

Surface geochemistry as an exploration tool in frontier, deep water, areas: Case studies from the Atlantic Margin

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Abstract: Surface geochemical prospecting involves the search for near-surface or surface anomalies of hydrocarbons, which could indicate the occurrence of petroleum accumulations in the sub-surface. The methodology, as applied in offshore basins, covers a range of techniques, from observation of visible oil seepage at the surface to detection of micro-seeps in near surface sediments using sensitive analytical technique. Since most rock types are not totally impervious to hydrocarbons, both light and heavy hydrocarbons will migrate upwards, from either mature source rocks or reservoirs, to near surface sediments. While the methodology for surface geochemical surveys is the subject of continuous development, the current, most favoured practice is to detect possible migration pathways from the deep to the near-surface with the aid of seismic data, often together with remote sensing data (satellite imaging etc.). The expression of such pathways at the surface is then the focus of surface geochemical prospecting grids. Most articles concentrate on the analysis of the samples and integration of the geochemical data with the geological framework. It is, however, important that the samples are collected properly and preserved in such a way that the original hydrocarbon assemblage present in the samples when they are brought onboard are preserved for analysis, i.e. care must be taken that there is no bacterial activity after the samples are collected and before they are analysed. Another important factor when undertaking surface geochemical studies is cost. In all such studies, sampling constitutes by far the greatest cost. It is therefore important that the methods used for sampling are streamlined for the purpose, i.e. that methods are not used merely because they give apparently impressive results without increasing the quality of the samples. It is very easy to double the sampling cost by using expensive techniques which do not enhance the quality of the samples. The authors have experience from a number of deep-water exploration areas. In this paper we will discuss sampling methods, preservation of samples and present data from three North Atlantic Margin studies and compare the geochemical data with drilling results where such are available.

INTRODUCTION

Surface geochemistry has been used in most deep water exploration areas such as the eastern North Atlantic (Bjørøy *et al.* 1999), the Barents Sea (Bjørøy & Løberg, 1993), West Africa (Cameron & White, 1999, Cameron *et al.*, 1999), the Mediterranean (Ferriday *et al.*, 2002), the Caspian Sea (Bharati *et al.*, 2000), the Gulf of Mexico (Thrasher *et al.*, 1996) and South East Asia, (Bjørøy, 2001). However, even though projects have been undertaken over many years, there remain considerable discussions in the industry regarding how to sample, how to preserve the samples, and which analyses will give the best results, etc. Some of the methods that are offered could easily double the sampling cost of a project compared with other methods. Backed by almost 20 years experience and collection / analysis of more than 12 000 cores for surface geochemistry, this paper will therefore look into the different methods and evaluate which provide the most meaningful data for the investment made.

A surface geochemistry project can be divided into five different phases; planning, sampling, preservation of samples, analyses and interpretation/integration of the data with the geology. To have a successful project all of these areas have to be looked at carefully and undertaken properly. Failure in any one of these areas could easily turn a good project into a failure.

PLANNING OF A SURVEY

There are a number of aspects that need to be considered when a survey is planned. If care is not taken at this stage hundreds of thousands of dollars can be lost even before a study is started. These days almost all the studies are undertaken over areas where there are seismic data available. This can be 2D or, even better, 3D seismic data. In most cases these data will be sufficiently good that all the geological features that need to be sampled are easily recognisable from the seismic. There are sometimes questions regarding the need for high resolution seismic before sampling in order to locate the exact position to sample. The technology that is used to obtain the high resolution required will vary depending on the water depth, type of sediment etc. Over the years Geolab have used Chirp, Pinger, Boomer, Sparker and Light Air Guns when our clients have requested it. However, we have only had to relocate less than 5% of the sample locations of those based on the original deep seismic. Taking into account the cost of doing the high resolution seismic, we felt it would be far better to take extra cores over locations where there are uncertainties from the deep seismic. As a rule of thumb, it is possible to collect an extra 20-40 samples, depending on water depth, per day spent on high resolution seismic, taking into account the extra cost in mob/demob and the extra personnel onboard.

Another aspect that can strongly affect the cost of a survey is the decision on what sampling equipment to use. In shallow water, down to 450 m, and on sandy/gravelly sea floor, it will be necessary to use vibro coring. There is basically no discussion regarding this. If the sea floor is clayey, there is quite often a discussion if piston coring or gravity coring should be used and also how long the core barrels used should be.

Regarding the question of whether piston coring or gravity coring should be used, we should first describe the two techniques. With piston coring the corer is lowered on the winch until it is close to the seafloor. When it is a certain distance above the seafloor, which will depend on the length of the core barrel, a mechanism releases the corer and it drops in free fall and penetrates into the sediment. A piston inside the core liner is forced upwards when the corer penetrates the sediment. When the corer is pulled out the piston is first pulled up until it is at the base of the corer head if the core barrel has not penetrated completely. The corer is then pulled out of the sediment and the piston creates a vacuum stopping the core falling out of the core barrel. The piston coring system is a good system, which gives good recovery in most cases when the system is used correctly. However, there can be some problems. Experiments undertaken by University of Bergen, Norway, showed the following when testing the piston coring technique from different heights and with different weights. Increased inertial energy by tripping and causing a free fall at a greater distance from the sea floor compressed the sediments and excessive impact speed resulted in the core barrel getting penetration, but very little recovery. In other words, high impact speeds usually cause the entire corer to penetrate as a solid mass, and after the uppermost sediments have entered the core barrel the corer will penetrate further without any sample entering the core barrel. Experiments showed that the best results were obtained using a lowering speed of 1.5 to 2.0 m/sec. They concluded that a heavy corer and a moderate speed gave the best results. (Maisey, 1996).

Piston coring is also fairly weather dependent due to the way the system is set up with counter weights, release systems etc. This can result in a number of days "waiting on weather" if the sampling is undertaken in areas with poor weather, such as the North Atlantic Margin.

Regarding gravity coring, this is probably the simplest coring system available today. There is no counter weight and release system to worry about, only the wire rope, the corer weight and the steel core barrel. The corer weight is regulated to give best possible penetration. The lowering speed is the speed of the winch. Our experience has shown that a speed of approximately 100 – 120 m/min (1.7 – 2.0 m/sec) is the ideal speed. Using a fast winch like this will also result in fast recovery of the corer. Instead of using a piston inside the core liner to stop the core falling out of the liner when the core is recovered, a non-return valve is fitted inside the corer head. This, together with a specially designed copper-beryllium core catcher, gives almost the

same effect as the piston in the piston coring system. Using a non-return valve and core catchers we believe gives good recovery. A core recovery of 70 – 90 % of the penetration is normal, Table 2. Before 1985, gravity coring was mainly done from derricks, cranes or A-frames similar to piston coring and is still performed like this by some survey companies. A special corer docking system (Figures 1-2) was developed in the mid 80's. This resulted in a far safer way of collecting the samples, with no loose parts swinging with the ship's movement. It is therefore now possible to collect samples in rougher weather than before. The weather down time has been reduced. It is in fact seldom that there is any weather down time using this system. Our experience has shown that it is perfectly safe to sample in force 7 (14-17 m/sec) and we have sampled in many instances in Force 8 (gale force, 17 – 20 m/sec). What weather we can sample in will of course depend on the ship used in each instance. Figure 2 shows sampling along the Atlantic Margin in Force 7.

The main problem with using piston coring for surface geochemical samples is the low number of samples that can be collected per day. Piston coring will give a far lower number of cores per day than gravity coring. An example of this is from a study undertaken in the Norwegian Sea. The water depth varied from 850 m to 1970 m over the area. The production with gravity coring for surface geochemistry was 26 samples per day on average, including some very long transits, up to 5 hours, between sample locations. A total of 280 samples were collected. Another survey company completed a geo-technical survey over a part of the area with average water depth of 1 220 m and hardly any transit time between locations, using piston coring. Samples from the geotechnical cores were also collected by SGS for geochemical analysis. The production was 10 cores per day for this survey. The penetration and recovery data of the piston cores were similar (i.e. within 10%) to those collected with gravity coring over the same area. If piston coring had been performed instead of gravity coring on the surface geochemical survey, the survey would have taken a minimum of 12 more days, i.e. an extra of US\$ 150 000 – 200 000. There is no published evidence that piston coring will provide better samples, i.e. better recovery, if proper care is taken with gravity coring i.e. using a specially designed non-return valve and special core catchers.

Depending on transit distance between sample locations it is possible to collect 15 – 25 samples per day in an average water depth of 2000 to 2 500 m and 25 – 40 samples per day in average water depths of 1000 – 1500 m using gravity coring with the special corer docking system described above and a fast winch (100 – 120 m/min). These numbers are based on more than 30 surveys over the last 8 years.

There has been a tendency lately to use increasingly longer core barrels. In the late 80's, some companies started to take 6 m cores and over the last years there has been some service companies that advocate for the use of 9 m

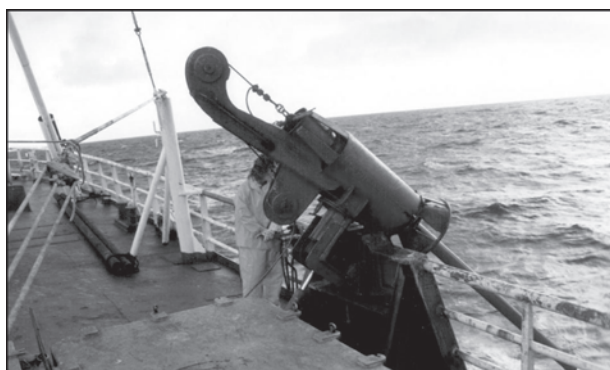


Figure 2. Sampling in Force 7, using the gravity corer docking system.



Figure 1. Special docking system for gravity coring.

and even 12-15 m core barrels. The arguments are that the longer cores, the better the samples would be, i.e. the deeper the more hydrocarbons will be present in the samples. This is supposed to be the case, especially when the samples are from areas with micro seeps. Our studies have shown that this is not the case. Experiments undertaken on 6 m cores where micro seeps are found, show that there is hardly any variation in the amount of hydrocarbons in the samples from approximately ½ m below the oxic/anoxic boundary down to the bottom of the core, (Figure 3; Table 1). Cores were collected from three different areas, i.e. West of Ireland, Norwegian Sea and the North Sea. All three places had soft seafloor and 6 m penetration. There was almost 100% recovery for all three cores. Samples were collected from the top of the core and then with an increase of ½ m down the core. The samples were canned and frozen to -80°C and brought to the laboratory for analysis. The samples were thawed out before being extracted with hexane and analysed by gas chromatography. Squalane was used as an internal standard for quantification of the extract. Our data show a sharp increase in the extract after the oxic/anoxic boundary is passed and then hardly any variation for the amount of extract. There is one exception to this. The sample from the North Sea shows a sharp increase in extract for the sample from 4 m compared with the samples from above and below this level (Figure 3, Table 1). A close examination of the sediment for the different samples showed this sample to contain a mixture of fine sand/silt while the other samples were mainly silty clay. We believe that the reason for the increase in extract for this sample is the change in lithology, i.e. the silt/sand resulted in more seeped hydrocarbons being collected here compared with the finer sediments.

The gas chromatograms of the analysed samples in the cores show a significant difference between the samples from the top of the cores and those collected below the oxic/anoxic boundary. Figures 4a-i show the results from three different regions. Samples taken from above the oxic/anoxic boundary did not show any hydrocarbons present in the gas chromatograms, only non-hydrocarbons and are not shown in Figure 4. The samples taken at approximately

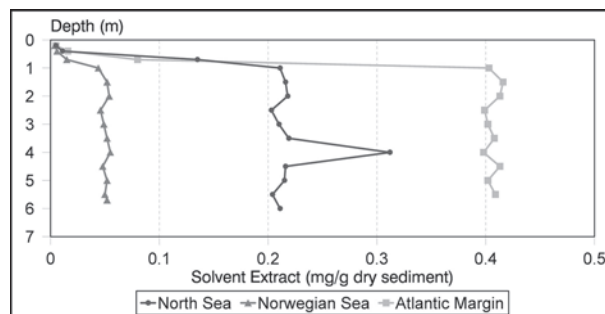


Figure 3. Solvent extraction data from three different cores.

Table 1. Yields from solvent extraction of sediments in mg/kg.

Depth (m)	North Sea	Norwegian Sea	Atlantic Margin
0.2	0.005	0.004	0.005
0.4	0.011	0.006	0.016
0.7	0.135	0.015	0.080
1.0	0.211	0.044	0.403
1.5	0.216	0.052	0.416
2.0	0.218	0.054	0.413
2.5	0.203	0.046	0.399
3.0	0.210	0.049	0.402
3.5	0.219	0.052	0.408
4.0	0.312	0.055	0.398
4.5	0.216	0.048	0.413
5.0	0.215	0.052	0.402
5.5	0.204	0.050	0.409
5.7	0.052		
6.0	0.211		

the oxic/anoxic boundary, or a few centimetres below this, show hardly any hydrocarbons except for some high molecular weight n-alkanes originating from recent material (Figures 4a, d, g). Gas chromatograms of the extracts of samples taken well below the oxic/anoxic boundary show hardly any difference at all (Figures 4b-c, e-f, h-i). Over the years, a large number of samples, both from 4 m and 6 m cores have been analysed and they all show the same, i.e. hardly any variation between samples from the anoxic part of the core. Based on 20 years experience and collecting/analysing more than 12 000 cores for surface geochemistry, we believe that where differences are found, both regarding amount of extracted material and differences in the composition of the samples, this is due to a variation in the lithology of the samples and has nothing to do with the depth of the samples as long as the samples are collected well below the oxic/

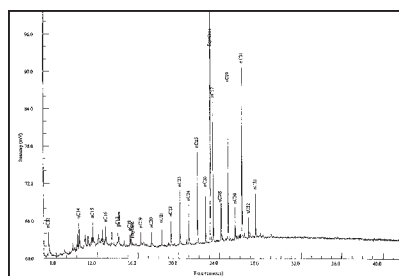


Figure 4a. Gas chromatogram of extract of sample from 0.5 m, Norwegian Sea.

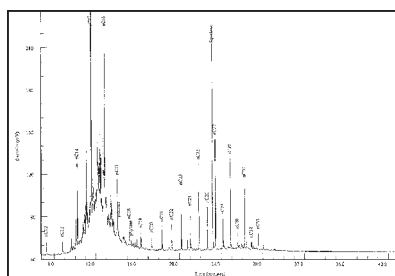


Figure 4b. Gas chromatogram of solvent extract of sample from 4 m, Norwegian Sea.

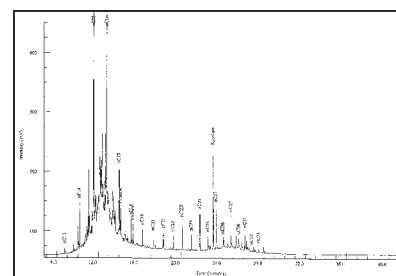


Figure 4c. Gas chromatogram of solvent extract of sample from 5.5 m, Norwegian Sea.

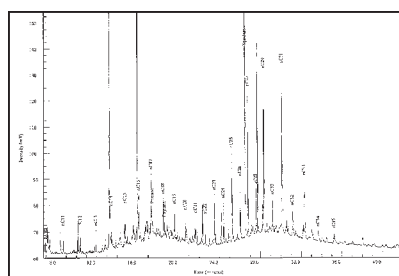


Figure 4d. Gas chromatogram of solvent extract of sample from 0.5 m, North Sea.

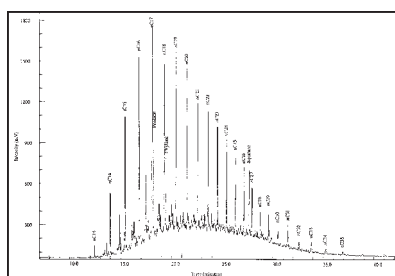


Figure 4e. Gas chromatogram of solvent extract of sample from 4.0 m, North Sea.

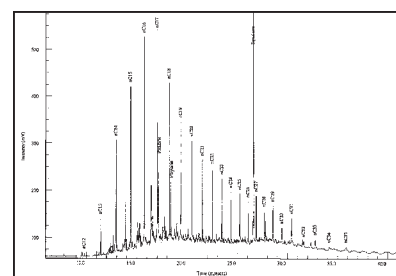


Figure 4f. Gas chromatogram of solvent extract of sample from 5.5 m, North Sea.

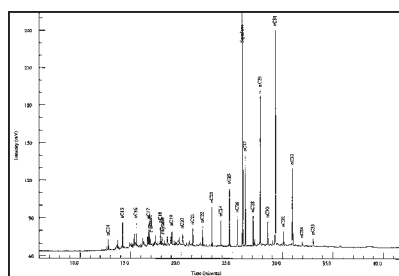


Figure 4g. Gas chromatogram of solvent extract of sample from 0.5 m, Atlantic Margin.

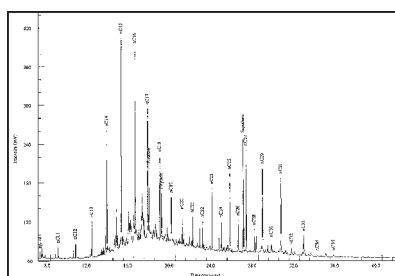


Figure 4h. Gas chromatogram of solvent extract of sample from 4.0 m, Atlantic Margin.

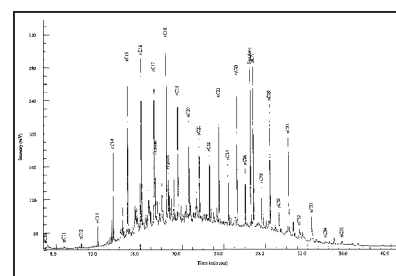


Figure 4i. Gas chromatogram of solvent extract of sample from 5.5 m, Atlantic Margin.

anoxic boundary. Use of long core barrels, i.e. longer than 4-6 m, will result in using more time/money in collecting the samples. This is both due to needing more time to bring a long core onboard and making the corer ready for the next drop and the need for more personnel on deck to handle the longer cores. Based on this, we believe that, as with piston coring versus gravity coring, the following statement is true: Using longer core barrels will reduce the number of samples that can be collected per day compared with shorter core barrels. There is no published scientific evidence that longer cores will give better quality samples.

The final item that has to be evaluated for a survey is whether or not an ultra short baseline (USBL) system should be used. Again there are various arguments for and against the use of such systems amongst different survey companies. In our opinion, an USBL system is necessary if samples are to be collected at water depths more than 200 - 300 m. The offset of the corer compared with the position of the ship will depend on various things such as current, which might be different at depth than at the surface, corer weight etc. We have experienced the corer

being located more than 200 m away from the ship's position at a water depth of 3300 metres. We have also experienced the corer being 30-40 m away from the ship's position at a water depth of 1000 metres. Therefore, even if in many cases the corer may be close to the ship's position, it is always recommended that a USBL system is used in order to know exactly where the core is taken when working at water depths > 200 to 300 metres. Most USBL systems on the market today have an accuracy better than + 1% of the water depth. We have developed a system where the transponder is embedded inside the corer head, making it simple to use and completely out of the way, when using gravity coring. This makes it as easy to take cores using the USBL system as not using it. With an USBL system, the corer is dropped down to 30 - 50 m above the sea floor, the ship is then moved, using thrusters and the main engine, to bring the corer inside the designated target area. The corer is then lowered into the sea floor using the winch at 100 - 120 m/min.

Considering all the above, it is therefore our opinion that the optimal techniques for a surface geochemical survey are the following:

In shallow water (<450 m) sand and/or gravel, use vibro corer system.

With clayey sea floor, use gravity corer. If shallow water (< 200 – 300 m) it is not necessary to use an USBL system. If in deep water use an USBL system to get the exact positioning of the corer.

If good 2D or 3D seismic is available, it is not necessary to use any form of high resolution seismic to pinpoint the exact location of the feature that is targeted for sampling. It will be far better to take a few extra samples over the area where the feature is located, if the deep seismic cannot pinpoint this exactly.

Preservation of samples

Another important aspect regarding surface geochemical surveys that needs to be addressed in the planning stage is the preservation of the samples. This is extremely important since the wrong decision can easily destroy the samples, i.e. the hydrocarbons found in the samples during the analysis are not the same as those present in the samples when collected. The samples have to be preserved in such a way that the hydrocarbons detected in the samples during the analyses are those that were there when the samples were recovered, and not hydrocarbons produced by bacterial activity during storage. This is an issue that has been addressed by various authors, Kvenvolden *et al.*, (1979, 1980) and BJORØY and Ferriday (2002) but there are still survey companies that, in our opinion, do not take the proper precautions.

Various methods for preservation of samples were tested during the early 1980's. These are described in detail by BJORØY and Ferriday (2002) and will not be repeated here. They concluded that the only method of preservation that would guarantee no biodegradation for any type of sample was to freeze the samples to a very low temperature. We therefore believe that the correct method for preservation of samples is to put samples in pre-cleaned cans, flush with nitrogen, seal and put in freezers at – 45 to – 80 °C (BJORØY & Ferriday, 2002).

Collecting samples in cans and adding water with bactericide before storing these in air temperature, or even in household freezers, gives no guarantee that the samples, especially if these are hard clay, will have gone into suspension in the water so that the bactericide can act on the bacteria. The possibility that the analyses are performed on hydrocarbons generated by bacterial activity, instead of the hydrocarbons in the samples when collected, is therefore large when this preservation method is used. There is strong evidence that the gases in particular are affected and that it is easy to reach a “biogenic gas” conclusion when it should really be “thermogenic gas” (BJORØY & Ferriday, 2002).

ANALYSES

There are a number of analyses, both screening (which are normally undertaken on all the samples) and follow

up analyses (which are undertaken on the samples that are found by the screening analyses to contain thermogenic hydrocarbons). Various organisations will offer different types of analyses, i.e.: headspace gas, occluded gas, adsorbed gas, simple grain size distribution, TOC/TC, solvent extraction, quantitative gas chromatography, total scanning fluorescence (TSF) as screening analyses; and carbon isotope analysis of C₁ to C₄ by GC-IRMS, GC-MS of biomarkers and aromatic compounds, separation of extract into saturated and aromatic fractions, carbon isotope analysis of fractions and GC-IRMS of n-alkanes and isoprenoids in fractions as advanced methods. The different analyses were discussed in detail by BJORØY and Ferriday (2002) and will not be repeated here. Their conclusion was that the following analytical program was recommended: occluded gas, adsorbed gas, simple grain size distribution, TOC/TC content, solvent extraction and quantitative gas chromatography as screening analyses, followed by carbon isotope analysis of C₁ to C₄ by GC-IRMS and GC-MS of biomarkers and aromatic compounds as follow up analyses. In certain areas, separation of the extract into saturated and aromatic fractions, carbon isotope analysis of fractions and GC-IRMS of n-alkanes and isoprenoids in fractions can also be useful.

INTERPRETATION AND INTEGRATION WITH THE GEOLOGY

The analytical data will show where thermogenic hydrocarbons, either gases or liquid hydrocarbons or both, occur in surface sediments. The data will also give information regarding maturity and the type of source rock that has generated these hydrocarbons. However, if this information is not integrated with the geological information of the area, the data are basically meaningless and all the money spent on the project will be wasted. Hydrocarbons generated in a basin will seep to the surface, not by diffusion through the overlying sedimentary sequences but through various conduits where the seepage of the hydrocarbons will be easier. It is therefore extremely important that the geology of the area where the study is undertaken is sufficiently known such that potential conduits can be recognised. Thrasher *et al.* (1996) showed how liquid hydrocarbons from a field had seeped through an up-dipping sandy conduit to the surface tens of kilometres away from the field.

CASE STUDIES

The three case studies in this article were undertaken between Shetland and the Faeroes during 1996 and 1998.

Regional Geology

The area of the surveys is geologically located over the Færoes - Shetland Basin, lying to the north west of the West Shetland Platform and the Scottish mainland. The area is part of the eastern Atlantic margin, with the Møre

Basin offshore Norway to the northeast and the Rockall Trough offshore Ireland to the south-southwest. The region contains several large ridge structures, notably the Corona-Westray ridge system within the central part, trending northeast - southwest, parallel to the continental margin; also the Rona Ridge which separates the F eroe-Shetland Basin from the West Shetland Basin towards the mainland.

Post Precambrian basement cover is of Devonian to Recent age, although sections of Jurassic age or older are only penetrated in a few wells. The Devonian to Lower Carboniferous consists of 'red-bed' sandstones and shales, while the main basin fill is inferred to consist of laterally very variable amounts of syn-rift Jurassic to Lower Cretaceous sediments including some potential reservoir sandstones. The most potential source rocks in the area are, as in the North Sea, the marine shales of the Upper Jurassic Kimmeridge Clay Formation. The Lower Cretaceous sediments, again little penetrated by drilling, are inferred to consist of mainly sandstones and siltstones. The Upper Cretaceous consists of post-rift marls, shales and thin limestones, the basin containing up to 10 000 feet of Upper Cretaceous argillaceous lithologies. There is a major unconformity at the end of the Cretaceous and into the early Paleocene, marking the start of a period of both thermal uplifts and (mainly) subsidence and of faulting. During the late Paleocene deep marine turbidites were deposited, these including the sandstones representing the Paleocene plays that are now the focus of exploration in the area. Tectonic activity was accompanied in the late Paleocene (Thanetian) by extensive volcanic activity,

continuing into the early Eocene (Ypresian). This was manifested by the introduction of sills and the extrusion of sub-aerial lava flows of basaltic composition to the northwest of the Corona Ridge and along the northeast margin of the Shetland Platform. These represent generation of new oceanic crust, associated with the seafloor spreading of the North Atlantic. The basalts, which occur at several levels within the host mudstones and thin sandstones, present some hindrances to exploration due to their seismic reflectivity, often acting as the acoustic basement. Apart from the mudstones, there have also been recorded lacustrine sediments and coals within the basalt host sediments. Later in the early Eocene there was deltaic sedimentation, which was terminated by a major marine transgression, and Eocene to recent sediments consist mainly of shelf sands.

Sampling

Three separate surveys were undertaken between Shetland and the Faeroe islands during 1996 – 1998. A total of 765 sample locations were selected from 2-D seismic data. Regarding the north-western part of the area, i.e. over the Faeroes shelf, sea floor information indicated that there would be hard sea floor in parts. The survey ship, M/V Geoboy was equipped for both vibro coring and gravity coring for this part of the survey. Most of the samples were collected using gravity corer with a 4 m core barrel, while 85 stations over the shallower part of the Faeroes shelf were sampled using a vibro corer with a 3 m core barrel, after attempts with gravity coring had failed.

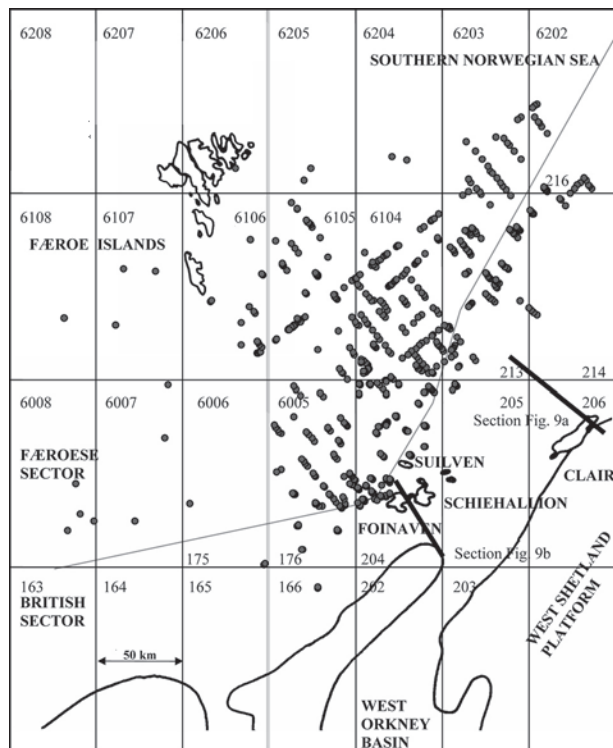


Figure 5. Sample locations.

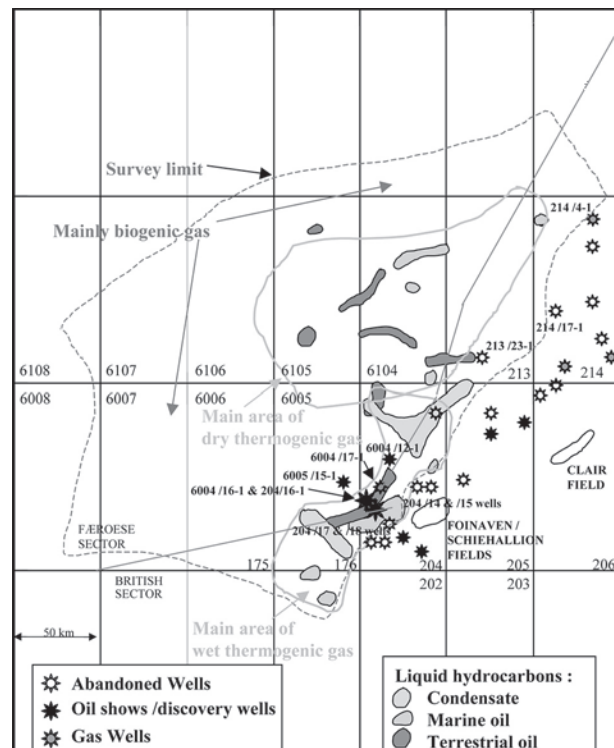


Figure 6. Drilling results compared with gaseous and liquid hydrocarbons in surface geochemical samples.

Table 2. Coring performance in Faeroe-Shetland surface geochemical surveys.

Area	Average Water Depth (Gravity)	Average Water Depth (Vibro)	Average USBL Offset from target	Average Penetration (Gravity)	Average Penetration (Vibro)	Average Recovery (Gravity)	Average Recovery (Vibro)	Average cores/day (Gravity)	Average cores/day (Vibro)	Average cores/day (Piston) (Estimated)
Faeroes	614 m	221 m	4.2 m	3.5 m	2.7 m	3.15 m (90 %)	2.4 m (89 %)	38	23	
White Zone N	1017 m		7.8 m	3.3 m		2.64 m (80 %)		34		
White Zone S	1118 m		5.6 m	3.4 m		3.03 m (89 %)		28		
Totals/Averages	916m	221m	5.9m	3.4m	2.7m	2.94m (86%)	2.4m (89%)	33	23	(10)

A USBL system was used for location of the corer, even in the shallower parts where vibro coring was used. M/V Geoboy is equipped with a moon pool for the USBL system so it was possible to transit between the different locations at full speed (10 knots). Table 2 shows the performance for the sampling over these areas.

During the Faeroes Shelf survey, gravity coring was tried first. If this did not give a successful core, i.e. longer than 1.0 m, in the first attempt a second attempt was made. If this also failed, vibro coring was performed if the water depth was less than 450 m. For the other two surveys only gravity coring was used due to the large water depths. Again a second attempt was tried if the first attempt did not give satisfactory result. This gave a total of 850 attempts for the three surveys, consisting of 634 successful gravity core samples and 75 successful vibro core samples. There was failure at 10 vibro core locations and at 46 gravity core locations in water depths greater than 450 m. Most of the locations which failed with gravity coring, and where the water depth was too great for vibro coring, were on the Faeroes shelf. The main reason for the failure was that there were significant amounts of rocks and boulders in this area. There were a few failures in the deeper part of the area between the Faeroes Shelf and Shetland, again for the same reason. A map showing the sampled locations for the three surveys is shown in Figure 7.

During the three surveys a total of 72 hours was lost due to poor weather (Force 9 and 10). When taking this into account together with excluding the transit time from mobilisation port to sampling areas and back to demobilisation port after the completion of the sampling, the total time used for gravity sampling was 20.5 days. This gives an average of 31 locations per day including the 131 locations that were tried twice with gravity corer.

As mentioned above, a USBL system was used on all three surveys. The target area was defined as being within a radius of 25 m from the planned sampling location. The ship was brought into position and the corer was free fallen to 30–50 m above the sea floor. The ship was then moved using the main engine and the side thruster to bring the corer as close to the location as possible. When this was achieved, the corer was lowered into the sea floor at approximately 100 m/min. Due to the poor recovery it was

also tried to lower the corer to 10 m above the sea floor and then free fall it. This would give the same effect as the Kullenberg free fall method (Kullenberg, 1947). There was only marginally better recoveries, if any, using this technique. The average penetration with the gravity corer was 3.36 m and an average recovery of 2.96 m (88%). The average offset for all samples in the three studies was 5.8 m, Table 2.

Preservation of samples

Approximately 30 cm was cut off from the lower end of the core using a handsaw. The sediment was extruded from the liner and split into two. Each of the two samples were put into separate 1 litre cans ensuring that all fragments of liner generated by its cutting were removed. The cans were flushed with nitrogen to remove as much of the oxygen as possible before they were sealed with a press-down lid. The cans were then stored in special freezers at -80°C . The samples were put into the freezers within 5 minutes of the corer being brought onboard. The freezing of the samples to very low temperatures is the only way to guarantee that there will be no bacteriological activity after the samples are collected (Bjørøy & Ferriday, 2002). The samples were transported to the laboratory for analyses in the special freezers after the surveys were completed, and kept in such freezers until the night before each sample was due for analysis. At this point the number of samples planned for analysis the next day would be removed from the freezers and allowed to thaw out overnight.

Analyses

A full suite of analyses was performed on the samples. The analyses can be divided into screening analyses and follow-up analyses. The screening analyses, consisting of headspace gas, occluded gas, adsorbed gas, simple sedimentological description, simple sedimentological separation, ($<$ and $>$ 63 μm), amount of water in the samples, total organic carbon, total carbon, solvent extraction using hexane and gas chromatographic analysis of the solvent extract, were undertaken on all the samples. The whole sample was used for headspace gas, occluded

gas, sedimentological description and amount of water in the sample while for the remaining analyses, the < 63 µm was used. Based on the results of the screening analyses, samples were selected for the follow-up analyses. Samples for GC-MS and TSF analyses were picked based on the gas chromatograms of the extracts and the amount of extract. Both aromatic and saturated components (biomarkers) were analysed by GC-MS. These analyses, together with the gas chromatograms of the extracts, give evidence as to whether liquid hydrocarbons have seeped to the surface and can be used to determine the type and maturity of source rock which generated these hydrocarbons. The gas analysis results were used to select samples for combined gas chromatographic/carbon isotope (GC-IRMS) analysis of the gas fractions. Where possible, methane, ethane, propane and butane were analysed. This analysis gives information as to whether the gas is biogenic, thermogenic or mixed gas. It is also possible to get an indication of the maturity and type of source rock generating the gas. Details regarding the analytical procedures and the information that can be found for each type of analysis are discussed in Bjorøy and Ferriday (2002).

GEOCHEMICAL RESULTS

Gas Data

The samples from the Faeroes continental shelf vary significantly. The headspace and occluded gas data show that most of the samples contain biogenic gas. Later studies over other Atlantic Margin areas show this to be typical for the North Atlantic Margin as described by Bjorøy *et al.* (1999). The adsorbed gas data, however, show far more variation. Most of the samples were again found to contain biogenic gas, especially on the Faeroes Shelf and the northeastern part of the White Zone. However, a number of samples contained dry thermogenic gas, these mainly occurring in the north of the area, in quadrants 6105, 6104 and 6103 on the Faeroes Shelf and quadrant 213 on the UK Shelf (Figure 6). A significant number of samples were also found to contain wet, oil-associated gas. These occur mainly in the southern part of the examined area, i.e. Faeroes Shelf quadrant 6004 and UK quadrants 176 and 204, together with a few scattered locations in UK quadrants 213, 214 and 166. A large proportion of the samples with significant quantities of wet, oil associated gas found in UK quadrant 204 most probably represent the petroleum system associated with the Foinaven, Schiehallion and Sulven oil fields, which are located a few kilometres to the east of these core sites (see Figure 6).

Liquid Hydrocarbon Data

There is a significant variation in the extract yield for the analysed samples, 0.3 to 85.9 mg/g dry sediment. Most

of the samples have fairly low values, i.e. below 5.0 mg/g dry sediment. However, rich contents do not necessarily imply rich contents of thermogenic hydrocarbons, as the bulk of the samples contain hydrocarbons from the recent (unaltered) organic matter (ROM) present in the sediment. It is therefore important that the gas chromatograms of the extracts are examined together with the extract data. The recent organic matter (ROM) makes up the bulk of the very prominent odd numbered n-alkanes of heavier molecular weight and contribute also the envelope(s) of unresolved compounds (UCM) in the gas chromatograms. If the seeped hydrocarbons have been altered by bacterial activity, the remains of this will be registered in the UCMs, defined as the area above the baseline of the envelope of unresolved compounds as seen in the chromatograms. Some of the samples, but not all, contain hydrocarbons of thermogenic origin, which have seeped to the surface, as discussed below.

In general, the gas chromatograms show five different patterns (Figures 7a-e). Most of the analysed samples show no indications of seeped material, i.e. the gas chromatograms indicate the samples to contain only hydrocarbons from recent organic matter, and are classified as Type A. An example of this is shown in Figure 7a. Such samples with no indications of seeped hydrocarbons are found over the whole of the studied area. Another large proportion of the samples shows a small influence of seeped hydrocarbons and are classified as Type B. The smooth pattern for mature n-alkanes and typical pristane/phytane ratios for oil-associated hydrocarbons are found in the front end of the gas chromatograms, i.e. up to C₂₂. The higher molecular weight ends of the gas chromatograms are dominated by odd numbered n-alkanes, i.e. reflecting input from the plant material in recent organic matter, Figure 7b. Again, samples from large parts of the studied area have this type of extract chromatogram. A third pattern, found for a number of samples, shows a large abundance of lighter hydrocarbons, and high pristane/phytane ratios, and are classified as Type C. A pattern such as this would indicate condensate type seeped hydrocarbons. The high molecular weight part of the gas chromatograms are, however, again dominated by odd numbered n-alkanes, i.e. input from the plant material in recent organic matter, Figure 7c. This pattern is significantly different to that of Type B, i.e. the seeped hydrocarbons of Type C have a significantly higher maturity.

Two groups of samples show gas chromatograms indicating seeped oil. There is significant variation between the gas chromatograms for these two groups of samples. One group of samples has a large abundance of n-alkanes in the C₁₇ to C₂₈ range and a relatively low pristane/phytane ratios and is classified as Type D. The pattern seen here indicates the seeped hydrocarbons originated from a source rock with a significant input of terrestrial organic matter, possibly mature kerogen type III/II or even kerogen type III, Figure 7d. The terrestrial input in the kerogen sourcing

these hydrocarbons is verified by the GC-MS analyses which show a small abundance of diasteranes and a relatively large proportion of C_{29} regular steranes compared with C_{27} regular steranes, Figure 8d. This type of hydrocarbon assemblage is found in samples in various locations throughout the study area, see Figure 6. The final group of samples, classified as Type E, has gas chromatographic patterns similar to those found for mature oils of more marine kerogen Type II, with a smooth n-alkane distribution, ranging from C_{15} to C_{30} , Figure 7e. Most of the samples with this pattern have pristane/phytane ratios of 1.8 to 2.2, typical for mature hydrocarbons from kerogen Type II. The samples with this type of seeped oil occur in UK quadrants 201, 213, and the southern part of 216, as well as in Faeroes quadrants 6004, 6005, 6104 and 6105, Figure 6.

Total scanning fluorescence (TSF) analysis was undertaken on all the samples which were found by GC analysis to contain significant seeped hydrocarbons, but was also performed on some samples that were indicated to have relatively minor amounts. As has been found with

other studies (Barwise and Hay, 1996; BJORØY and Ferriday, 2002), the TSF data were often found to disagree with the GC data, i.e. samples which by GC analysis were clearly found to contain seeped hydrocarbons were indicated to be barren by TSF, and vice versa. The TSF data are therefore not included in any further evaluation since the GC analysis, which is on a molecular basis, is considered more accurate than the TSF, which is a bulk analysis.

All the samples that were found to contain seeped hydrocarbons by GC were analysed for both biomarkers and aromatic compounds using a high-resolution GC-MS instrument. The aim of this examination was to establish the maturity level of the seeped hydrocarbons, and to characterise the likely source rocks for the different hydrocarbon types.

A fundamental challenge regarding interpretation of GC-MS data for surface geochemistry is the distinction between organic compounds associated with recent organic matter (ROM), which are most commonly dominant, and compounds associated with seeped (thermogenic) hydrocarbons. However, certain guidelines can be applied

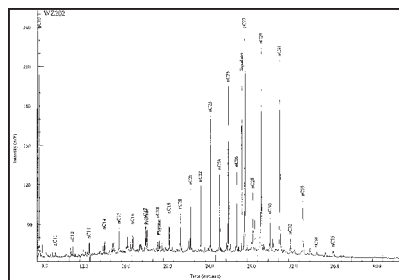


Figure 7a. Gas chromatograms of solvent extract showing hydrocarbons from only recent organic matter (ROM). (Type A)

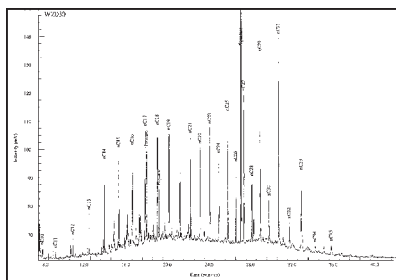


Figure 7b. Gas chromatogram of solvent extract of samples showing a mixture of thermogenic HC and ROM (Type B)

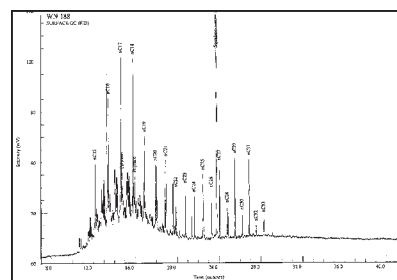


Figure 7c. Gas chromatogram of solvent extracts showing a mixture of seeped condensate and ROM. (Type C)

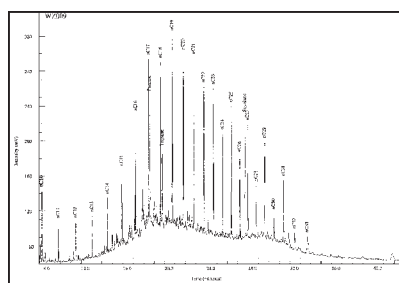


Figure 7d. Gas chromatogram of seeped HC generated by kerogen III or III/II. (Type D)

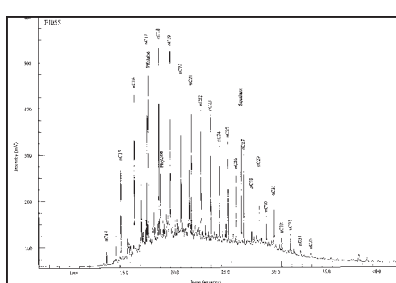


Figure 7e. Gas chromatogram of seeped HC generated by kerogen II. (Type E)

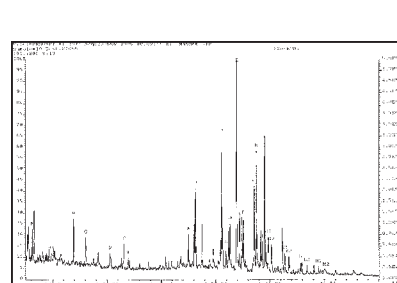


Figure 8a. Fragmentogram M/Z 191 of seeped HC, Type E.

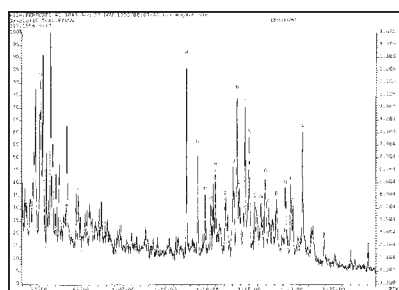


Figure 8b. Fragmentogram M/Z 217 of seeped HC, Type E.

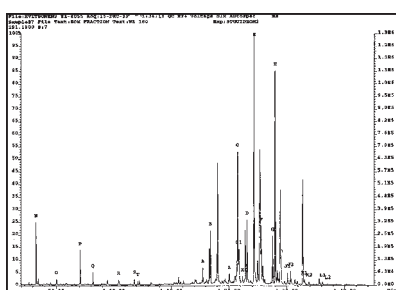


Figure 8c. Fragmentogram M/Z 191 of seeped HC, Type D.

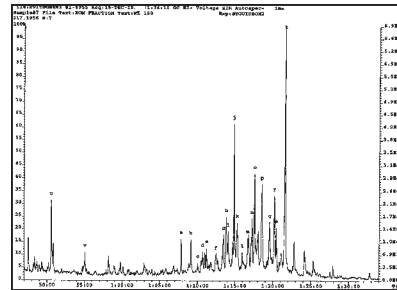


Figure 8d. Fragmentogram M/Z 217 of seeped HC, Type D.

to distinguish between these two suites of compounds. The ROM compounds always have a low maturity signature, although certain compounds can be the same as found in seeped material, e.g. hopenes and bb-hopenes. Direct examination of the fragmentograms is often made difficult because of this, and it is then useful to employ selected ratios that are considered to be reliable discriminators of thermogenic hydrocarbons, as an aid in assessing the presence and contribution from thermogenic hydrocarbons in a sample. For reference, biomarkers associated with oils and mature source rocks are discussed in a number of articles and publications, amongst others are Tissot and Welte (1984), Philp (1985), Waples and Machihara (1991) and references therein.

Biomarker data from the saturated hydrocarbon fraction are usually good source rock type indicators. Because biomarkers are derived from biological precursor molecules in specific organism types, and because the latter exist under certain environmental conditions, it is logical to attempt to use biomarkers as indicators of these conditions. Steranes are in general indicators of photosynthetic biota, both terrestrial and aquatic, while triterpanes are indicators of depositional and diagenetic conditions (Waples & Machihara, 1991). The sterane distribution in the extract may therefore provide valuable palaeo-environmental information. A preponderance of C_{29} steranes for example would indicate a marked contribution of terrestrial organic matter, while a C_{27} dominance would indicate a dominance of marine phytoplankton (Huang & Meinschein, 1979).

For the samples from this study which are classed as Type E (marine kerogen oil-associated), the m/z 191 trace shows the pentacyclic triterpanes to dominate over the tricyclic terpanes, with only minor variations between the individual samples. This pattern (Figure 8a) is typical for hydrocarbons derived from mature marine source rocks. One compound amongst the pentacyclics, that of 28,30 bisnorhopane (peak Z), is a minor but important compound. This is ubiquitous in Upper Jurassic source rocks in the North Sea, and is found in all the samples classed as Type E by the GC analyses in this study. The triterpane pattern varies only slightly for the samples, supporting a marine source. It is, however, difficult to assess the maturity of the samples from these data, since some ratios, e.g. Tm/Ts (peaks B and A) and 22R/22S (ab homohopane peaks H and G) indicate a low maturity while other ratios indicate an oil window maturity. The main reason for this discrepancy is the influence of triterpanes from the ROM. When this is taken into account, the various fragmentograms (m/z 177, 191 and 205) indicate the Type E samples to contain thermogenic hydrocarbons sourced from a marine source rock containing some terrestrial organic matter contribution and having an oil window maturity.

The m/z 217 fragmentograms for the steranes show some variation for the Type E samples, especially in the ratio of regular- to rearranged steranes. There is, however,

a good abundance of rearranged steranes in all the analysed samples, clearly inferring the hydrocarbons to have been generated in a marine source rock, probably with some terrestrial contribution, Figure 8b. The variation in the relative abundance between the regular- and rearranged steranes is probably due to the variation in ROM content of the samples, and this makes difficult any accurate evaluations regarding either source rock type and maturity. The evaluation of the fragmentograms indicates a slight dominance of C_{29} steranes in some of the Type E samples, while most of them have roughly sub-equal abundances of the C_{27} and C_{29} steranes. When evaluating oils and source rocks, the relative abundances of C_{27} : C_{28} : C_{29} steranes can normally be illustrated in a ternary plot using the 20R aaa isomers (Huang and Meinschein, 1979). However, when analysing the steranes in surface geochemical seeps, the data are almost always affected by ROM material, which will distort normal ternary plots. This is also the case for the most of the analysed samples in these projects. There is, however, an indication that the Type E samples which are not affected by ROM fall within the category of 'open marine' to 'mixed open marine – terrestrial' sourcing. The rest of the fragmentograms for the steranes are in good agreement with what is described for m/z 217 above.

The amounts of 28,30 bisnorhopane vary strongly between samples classed as Type D (i.e. oil-associated, mixed marine/terrestrial source with most variable terrestrial input) by the GC analyses. It can be observed from the fragmentograms that in general the samples having the greatest yields of tricyclic terpanes also have the highest yields of 28,30 bisnorhopane and the extended C_{32} - C_{35} hopane series. These patterns could typically be related to the samples having chromatograms almost like those of Type E as discussed above. Samples showing Type D chromatograms could typically be related to samples having less abundant tricyclic terpanes, 28,30 bisnorhopane and the extended C_{32} - C_{35} hopanes, and a more terrestrially biased sterane distribution. Examples of triterpane and sterane fragmentograms typical of Type D seeps are shown in Figures 8c-d.

Samples from GC-classified Type C, i.e. containing condensate / light oil, were found to contain virtually only ROM biomarkers. This is to be expected since the quantity of steranes and triterpanes is very low in this range of oil, and would be completely masked by the ROM components.

The Type B classified samples, i.e. containing small amounts of seeped hydrocarbons, have significant variations in their terpane fragmentograms (m/z 177, 191 and 205), the main variation being in the pentacyclic triterpanes. Some of the samples have similar distributions to those of the Type E samples, while others show a clear dominance of ROM-derived components. As mentioned above, one compound amongst the pentacyclic triterpanes is minor but important, 28,30 bisnorhopane (peak Z), being ubiquitous to the marine Upper Jurassic of the North Sea. This is recorded in all the samples of Type C, but in greatly varying abundance, from being hardly distinguishable from

the background to being the most dominant peak in the fragmentogram. Due to the obvious influence of the ROM components on the biomarker data, these samples are not discussed further.

Maturity of seeped hydrocarbons

Assessing maturity from biomarkers is essentially based on calculating ratios of biological precursor compounds to the more thermally stable isomers. The most commonly applied parameters are, amongst others, the 20S/20S+20R ratio for the steranes; and the Tm/Ts and 22S/22S+22R ratios for the hopanes. The 20S/20S+20R ratio can be calculated from either of the C₂₇, C₂₈ or C₂₉ steranes. The equilibrium value for this ratio (0.5-0.6, i.e. 50-60%) is reached around the peak oil generation stage (0.8% vitrinite reflectance equivalent for marine Type II kerogen). For the samples studied this ratio shows values ranging from about 0.05 to 0.30, which indicates a maturity ranging from immature to close to the top of the oil window (approx. 0.6% Ro for Type II kerogen). There are, however, differences in the calculated ratios that can be ascribed to the type of hydrocarbons. The samples showing the most 'marine' sourcing (Type E) generally have ratios of around 0.30, while the more 'terrestrial' (Type D) typically have ratios between 0.15 and 0.25. The measurements are, however, significantly affected where ROM material is present, this being clearly seen from the results of the Type B and C samples. The most immature ratios are shown by the Type B and C samples which show dominant contributions from ROM on the GC chromatograms. Similar observations are made for the 22S/22S+22R ratio data, where the equilibrium value (0.6) is reached around the top of the oil window. The samples containing Type B hydrocarbons according to the GC chromatograms typically have ratios >0.55, i.e. close to equilibrium; while the Types D and E hydrocarbons from GC typically have values in the range 0.45-0.55. In contrast to these ratios, the ratio of Tm/Ts begins to decrease quite late during maturation and should therefore be useful to supplement the parameters discussed above, however only at maturity levels greater than 0.75% Ro, and is not relevant for these samples. It will therefore not be possible to use these maturity estimators if there are intermixed seeped hydrocarbons and ROM components.

Assessment of the maturity of hydrocarbons based on aromatic parameters has been a useful technique for some time, where for example the use of the methyl phenanthrene index (MPI) has been found to be useful for oils from terrestrial sources (Radke *et al.*, 1982). Other aromatic maturity parameters are based on substituted naphthalenes and dibenzothiophenes (Radke *et al.*, 1984, Kvalheim *et al.*, 1987). It can be difficult to use the aromatic parameters due to the possibility of water washing (i.e. aromatic removal) in the formation, also the lighter aromatics are sensitive to work-up of the samples and can be lost. However, with the large contribution of

hydrocarbons from ROM in many of the samples, which has clearly affected the sterane and triterpane maturity parameters for most of the samples, the aromatic maturity parameters are probably the most reliable parameters in this study.

For the aromatic compounds, the fragmentograms were examined and the relative amounts of the different compounds measured and the maturity assessed, based on the calculated MPI ratios (Radke *et al.*, 1982, Radke & Welte, 1983) and the sulphur aromatic (dibenzothiophene) ratios. The relative amounts of aromatic hydrocarbons detected by GC-MS analysis appears to vary between samples, but both the methylated naphthalenes and phenanthrenes occur in fairly significant amounts in most samples. The dibenzothiophenes are also detected in most samples, though in widely varying amounts. The level of aromatic hydrocarbons can also be used as an indication of seepage. Although seeped hydrocarbons can be completely masked in the ordinary GC chromatograms, they can be inferred in the GC-MS fragmentograms by the presence of aromatics, especially the dibenzothiophenes, which are indicative of hydrocarbons derived from mature kerogen.

The assessed maturities, based on the aromatic parameters, vary in the different hydrocarbon types discussed. The more marine type (Type E) hydrocarbons are suggested to have a maturity corresponding approximately to 0.7% Ro, while the more terrestrial type (Type D) hydrocarbons are probably less mature, being suggested to be approximately 0.5-0.6% Ro. The condensate / light oil (Type C) hydrocarbons are estimated to have a maturity of 0.9-1.0% Ro.

Sourcing of hydrocarbons

The gaseous hydrocarbons appear to have quite complex compositions. The headspace and occluded gases generally show a clear biogenic composition, although this cannot be supported by carbon isotope analysis, due to insufficient yields. This is most likely due to biological activity within the sediment. The adsorbed gases typically show a thermogenic signature with compositions ranging from fairly dry to fairly wet. There is quite a good correlation between the samples with rich yields and wet compositions. The carbon isotope data suggests the adsorbed gas in the bulk of samples to have maturities suggesting association with oil.

INTEGRATION OF THE SURFACE GEOCHEMICAL DATA WITH THE GEOLOGY

The seismic data used for the selection of the sample sites is presently not freely available to integrate with the geochemical data since the selection of the sample sites was undertaken by the participating oil companies. The tentative integration is therefore based on published

interpreted geological sections, e.g. Jowitt *et al.* (1999). One of the interpreted sections here is along a seismic line oriented southeast – northwest covering the Corona Ridge, Flett Ridge and Rona Ridge, Figure 9a. A number of samples were collected over the Corona Ridge. Most of these samples were found to contain condensate/light oil (Type C) and oil of marine origin (Type E). Another interpreted section in Jowitt *et al.* (1999), also along a southeast – northwest seismic line, covers the North Judd Basin, Westray Ridge and Rona Ridge, Figure 9b. A number of samples collected over the North Judd Basin were found to contain hydrocarbons of Type D, i.e. hydrocarbons with more terrestrial input than that found for the Corona Ridge samples. Jowitt *et al.* (1999) suggested the source kitchen for the Foinaven and Schiehallion fields to be in the northeastern part of UK quadrant 204. Based on the limited geological information available and the integration between this and the surface geochemical data, we agree with such sourcing regarding the oil, however there seems to be another possible source kitchen for the gas further west.

COMPARISON WITH DRILLING RESULTS

To date, only four wells have been drilled in the Faeroes sector of the shelf, with variable results (see also Figure 6).

Well 6005/15-1 was drilled in the summer of 2001 and reached TD of 4 000m in Palaeocene strata. The well was dry, however with traces of hydrocarbons. None of the surface geochemical samples collected in the immediate vicinity of this well were found to contain any seeped hydrocarbons, although the well lies closer to the western edge of the main wet thermogenic gas area of the samples, as shown in Figure 6. We will therefore conclude that there is fairly good agreement between the surface geochemical data and the drilling results.

Well 6004/12-1 is located to the east of the first well, and close to the Faeroes/UK boundary. The well was completed during the autumn of 2001 and reached a TD of 4 354 m in Palaeocene strata. Oil shows were detected in the well which was plugged and abandoned. A number of samples in the vicinity of this well were found to contain small amounts of seeped hydrocarbons, this being within the wet thermogenic gas area. Again, since we do not have available any seismic over the area, it is not possible to determine if these seeps originate from the drilled structure. It is, however, an indication that there is an active petroleum system in the area.

Well 6004/16-1 is located close to the Faeroes/UK boundary. The well was completed November 2001 and reached a TD of 4246 m in Palaeocene strata. The well was reported to have an oil column of 170 m. The well is located in an area where a number of samples were found to contain relatively large quantities of seeped oil. Again, as with the wells above, there is no seismic available so it

is impossible to determine the pathway for the seeped oil found in a number of surface geochemical samples in the vicinity of the well. It is, however, a strong indication that the oil found in these surface geochemical samples originated from the structure drilled. The oil-bearing structure, now named the Marjan field, has since been confirmed by the drilling of well 204/16-1 in the British sector.

Well 6004/17-1 is located to the north east of wells 6004/16-1 and (UKCS) 204/16-1, in an area where wet thermogenic gas was recorded for a number of the collected surface geochemical samples. There is only sparse information regarding the drilling results, but it appears that the well contained gas and was plugged and abandoned. It is therefore likely that the thermogenic gas found in the samples close to this well originate from the same source as that of the gas in the well.

A much greater number of wells have been drilled on the UK sector of the shelf. There is very little information available regarding these wells, but all wells drilled within the area of the UK shelf that were included in the area covered by the surface geochemical studies have all been plugged and abandoned apart from well 204/16-1 mentioned above. The following UK wells are located outside but close to the eastern boundary of the sampled area:

Well 204/14-2, close to the Suilven field. This well was drilled in 1998 close to the eastern edge of the sampled area. None of the surface geochemical samples in the vicinity of this well were found to contain seeped hydrocarbons.

Wells 204/15-1 and 204/15-2, also close to and north of the Suilven field. These two wells were drilled in 1999 and 2001 respectively. None of the samples collected west of these wells were found to contain any seeped hydrocarbons.

Wells 204/17-1 and 204/18-1 were plugged and abandoned. These are located close to where surface geochemical samples were found to contain seeped liquid hydrocarbons. This would indicate that there are structures in the vicinity that may be leaking hydrocarbons. With the sparse information in the public domain it is not known if these wells were completely dry or if they contained shows that might have been the source for the seeped hydrocarbons.

Well 213/23-1 was completed in 1999 as dry. The well is located further east than the collection of the samples for surface geochemistry. Some samples were collected over block 213/22, but none of these samples contained seeped hydrocarbons.

Well 214/4-1 was completed in 1999 as dry, with gas. The well is located where no samples were collected for surface geochemistry. A few samples were collected to the north of the well, one of these showing a minor amount of seeped hydrocarbons while the remaining three samples in the area did not contain any seeped hydrocarbons.

Well 214/17-1 was completed as dry in 1998. There

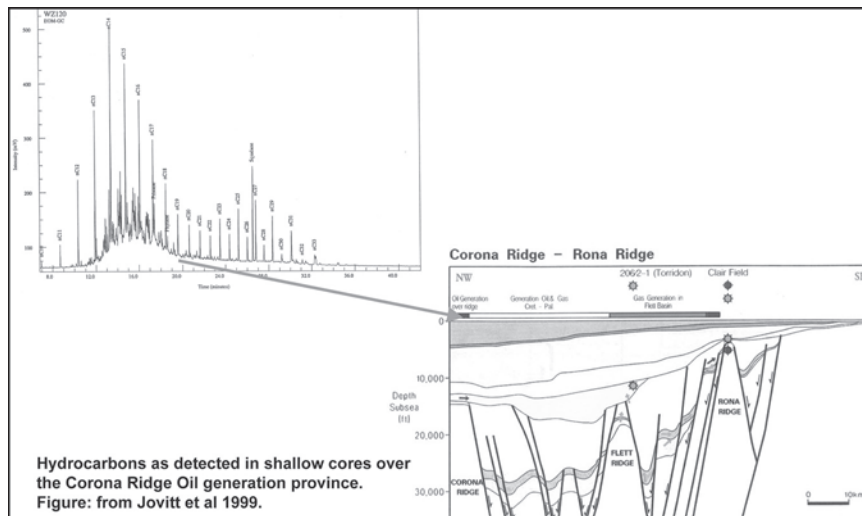


Figure 9a. Section through Clair.

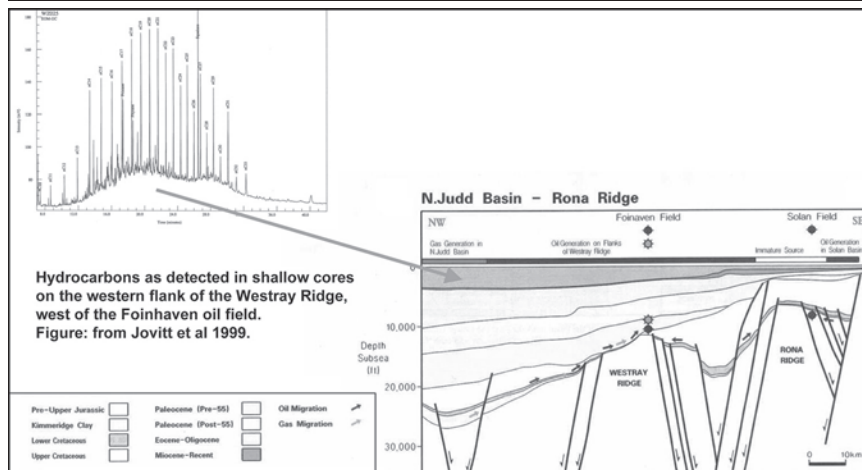


Figure 9b. Section through Foinaven Field.

are a number of surface geochemical samples located in the vicinity of the well. None of these contain any seeped hydrocarbons.

CONCLUSIONS

The three surface geochemical studies detected seeped hydrocarbons. Most of the samples were found to contain biogenic gases in the headspace and occluded gas fractions while a number of samples contained petrogenic gases in the adsorbed fraction. None of the samples contained any dry gas generated from terrestrial material. They were all found to have isotope compositions indicating oil-associated gases.

Analysis of the liquid hydrocarbons in the samples indicated the presence of seeped thermogenic hydrocarbons in a minority of samples. There were basically four types of seeped thermogenic hydrocarbons.

1. A large number of samples contained minor amounts of seeped hydrocarbons together with significant amount of hydrocarbons from recent organic matter (ROM). This kind of signature was found spread over large areas, indicating active micro seepage in the area.
2. Some of the samples were found to contain light hydrocarbons of condensate/very light oil type. It is not possible to determine the type of source for these

hydrocarbons, but most likely it is an Upper Jurassic Kimmeridge Clay Formation type source of high maturity. The samples with this signature are spread amongst the samples with seeped hydrocarbons of a lower maturity. This could indicate that there are source rock formations of variable maturity in the area.

3. Some samples in the north and east of the surveyed area were found to contain seeped hydrocarbons originating from a source rock with a significant terrestrial input, tentatively concluded to be a Middle Jurassic type source rock. However, we cannot exclude the possibility for involvement by Cretaceous source rocks, especially since this oil type has a lower maturity than the marine type oil.
4. Some samples were found to contain seeped hydrocarbons originating from a marine source rock of Kimmeridge Clay Formation type. Most of the samples with this signature are found in the southeastern corner of the sampling area. Some of these samples are probably associated with the system for the Foinaven, Schiehallion and Sulven fields.

When comparing the results from the surface geochemical studies with the drilling results there is a good correlation. Admittedly, there is no seismic information available to tie in the seeped hydrocarbons with potential

conduits. However, wells which were dry did not have any geochemical samples with seeped liquid hydrocarbons in the vicinity, while wells that were reported to have struck oil did have surface geochemical samples with seeped hydrocarbons close by.

The three surveys have also located a number of surface geochemical samples with seeped hydrocarbons located distant from any of the present wells. Only future drilling will show if these samples contain seeped oil from commercial oil deposits.

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