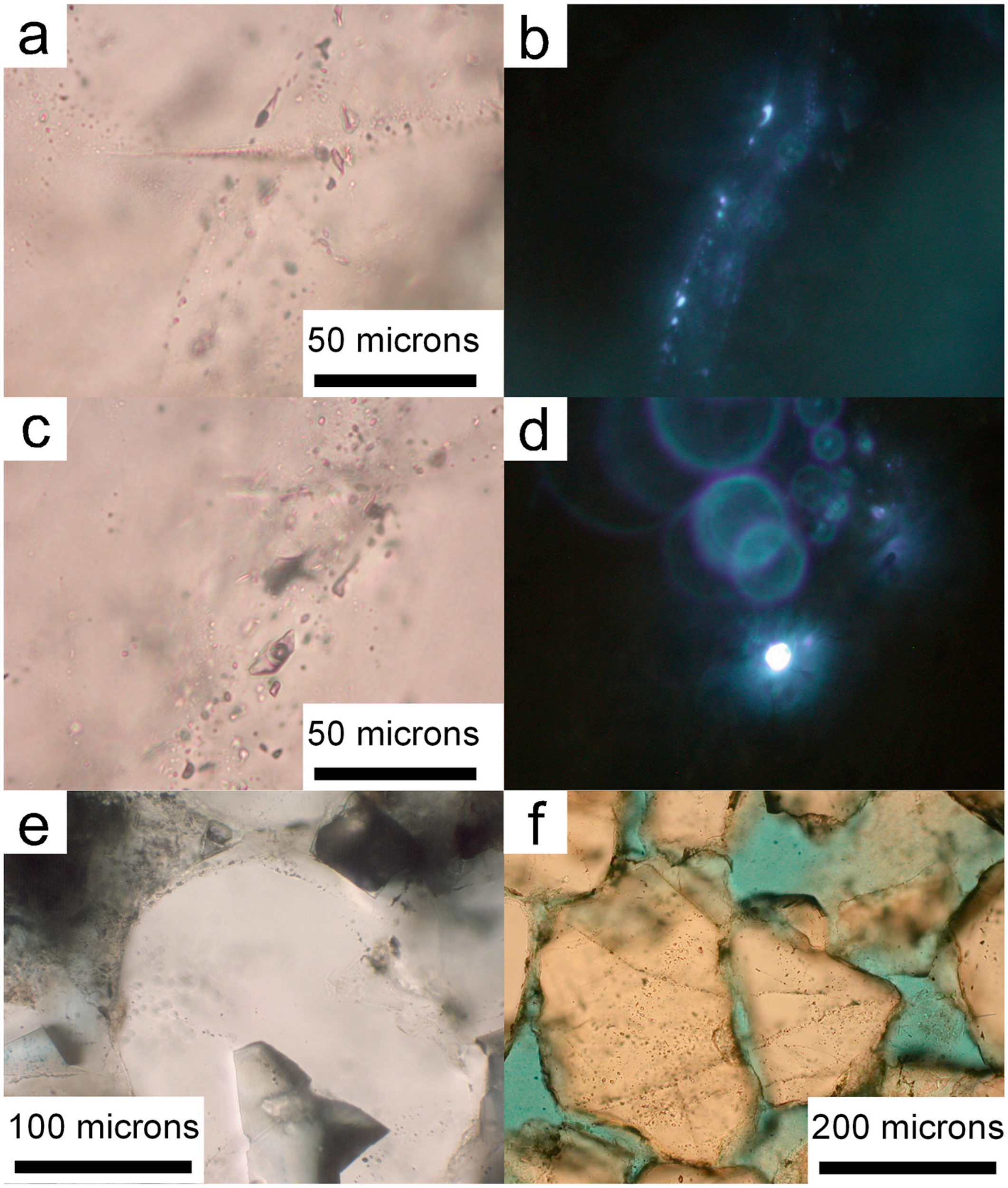

Fig. 5. Photomicrographs showing HCFI and aqueous inclusions. (a) Trail of Type 1 inclusions in detrital quartz grain. (b) Same view as (a) showing blue fluorescing HCFI. (c) Three phase (L_{H2O} + $L_{HYDROCARBON}$ + $V_{HYDROCARBON}$) HCFI inclusion in detrital quartz grain. (d) Same view as (c) showing blue fluorescing hydrocarbon liquid phase (e) Type 3 inclusions in authigenic quartz cement. (f) Trail of Type 4 inclusions crosscutting grain boundaries.

5. Fluid inclusion studies

5.1 Hydrocarbon bearing fluid inclusions (HCFI)

HCFI were recorded in 23 sandstone samples (i.e. 22 Jurassic and 1 Cretaceous; see Table 4). The majority are secondary and occur in inter- and intragranular trails. HCFI trapped during cementation have been recorded in a Jurassic sandstone sample from Well 26/27-1B and 26/28-2. In general, HCFI are typically very small (<5µm) however, rare relatively large inclusions (~ 20µm) have been recorded. The degree of fill (F) of the HCFI varies greatly between samples with both monophase (L) and two-phase (L +V) inclusions common. However the ratio of vapour to liquid remains relatively constant within fluid inclusion assemblages (i.e. along sealed microfractures) and therefore it is unlikely that these inclusions underwent any significant post-entrapment modifications. Some rare HCFI contain both hydrocarbon and aqueous fluids (Fig. 5c). When examined under UV light the HCFI fluoresce blue-white (Type 1 inclusions) or yellow-green (Type 2 inclusions). Fluorescence colour is commonly related to API gravity (Bodnar, 1990) with blue-white fluorescence colours associated with light, mature oils (API gravity ~ 40-50^{o}) and yellow-green fluorescence colours typically representing heavier, less mature oils (API gravity ~ 25-35^{o}). However care must be taken as the complex controls on fluorescence in hydrocarbons often lead to variations in the relationship between fluorescence colour and API gravity in inclusions (George *et al.* 1997, 2001). In particular geochemical work (George *et al.* 2001) suggests that HCFI with blue fluorescence colours may have lower densities than suggested by Bodnar (1990).

Homogenisation temperatures were recorded from 28 Type 1 HCFI and 48 Type 2 HCFI inclusions. Type 1 inclusions display a bimodal distribution of T_H, with values ranging from 65.4 to 109°C and 142.1 to 181.8°C (Fig. 6). This suggests that Type 1 inclusions reflect multiple oil charge events. Type 2 inclusions exhibit a narrow range of T_H values (92.6 ± 20°C; Fig. 4) however, a bimodal distribution is also indicated reflecting at least two oil charge events.

Table 3: Classification of fluid inclusion types

TYPES	PHASES PRESENT	COMPOSITION	FLUORESCENCE	DISTRIBUTION
1	L, L + V	Hydrocarbon	Blue	Hosted in trails of inclusions crosscutting detrital grain boundaries or as isolated inclusions
2	L, L + V	Hydrocarbon	Yellow	Hosted in trails of inclusions crosscutting detrital grain boundaries or as isolated inclusions
3	L, L + V	Aqueous	-	Hosted in authigenic siliceous cements around detrital quartz grains
4	L + V	Aqueous	-	Rare trails of inclusions crosscutting detrital grain boundaries

Classification is based upon morphological and paragenetic features and the proportion of the major phases observed at room temperature. L = liquid, V = vapour.

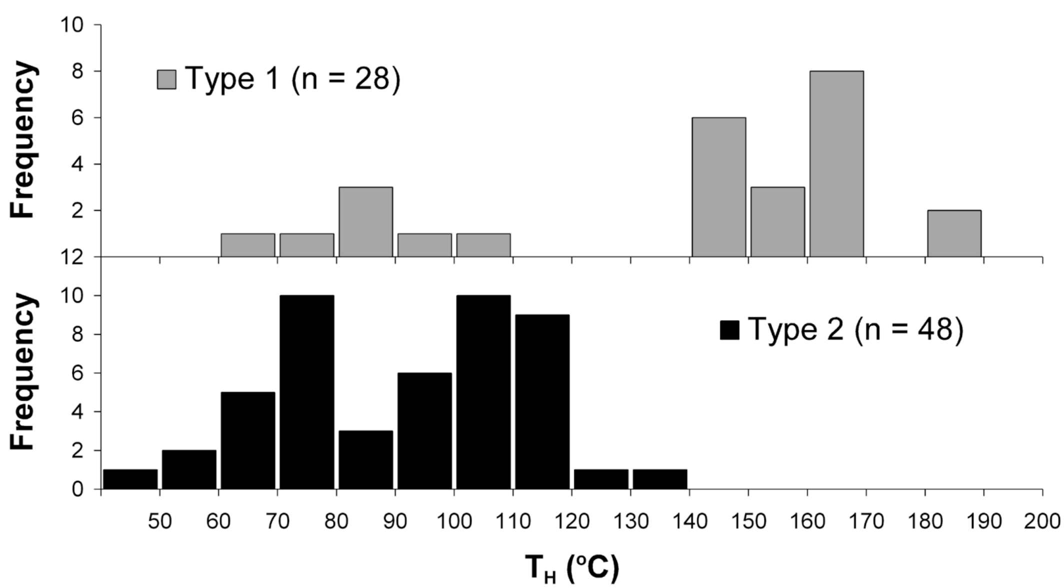

Fig. 6. Frequency distribution histogram for homogenization temperatures of Type 1 and Type 2 HCFI.

Table 4. Distribution of HCFI (Type 1 and Type 2 inclusions) in the Porcupine Basin**.**

Well	Sample Depth	Age	Inclusion Type	Inclusion Setting	T_H
26/27-1B	2164m	Jurassic	2	Carbonate Cement	-
26/28-1	2256m	Jurassic	2	Secondary Trail	55.3 to 86°C
	2410m	Jurassic	2	Secondary Trail	41.6 to 88.3°C
26/28/2	2185m	Jurassic	1	Secondary Trail	156.8 to 166.8°C
		Jurassic	2	Quartz Cement	104.4 to 120.7°C
26/29-1	1330m	Jurassic	1	Secondary Trail	82°C; 142.1 to 159.7°C
		Jurassic	2	Secondary Trail	-
	1610-1615m	Jurassic	1	Secondary Trail	-
		Jurassic	2	Secondary Trail	-
	1773m	Jurassic	1	Secondary Trail	-
		Jurassic	2	Secondary Trail	102.2 to 108°C
34/15-1	3415m	Jurassic	1	Secondary Trail	-
	3790-3810m	Jurassic	1	Secondary Trail	-
35/2-1	3225m	Jurassic	1	Secondary Trail	-
		Jurassic	2	Secondary Trail	-
35/6-1	3710m	Jurassic	2	Secondary Trail	-
35/8-2	4007m	Jurassic	1	Secondary Trail	77.3 to 99.2°C
		Jurassic	2	Secondary Trail	72.7 to 105.6°C
35/30-1	4574m	Jurassic	1	Secondary Trail	-
	4639m	Jurassic	1	Secondary Trail	-
	4849m	Jurassic	1	Secondary Trail	-
	4959m	Jurassic	1	Secondary Trail	-
	5172m	Jurassic	1	Secondary Trail	-
43/13-1	3255m	Jurassic	1	Secondary Trail	-
	3265m	Jurassic	1	Secondary Trail	-
	3505m	Jurassic	1	Secondary Trail	-
62/7-1	2545m	Cretaceous	1	Secondary Trail	-
	3119m	Jurassic	2	Secondary Trail	-
	3121m	Jurassic	1	Secondary Trail	-
		Jurassic	2	Secondary Trail	65.4

5.2 Aqueous inclusions

Aqueous inclusions have been recorded in all sandstones. They are classified into Type 3 and Type 4. Type 3 inclusions are <5 μm in longest dimension and are hosted by siliceous and carbonate cements. Type 3 inclusions in Cretaceous sandstone cements are predominantly monophase liquid however, two-phase (liquid + vapour) Type 3 inclusions have been recorded in samples from Wells 35/8-2 and 35/19-1. Monophase Type 3 inclusions indicate that cementation in Cretaceous sandstones occurred at low temperatures (< 50°C; Goldstein and Reynolds, 1994).

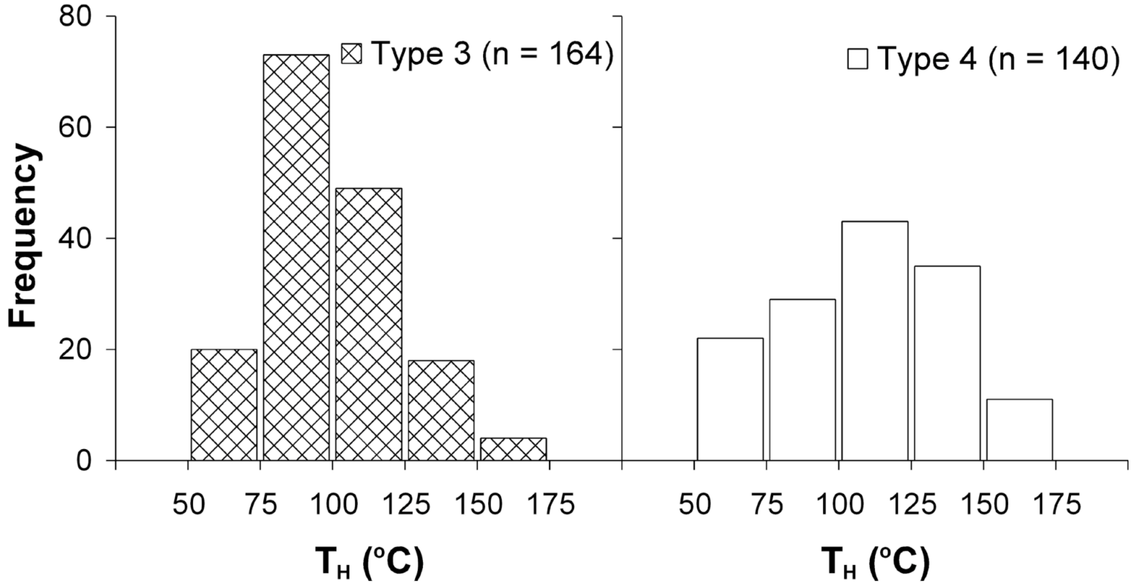

Fig. 7. Frequency distribution histogram for homogenization temperatures of Type 3 and Type 4 aqueous inclusions

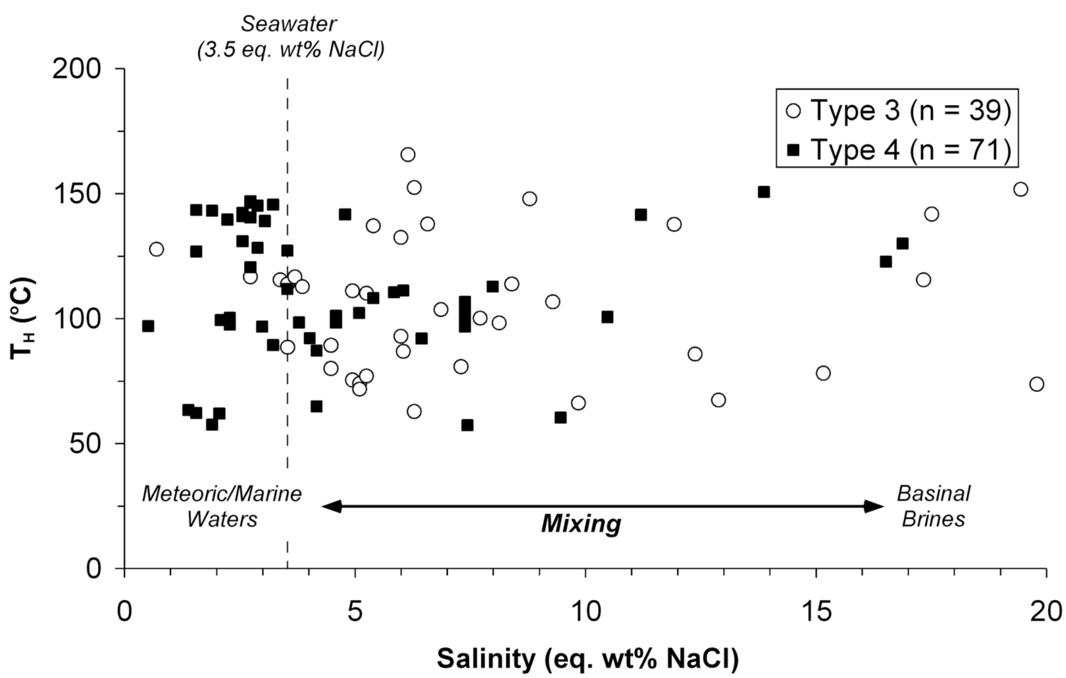

Fig. 8. Bivariate plot of salinity vs. homogenisation temperatures for Type 3 and Type 4 inclusions.

Type 3 inclusions in Jurassic sandstones are two-phase (liquid + vapour) and homogenisation temperatures generally range between 70 and 120°C (Fig. 5). T_{LM} was used to calculate fluid salinities that range from 0.71 to 19.8 eq. wt% NaCl (Fig. 8).

Type 4 inclusions are two phase (L+V) and were recorded in 5 Cretaceous and 10 Jurassic sandstone samples. They occur in trails along annealed microfractures which crosscut detrital grain boundaries and authigenic cements. They range in size from 2 to 10µm. Microthermometry yields T_H values that range from 57.1 to 174.6°C (mean = 110°C; Fig. 7). T_{LM} values of -0.2 to -13°C yield salinities of 0.53 to 16.89 eq. wt% NaCl.

6. Discussion

6.1 Oil migration pathways

HCFI are essentially confined to Jurassic sandstones and are trapped syn- to post-cementation. A Cretaceous sandstone from well 62/7-1 displayed a single trail of HCFI along an annealed fracture. HCFI were trapped during cementation in Jurassic sandstones sampled from wells 26/27-1B and 26/28-2 (Table 4), both located in the Northern Porcupine Basin the latter well is located in the undeveloped Connemara Oilfield. Elsewhere in the Porcupine Basin HCFI, in Jurassic sandstones, are confined to annealed microfractures which suggest that hydrocarbon migration is post cementation. Indeed, diagenetic sequences from well 35/8-2 suggest that hydrocarbon migration occurred late in the diagenetic history (Robinson and Canham 2001). This is consistent with fluid inclusion petrography from well 35/8-2 which recorded abundant HCFI along annealed microfractures transecting cements (Table 4). Therefore it is suggest here that hydrocarbon migration along microfractures was a significant element of the oil charge history in the Porcupine Basin. Hydrocarbon fluid migration controlled by microfracturing can occur at pressures of a few MPa (Zhang *et al.* 1990) and recent studies have identified similar fracture controlled hydrocarbon migration in sandstones from elsewhere along the North Atlantic margin (Parnell *et al.* 1999; Parnell *et al.* 2001). However, as noted by Parnell *et al.* (2001) the abundance of HCFI in annealed microfractures may reflect the preferential trapping of hydrocarbons during microfracture healing, and evidence for hydrocarbon migration along remaining intergranular pores may not have been preserved.

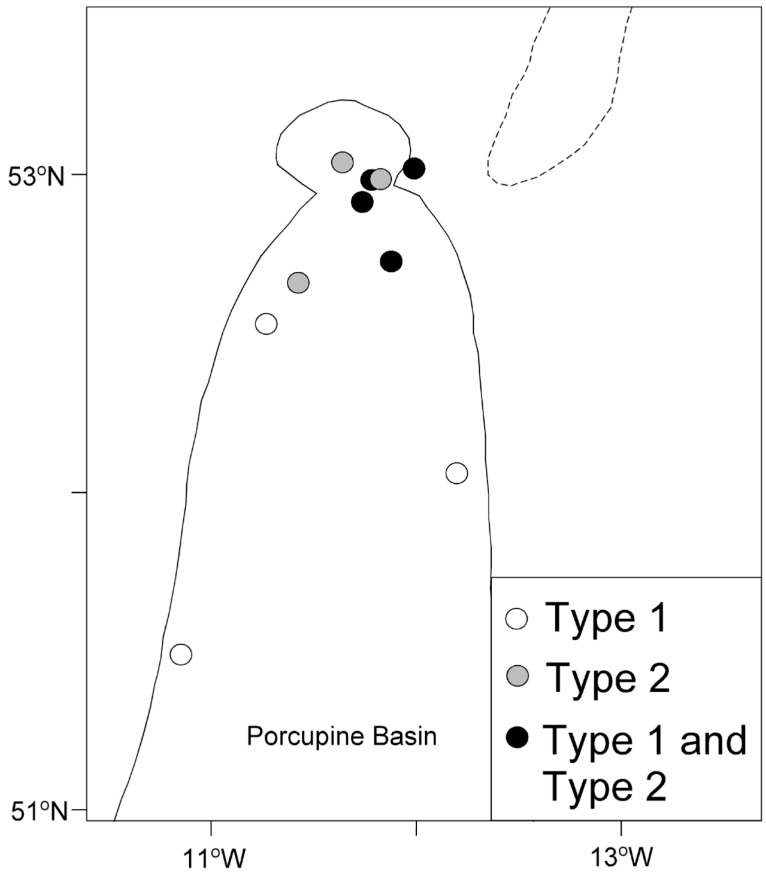

Fig. 9. Spatial distribution of Type 1 and Type 2 HCFI in the Porcupine Basin.

6.2 Fluid inclusion evidence for hydrocarbon compositions

Feely and Parnell (2001) first recorded blue-white fluorescing HCFI (Type 1 inclusions) in deeply buried (>3000m) Jurassic sandstones and yellow to green fluorescing HCFI (Type 2 inclusions) in shallower Jurassic sandstones. The spatial distribution of HCFI in the Porcupine basin (Figure 9) suggests that Type 1 inclusions occur in Jurassic sandstones throughout the Porcupine Basin, and Type 2 inclusions are more common in the North Porcupine Basin. Both Type 1 and Type 2 inclusions have been recorded in sandstone sampled from the Connemara Oilfield (well 26/28-1). A frequency distribution histogram for homogenization temperatures of Type 1 HCFI shows a bimodal distribution (Fig. 6), indicating two separate populations of Type 1 HCFI in the Porcupine Basin. Type 1 inclusions with high T_H values (>140°C) are recorded in

Jurassic sandstones from the Connemara Oilfield (Wells 26/28-2 and 26/29-1) while Type 1 inclusions with lower T_H values (<100°C) are recorded in Well 35/8-2.

Geochemical studies (Scotchman 2001) of potential source rocks and oils recovered from Jurassic horizons in the Porcupine Basin reported that oils from the Connemara Oilfield showed mixed marine and lacustrine sources while further south in the Porcupine Basin (well 43/13-1) open marine sourcing was dominant, leading to a potentially more gas prone source. Therefore, Type 1 HCFI (API gravity = 40-50°) probably represent light oils sourced in marine shales, with Type 2 HCFI (API gravity = 25-35°) originated from non-marine lacustrine rocks.

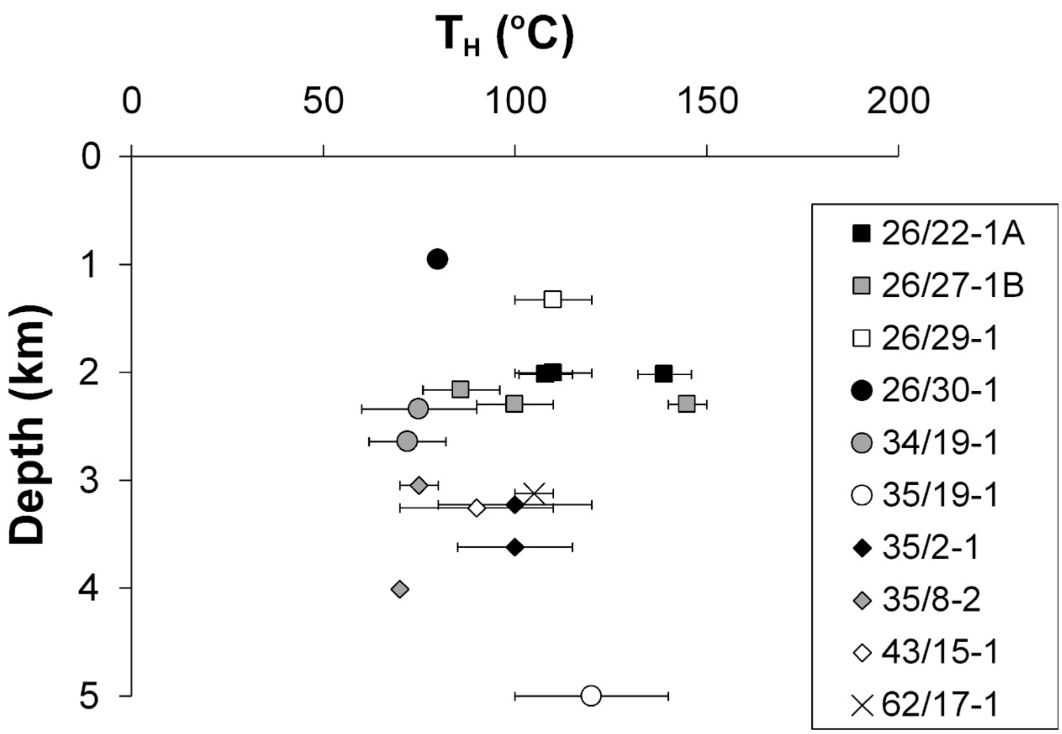

Fig. 10. Plot of the range and means of homogenisation temperatures of Type 3 inclusions in Jurassic sandstones, showing the variations of homogenisation temperatures with depth.

6.3 Aqueous fluids and basin evolution

In Cretaceous sandstone samples the majority of Type 3 inclusions are monophase liquid and were trapped at low temperatures (< 50°C; Goldstein and Reynolds, 1994). Therefore cementation in these sandstones was likely to have occurred early in the diagenetic history.

Type 3 inclusions in Jurassic sandstone samples are two-phase (liquid + vapour) and homogenise between 70 and 120°C. These temperatures do not vary significantly with depth (Fig. 10) and indicate that cementation commenced over a similar temperature range in all Jurassic sandstones. The wide range of fluid salinities in Type 3 inclusions may reflect downward migration of low salinity marine/meteoric waters (<5 eq. wt% NaCl) mixing with higher salinity basinal brines (> 10 eq. wt% NaCl).

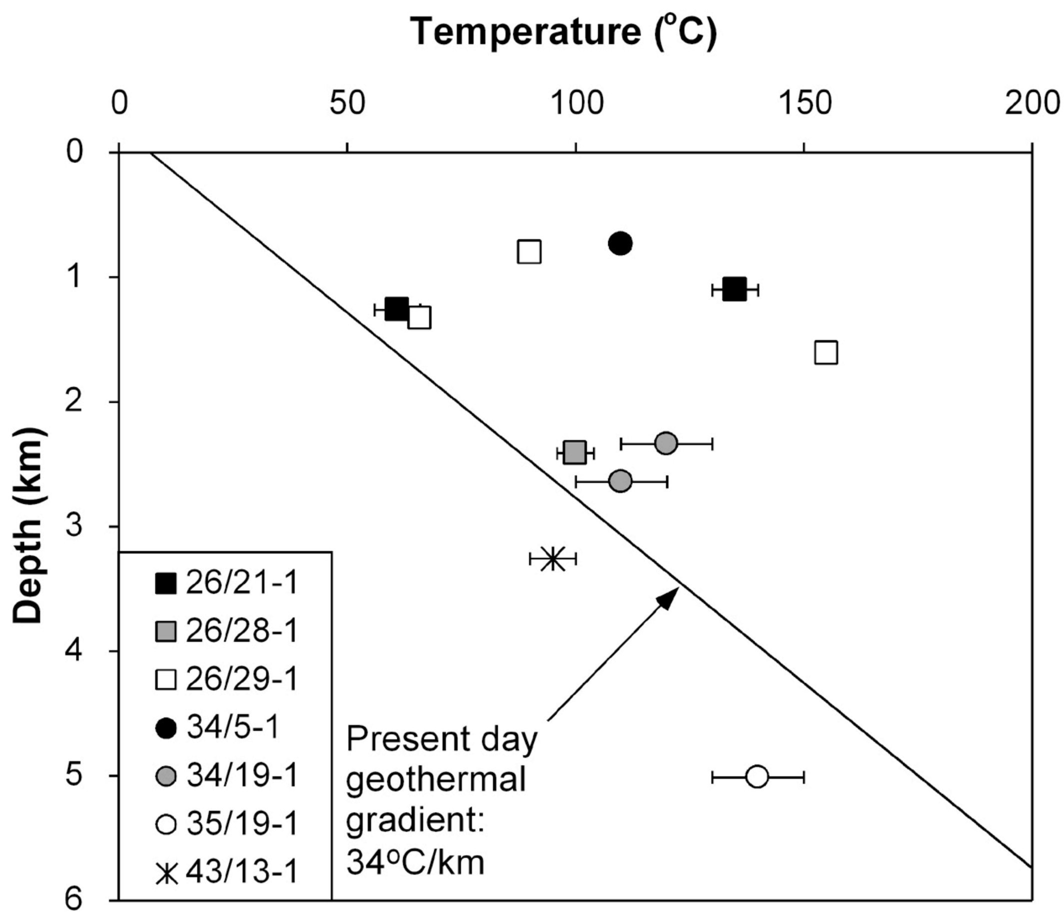

Fig. 11. Minimum trapping temperatures for Type 4 inclusions, indicating that the majority of samples have been heated above the present day geothermal gradient (from Corcoran and Clayton 2001).

Type 4 inclusions transect grain boundaries and cements reflecting aqueous fluid migration post cementation. These migration events may correlate with aqueous fluid pulses reported from Mesozoic sandstones in other basins along the Atlantic margins of Europe and North America e.g. the Jeanne D'Arc Basin (Parnell *et al.* 2001), West of Shetland (Parnell *et al.* 1999, Baron *et al.* 2007) and the Rathlin Basin (Middleton *et al.*

2001). Type 4 inclusions in the Porcupine Basin's Mesozoic sandstones homogenise over a wide range of temperatures (57.1 to 174.6°C). The current geothermal gradient in Porcupine is 34°C /km based on Horner-corrected bottom hole temperatures from wells 35/8-2, 35/19-1 and 43/13-1 (Corcoran and Clayton, 2001). These values are similar to average palaeogeothermal gradients in Mesozoic sections in the Porcupine Basin (~35°C), derived from vitrinite reflectance data (Ainsworth *et al.* 1990; Corcoran and Clayton 2001) and apatite fission-track analysis (McCulloch 1994). The homogenisation temperatures (and therefore minimum trapping temperatures) of Type 4 inclusions are greater than predicted from these geothermal gradients (Fig. 11) and therefore it is unlikely that these high temperatures were purely due to subsidence and burial.

Another possibility is that these rocks were heated by an igneous body or bodies. However there is little or no evidence for regional scale igneous activity in the Porcupine Basin. Although a median ridge in the south of the Porcupine Basin has been interpreted to be volcanic in origin (Tate *et al.* 1993) recent work has shown that it is instead related to the serpentinisation of the mantle during crustal thinning (Reston *et al.* 2004). In addition a number of scattered volcanic and intrusive igneous rocks have been recorded in Lower Cretaceous and Jurassic sections but these are volumetrically minor and no correlation between igneous activity and the presence of high temperature fluids has been recorded.

A third possibility is that hot fluid pulses recorded in the Porcupine Basin and other Atlantic margin basins (Parnell *et al.* 2001, Parnell *et al.* 1999, Middleton *et al.* 2001, Baron *et al.* 2007) are related to plume-related activity during the opening of the North Atlantic. Jones *et al.* (2001) argued that transient uplift in the Porcupine basin was related to an anomalously hot layer (up to 50km thick) of mantle material that underplated the entire region just before the onset of seafloor spreading during the early Eocene. Convection of hydrothermal fluids associated with the cooling of such a large volume of hot material beneath the lithosphere would have a major effect on the post-diagenetic fluid history of the Porcupine Basin and similar processes may account for distribution of hot fluid pulses in other Atlantic basins.

Acknowledgements

This report uses data and survey results acquired during a project undertaken on behalf of the Irish Shelf Petroleum Studies Group (ISPSG) of the Irish Petroleum Infrastructure Programme Group 4. The ISPSG comprises: Chevron Upstream Europe, ENI Ireland BV, Island Oil & Gas plc, Lansdowne Oil & Gas plc, Lundin Exploration BV, Providence Resources plc, Shell E&P Ireland Ltd, Statoil Exploration (Ireland) Ltd, Total E&P UK plc and the Petroleum Affairs Division of the Department of Communications, Marine and Natural Resources. The Petroleum Affairs Division of the Department of Communications, Marine and Natural Resources is acknowledged for providing access to well data, core and cuttings for this project.

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