Technical Report TR_002

Technical report produced for

Strategic Environmental Assessment – SEA2

POCKMARKS IN THE UK SECTOR OF THE NORTH SEA

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POCKMARKS IN THE UK SECTOR OF THE NORTH SEA

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Appendices

1. INTRODUCTION

The purpose of this report is to review current understanding of pockmarks in the UK North Sea, with specific reference to the methane-derived authigenic carbonate (MDAC). The report describes pockmarks, their formation and character, and their occurrence in the North Sea (with specific reference to the SEA2 areas). Particular attention is paid to present day pockmark activity and gas seepage.

1.1 Methane-derived Authigenic Carbonate (MDAC)

Methane-derived Authigenic Carbonate (MDAC) was first identified in the North Sea in 1983 (Hovland and Judd, 1988). It occurs as rock-like concretions formed when a carbonate precipitate cements the normal seabed sediment (see Figure 1). The carbonate is in the form of high-magnesium calcite, aragonite or dolomite: $CaCO_3$ to $CaMg(CO_3)_2$. Studies of the carbon isotopes ($\delta^{13}C$ -25 to -65‰) have demonstrated that the source of the carbon is methane rather than normal sea water or sediment porewater. The precipitation is attributed to the oxidation of methane:

$$CH_4 + SO_4 \rightarrow HCO_3 + HS + H_2O$$

This process is mediated by a microbial consortium of archaea (engaged in reverse methanogenesis) and sulphate reducing bacteria (Boetius *et al*, 2000).

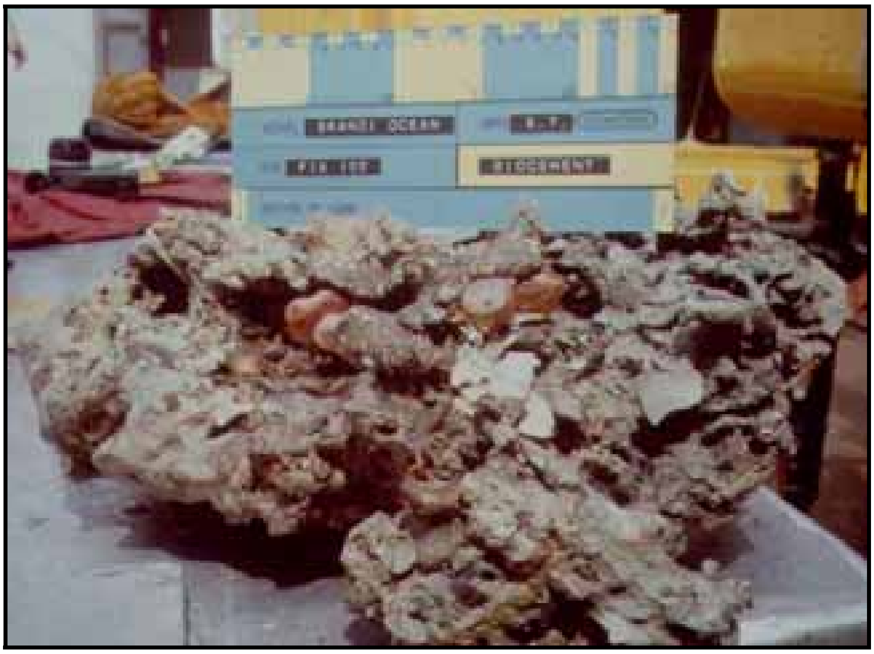


Figure 1: Methane-derived authigenic carbonate recovered from a pockmark in the Norwegian sector of the North Sea (photograph courtesy of Statoil)

MDAC occurs as crusts and slabs at the seabed (often covered by a thin layer of sediment), or as exposed lumps sitting on the seabed (see Figure 2). In the Kattegat erosion has exposed columnar MDAC structures (see Figure 3).

Figure 2: ***Methane-derived authigenic carbonate being taken from the seabed (photograph courtesy of Statoil).***

Figure 3: ***Panorama of the submarine landscape of 'the bubbling reefs', northern Kattegat. [From Jørgensen, 1994]***

The occurrence of MDAC is evidence of methane seepage. Unless there are other indicators of active seepage (e.g. bacterial mats or gas bubbles), the MDAC does not necessarily imply that the seepage is on going. However, MDAC, particularly if it is present in large quantities, does indicate that seepage has occurred over a prolonged time period. Although the rate of MDAC formation is unknown, examples of leaves and anthropogenic material (industrial slag) partially encrusted in MDAC indicate that formation occurs on a human, rather than a geological, time scale (Andrews, 1988; Judd *et al*., submitted).

The hard ground provided by these carbonates, the microbial utilisation of the methane, and, subsequently, the hydrogen sulphide may have impacts on the benthic ecosystem. [The hydrogen sulphide is utilised by the sulphur oxidising bacterium *Beggiatoa* which occurs as bacterial mats on the seabed.]

1.2 Pockmarks and gas seepage

Pockmarks are shallow seabed depressions, typically several tens of metres across and a few metres deep. Generally, they are formed in soft, fine-grained seabed sediments by the escape of fluids (gas or water) into the water column. An example is illustrated in Figure 4.

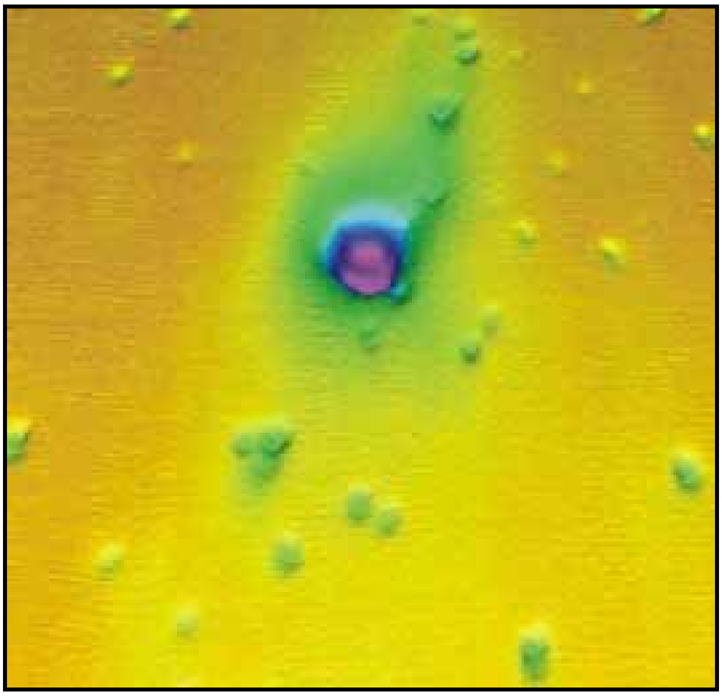


Figure 4: ***Multibeam Echo Sounder image of pockmarks in UK Block 15/25***

Pockmarks were first identified in the UK North Sea in 1970 during a rig-site survey in preparation for exploration in the Forties field. They are now known to occur extensively, particularly in areas characterised by post-glacial sediments of the Witch Ground Formation (in the Witch Ground Basin) and their equivalent, the Flags Formation, which occurs in enclosed basins in the northern North Sea.

North Sea pockmarks are formed by gas escaping from the seabed, hence the association between pockmarks and MDAC. However, as pockmarks are only formed in certain sediment types, gas seepage (and MDAC) also occurs in pockmark-free areas.

1.3 The Influence of Gas Seeps on Benthic Ecology

Reports of visual surveys of pockmarks have noted that they are characterised by an unusual and prolific fauna. For example, describing pockmarks in Norwegian Blocks 24/9 and 34/10, Hovland and Thomsen (1989) concluded that: "*The fauna inside the pockmarks is markedly richer in number and diversity than on and over the seabed outside the pockmarks*". These authors suggested that there is a "*causal relationship between gas-associated seabed features and local communities in the North Sea*", and that carbon from the methane would enter the food chain.

In contrast Dando *et al.* (1991) concluded that the pockmark ecosystem is dominated by photosynthesis rather than chemosynthesis. "*…the methane carbon is not contributing to the carbon of the surrounding infauna on a significant scale.*" Dando and Hovland (1992) concluded that changes in the species composition around methane seeps were caused by the high concentration of sulphides in the sediments and the presence of 'hard ground' (i.e. the methane-derived authigenic carbonate).

The ecology of pockmarks is the subject of a separate report. For the purposes of this report it is assumed that pockmarks are of potential significance to benthic ecology, possibly because they provide a favourable, sheltered, habitat. However, pockmarks which have active gas seeps may also be significant because:

- Of the utilisation of methane and its by-product, H_2S, by chemosynthesisers;
- Chemosynthetic organisms are a potential food-source for other organisms (e.g. filter feeders);
- MDAC provides a hard substrate suitable for colonisation by certain benthic organisms.

Figure 5 summarises the utilisation of methane at the seabed.

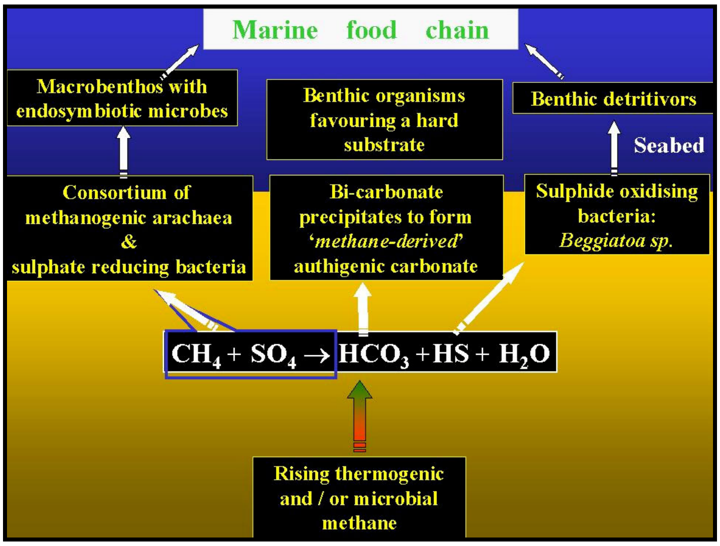


Figure 5: The utilisation of methane at the seabed

1.4 Other interests

Pockmarks, seeps and MDAC are also of interest to the offshore industries for the following reasons:

- In petroleum exploration seeps of thermogenic gases provide indications of the presence and character of petroleum at depth;
- Shallow gas accumulations are hazards to offshore petroleum drilling;
- Pockmarks are obstacles to offshore structures, seabed pipelines and cables;
- MDAC impedes the ploughing of trenches for pipelines and cables;
- Gas seeps provide methane (an important Greenhouse gas) to the hydrosphere and the atmosphere.

2. POCKMARK FORMATION

Pockmarks are formed by the expulsion of fluids from the seabed. The escaping fluid may be liquid (e.g. groundwater, as in Eckernförde Bucht, Germany), but in the majority of cases it is gas. The gas may originate from either the microbial decomposition of organic matter within the near-seabed sediments ('microbial', 'bacterial' or 'biogenic' gas), or from the thermocatalytic destruction of kerogens deep within the sediments ('thermogenic' gas). Typically the gas is primarily composed of methane (CH_4) which is commonly present in concentrations of >95%. The higher hydrocarbon gases (ethane, propane, butane and pentane) may also be present if the source is thermogenic.

Gas seepage observed in pockmarks is generally no more than a gentle bubbling which is insufficient to erode the seabed sediments. However, it is thought that there is a cycle of activity (illustrated in Figure 6) which accounts for pockmark formation:

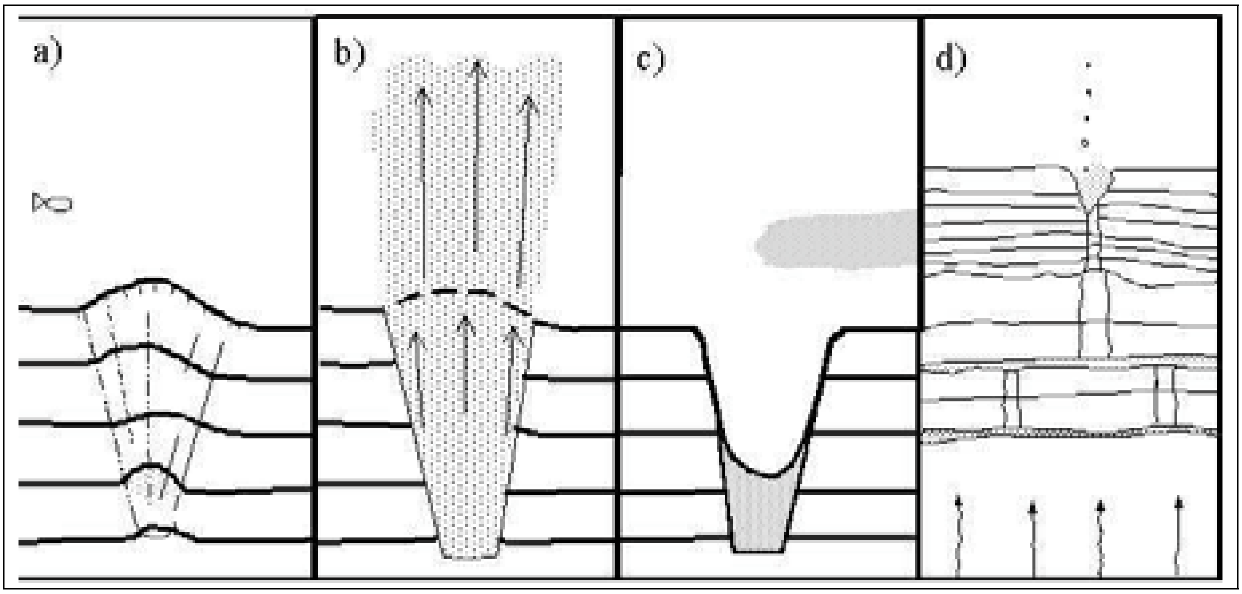


Figure 6: Conceptual model of the formation of pockmarks (after Hovland and Judd, 1988)

Stage 1: accumulation of gas beneath the seabed. Where the gas accumulates close to the seabed, the excess pore fluid pressure may inflate the sediments to form a seabed dome (Figure 6a).

Stage 2: release of the gas in a single event which fluidises the sediment and lifts it into the water column (Figure 6b). Fine-grained sediments are suspended in the water, and drift away in the current (Figure 6c). Coarse sediment falls back to the seabed; pockmark floors are often characterised by a lag deposit of relatively coarse sediment. Pockmark formation may be triggered by events such as earthquakes, or by the disturbance of the seabed, for example when ploughed by an iceberg (in pockmark areas with iceberg scours, the pockmarks are commonly located preferentially within the scours).

Stage 3: if gas continues to migrate from the underlying sediments, gas seepage may continue, utilising the pathway established by the initial gas escape. However, where the gas rises through a sequence of sediments which includes inter-bedded fine and coarse layers, migration from accumulation to accumulation may be periodic rather than continuous (Figure 6d). In such cases cyclic pockmark activity will occur. Relatively vigorous gas escape may occur at the beginning of each cycle; this will be followed by a gradual decrease in the flow rate as accumulations are emptied and gas overpressures dissipate.

Because the generation of gas and its migration towards the seabed occur over geological time periods, gas escape and pockmark formation are likely to be either continuous or intermittent over extended time periods. Thus it is not uncommon to find 'buried' or 'fossil' pockmarks in layered sediments. Pockmarks will not be preserved where the seabed is being eroded. Over much of the North Sea there has been neither erosion nor significant deposition since the climatic conditions stabilised after the last ice age. Consequently, seabed pockmarks may have formed at any time during that time period (approximately 8,000 years).

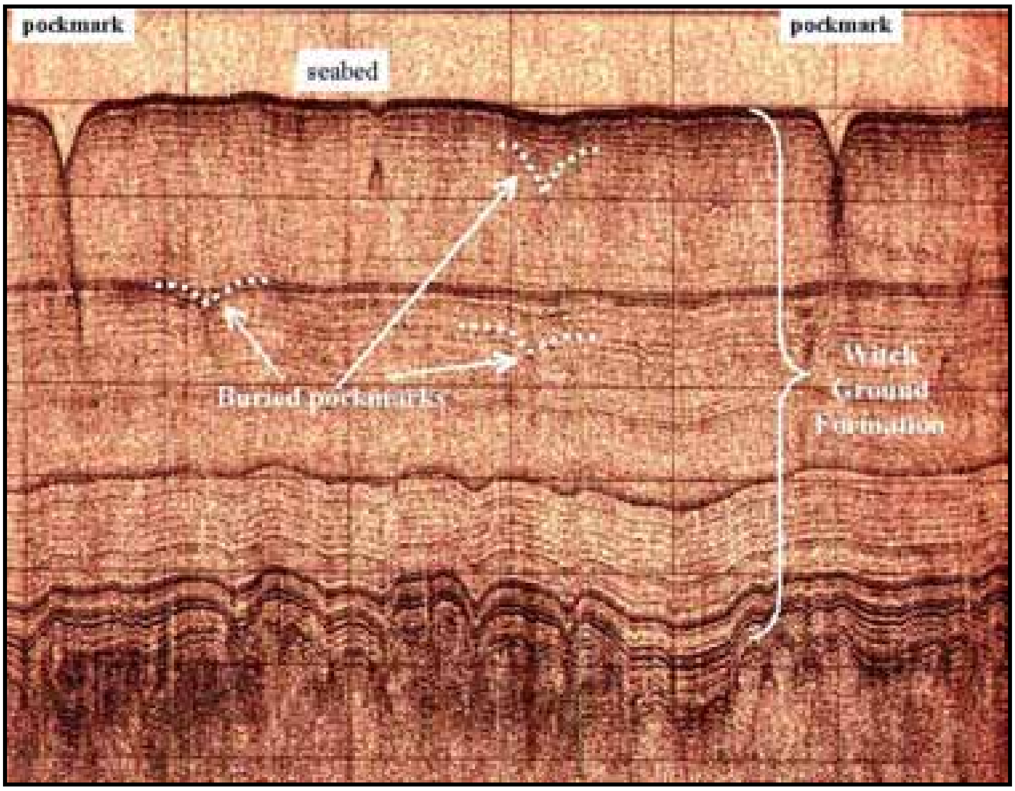


Figure 7: ***Seabed pockmarks and buried pockmarks (British Geological Survey deep-towed boomer data)***

Pockmarks are only formed where the seabed sediments are suitable. Where the sediments are not suitable there will be no morphological feature even if fluid escape does occur. So, pockmarks indicate that gas (or water) escape has occurred, but the absence of pockmarks does not necessarily indicate that gas (or water) escape has not occurred. However, where the sediments are suitable, the absence of pockmarks indicates the absence of fluid escape. Where sediments are not suitable for pockmark formation there may be no easily identifiable evidence of fluid escape.

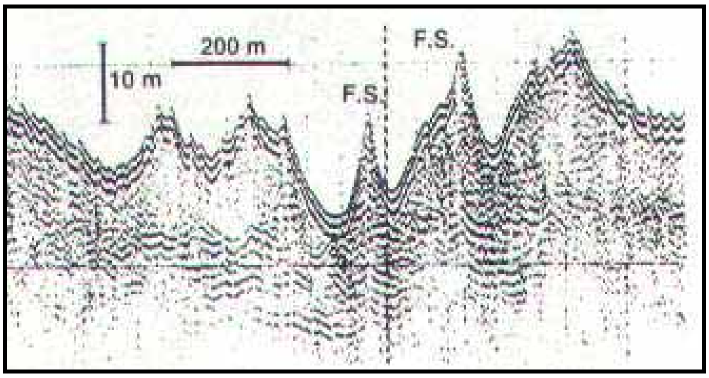
In contradiction of the last statement, Hovland (1993) described 'freak sandwaves' associated with shallow gas and suspected gas seeps in the southern North Sea, off the Belgian and Dutch coasts. He suggested that these features, which are considerably larger than the other sandwaves in the area (see Figure 8a and b), are established when mobile sand grains are not allowed to settle because of the escaping gas. A similar feature is shown in Figure 8c. This is located in UK waters to the south of the Southern North Sea SEA2 area.

The validity of this explanation for these features has yet to be tested.

In summary:

- Pockmarks are formed by fluid escape, therefore they occur only where there is a supply of fluid;
- Pockmarks are formed only where the seabed sediment is suitable (e.g. soft, silty clays). Where the sediment is not suitable there may be no morphological feature as evidence of fluid escape.
- Where the seabed is being rapidly eroded, any evidence of pockmark activity may be removed.

8a



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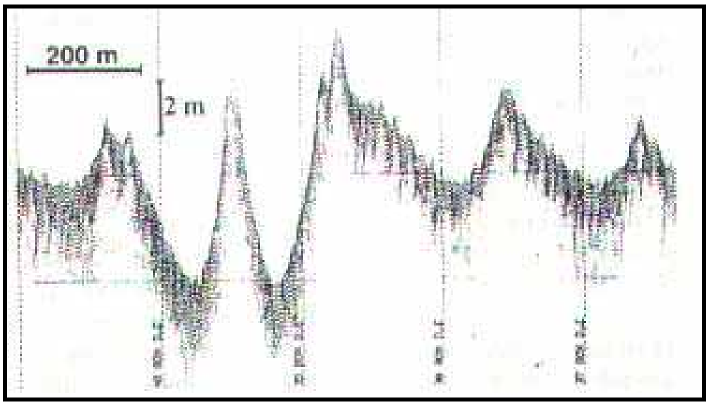

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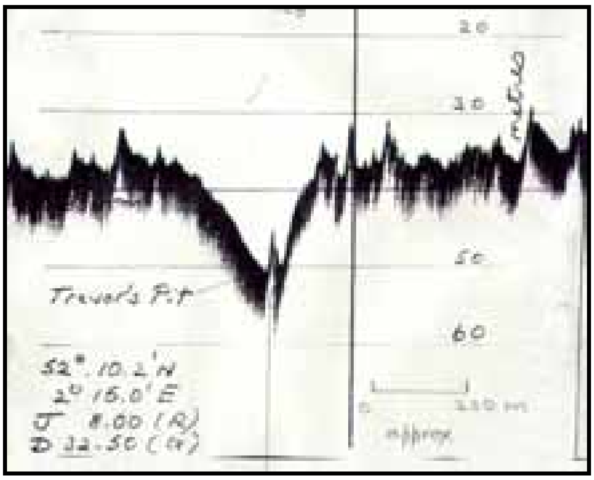


Figure 8

Freak sandwaves thought to have formed as a result of gas seepage.

a) and b): from the southern North Sea, (Belgian or Dutch sector (after Hovland, 1993);

c): Trevor's Pit, U.K sector of the North Sea (data supplied by R. Harden-Jones).

3. FACTORS WHICH DETERMINE POCKMARK DISTRIBUTION

In order to consider the distribution of pockmarks, it is necessary to investigate the availability of migrating fluids and the distribution of seabed sediment types.

3.1 Supply of seeping fluids

Whilst seeping fluids may include groundwater, the distribution of groundwater seeps is governed primarily by the availability of sufficient hydraulic head to drive their emission. On the continental shelf, groundwater emissions are restricted to coastal areas.

3.1.1 The generation of gas

Various gases may occur in marine sediments, for example CO_2 is a product of volcanic, hydrothermal and geothermal activity. However, the most common geological gas, and the gas most likely to be present in the geological environments found in the North Sea is methane (CH_4). Other gases which occur in association with methane are the higher petroleum gases [ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and pentane (C_5H_{12})], oxygen (O_2), carbon dioxide (CO_2), hydrogen (H_2) and hydrogen sulphide (H_2S). Because of the dominance of methane, it is the only gas whose origin and occurrence is considered here.

In the sub-seabed environment, methane is generated by two processes: the microbial decomposition of organic matter (microbial methane), and the thermocatalytic destruction of kerogens (thermogenic methane). Methane of these two origins may be distinguished by their carbon isotope ratios; the ratio between the two stable isotopes, ^{12}C and ^{13}C. By convention these are expressed relative to an international standard, the PeeDee Belemnite. Typical ratios are:

	$\delta^{13}C$
Microbial methane	-60 to -80‰
Thermogenic methane	-20 to -60‰

3.1.1.1 Microbial methane (also known as 'bacterial' and as 'biogenic' methane)

Microbial methane is generated by the decomposition of organic material by methanogenic archaea in organic-rich fine-grained sediments. This process may be summarised as:

$$2CH_2O \rightarrow CH_4 + CO_2$$

The methanogens are obligate anaerobes, consequently methane generation only occurs beneath the oxidation / reduction boundary. This is normally found at least a few centimetres beneath the seabed. The rate of methane generation decreases as the sediments are buried, however the maximum depth of methanogenesis is not known.

The produced methane may escape upwards through the sediment, in which case the majority will be oxidised by methanotrophs, but a small portion may escape into the water. Alternatively, the methane may be trapped in, and become buried with the original sediments. Consequently, source sediments for microbial methane include not only modern sediments (typically found in bays, estuaries etc.), but also ancient sediments, for example those which contain peats and lignites.

3.1.1.2 Thermogenic methane

Organic matter which survives burial through the depths at which methanogenic microbes are active is largely converted to amorphous organic material called kerogen under the influence of increasing temperature and pressure. In turn the kerogens are themselves 'cracked' to form crude oil and natural gas, of which methane is one component. The rank of coal also increases with increasing depth of burial. This is achieved by driving off volatiles, the principal volatile being methane.

Having the simplest and smallest molecules, methane is the most mobile of these petroleum compounds, hence it is the most likely to migrate to the seabed. The higher hydrocarbon gases and crude oil may accompany it. However, in the North Sea, where the source rocks are buried beneath a thick sequence of dominantly argillaceous (fine-grained) sediments, the crude oils are very unlikely to be able to migrate to the shallower sediments or the seabed.

3.1.2 Distribution of methane sources

The principal sources of gas in the SEA2 areas are as follows:

3.1.2.1 Coal Measures (Upper Carboniferous)

The Upper Carboniferous (Westphalian) Coal Measures are the principal source rock for the gas fields of the southern North Sea. They underlie virtually all of the Southern Area covered by SEA2, but also parts of the Central and Northern SEA2 areas. Coal seams also occur within the Middle (Namurian) and Lower (Dinantian) Carboniferous. These coals are thinner, and less frequent than those in the Westphalian, nevertheless they underlie substantial areas of the North Sea including the whole of the Southern SEA2 area, and parts of the Central and Northern SEA2 areas, as is shown in Figure 9.

3.1.2.2 Kimmeridge Clay (Upper Jurassic)

The Kimmeridge Clay is the principal source rock for the wet gas, condensate and oil fields of the central and northern North Sea. Their thickness and the depth of burial (maturity) largely control their productivity. In turn, these are determined by the geological structure of the North Sea; the most productive areas occur within the Central, Witch Ground and Viking Graben (see Figure 10).

3.1.2.3 Tertiary lignite

During the Tertiary the North Sea coastline lay some way to the east of the present coastline. Deltaic lignite (brown coal) occurs in some sediments deposited close to this coastline. Specifically, these are found south of about 59°15'N in the Beauly Member of the Moray Group (Upper Palaeocene to Lower Eocene), sands of late Oligocene and Miocene age (Hordaland Group), and sands and muds of the Pliocene (Nordland Group). The distribution of lignite is shown in Figure 11.

No Tertiary lignite is found in the Southern North Sea SEA2 area.

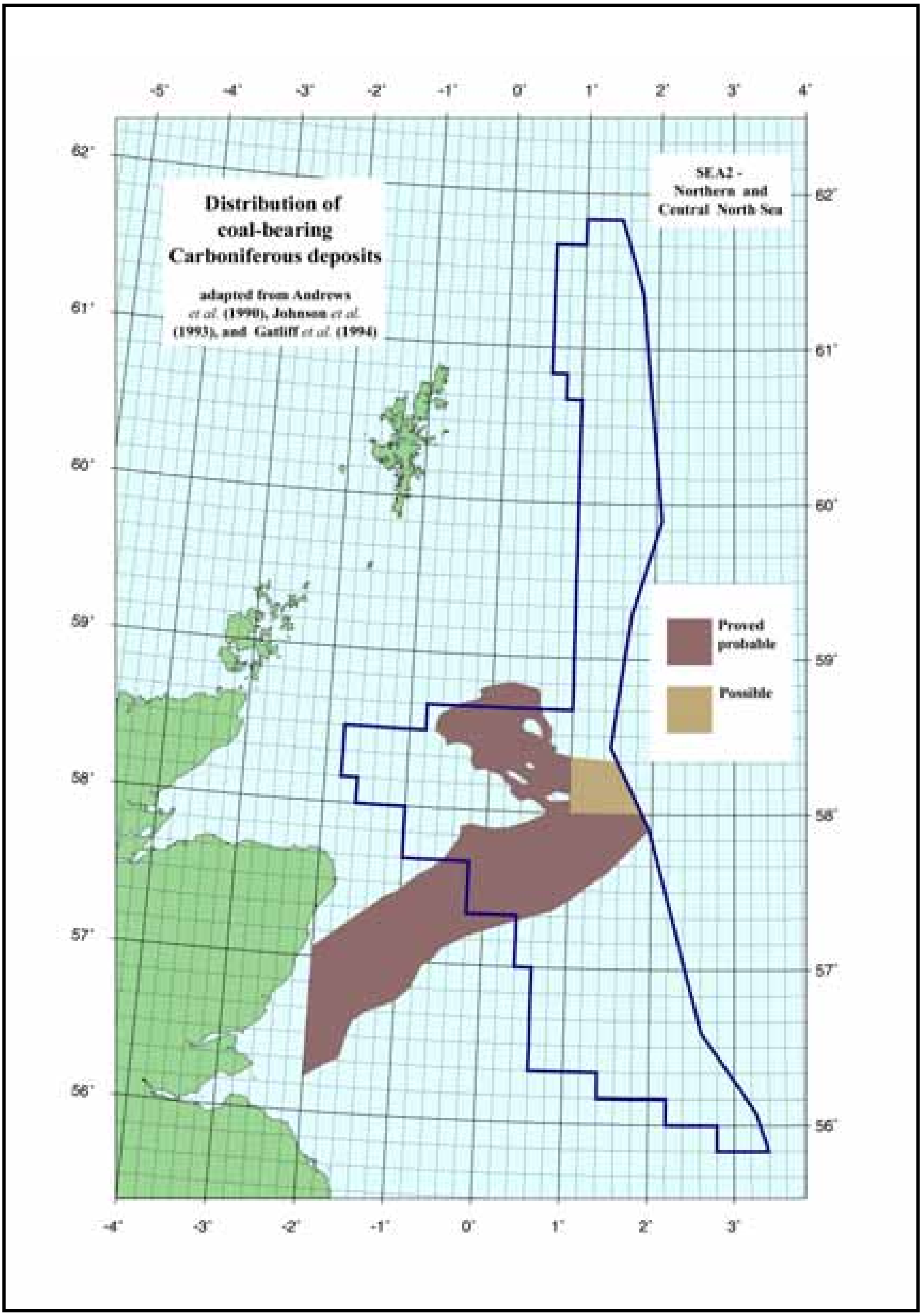


Figure 9: ***The extent of coal-bearing Carboniferous strata in the northern and central North Sea***

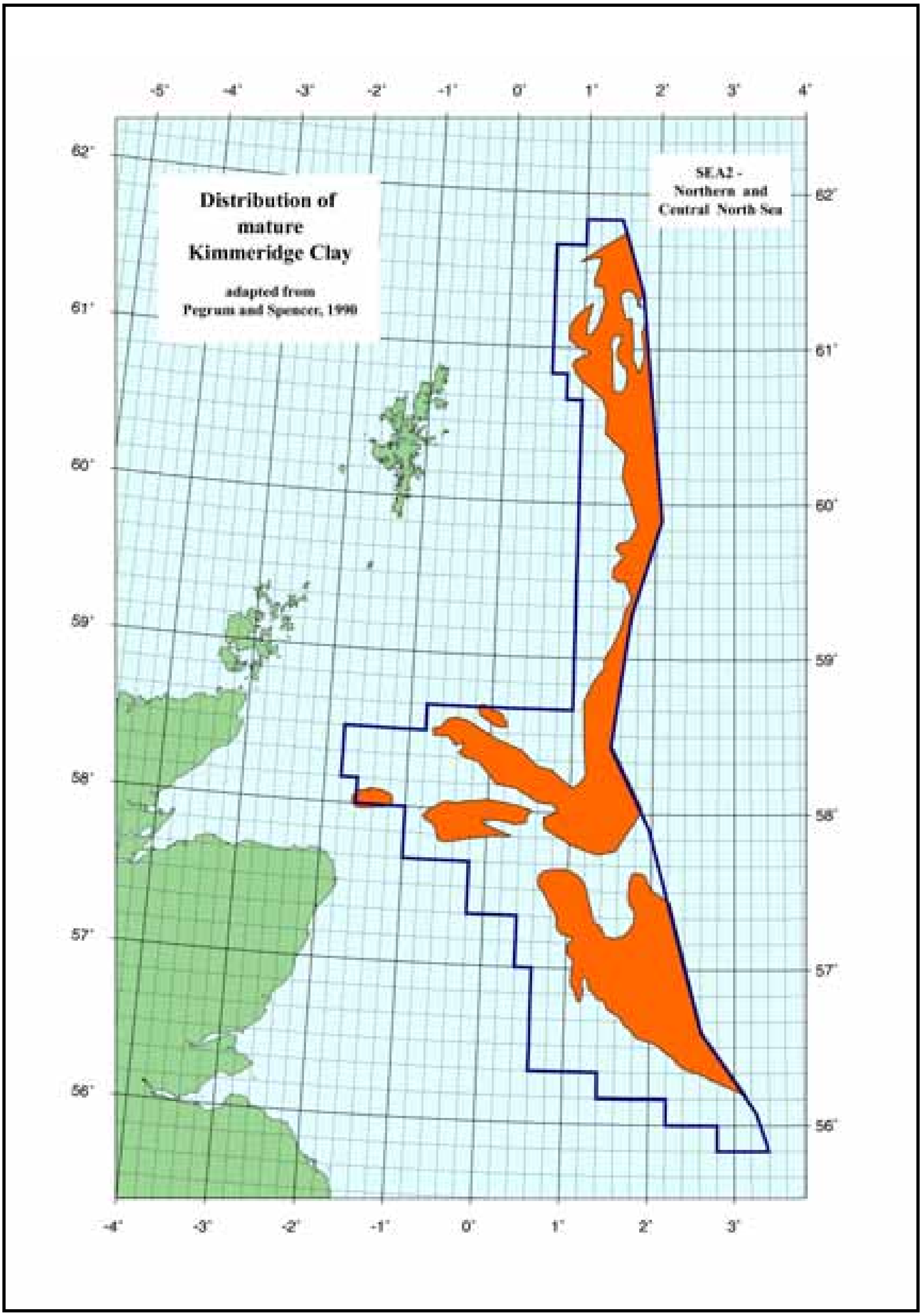


Figure 10: ***The extent of mature Kimmeridge Clay in the northern and central North Sea***

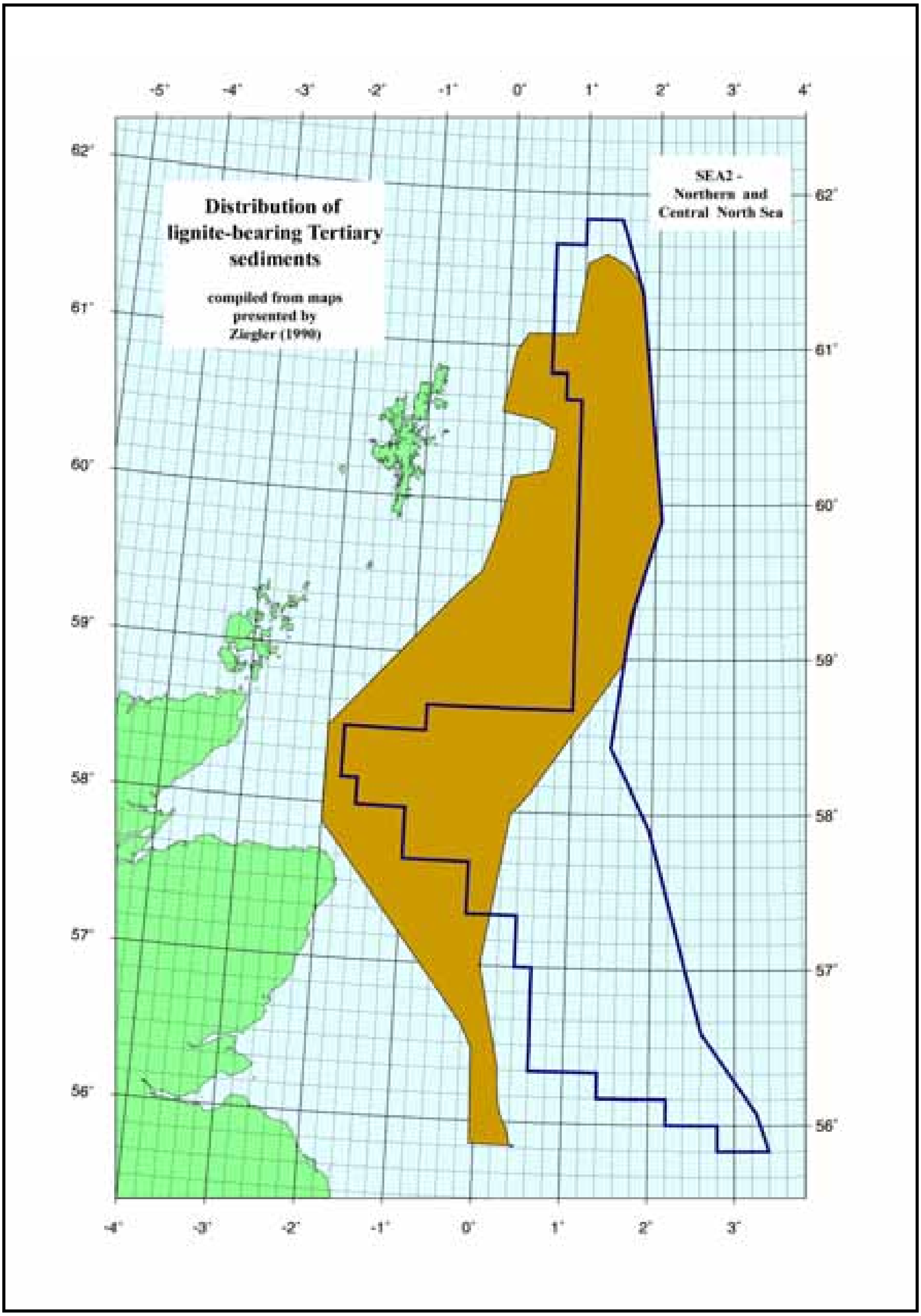


Figure 11: The extent of Tertiary lignite in the northern and central North Sea

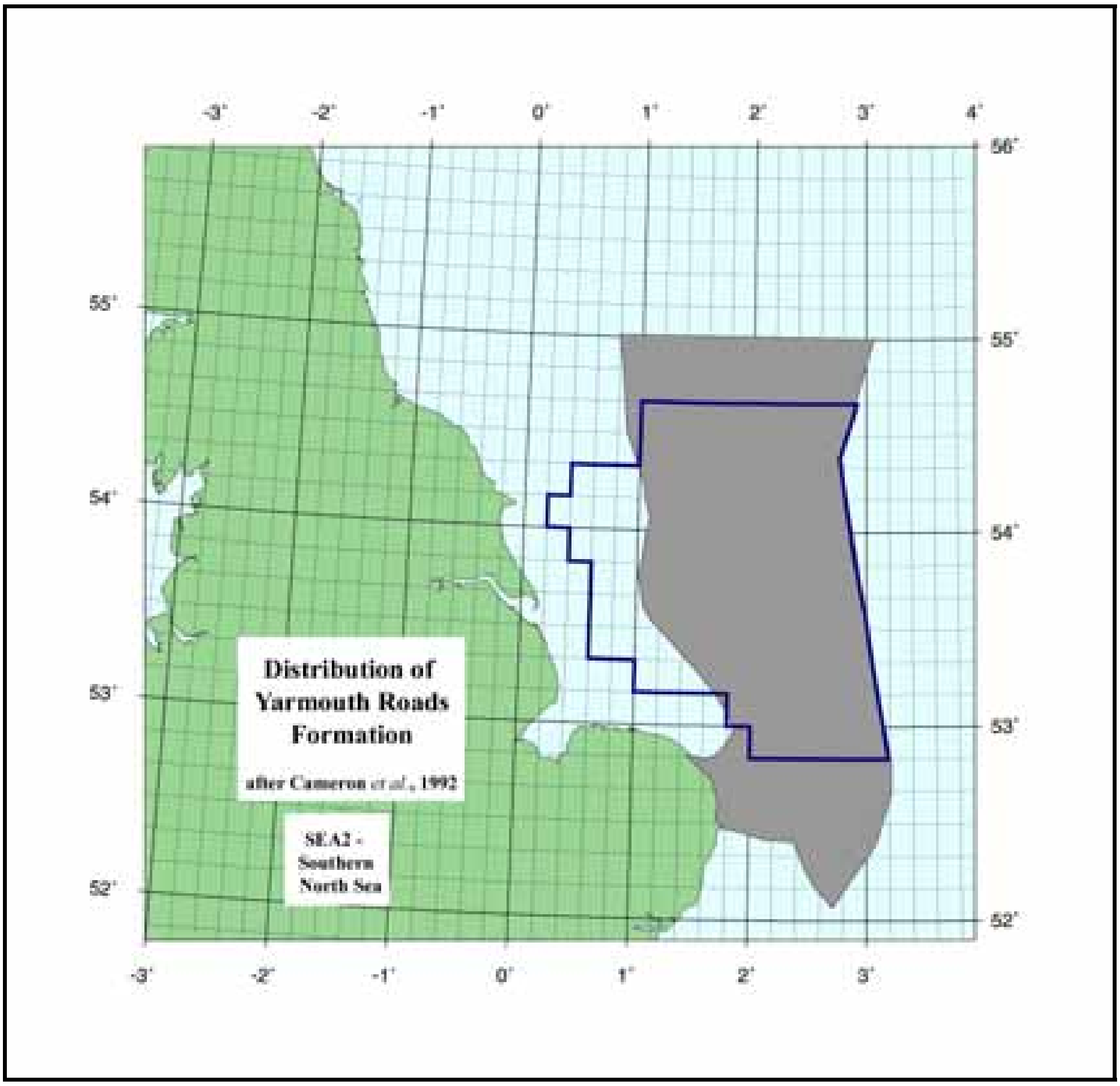


Figure 12: ***Extent of the Yarmouth Roads Formation sediments of the Ur-Frisia Delta***

3.1.2.4 Pleistocene deltaic and peaty deposits

During the Lower and Middle Pleistocene a large delta complex was formed in the southern North Sea, south of approximately at 55°N. This delta plain, named Ur-Frisia, was characterised by wetlands. The resultant sediments, the Yarmouth Roads Formation, contain abundant plant debris, peat and wood clasts. It is probable that gas has been generated by the decomposition of this organic matter. The extent of that part of the delta not removed by subsequent erosion is shown in Figure 12. North of 55 to 56°N, beyond the delta front, there are no such sediments.

3.1.2.5 Holocene peat

As the sea-level rose during the climatic amelioration that followed the last glacial period (the Weichselian), coastal peat was formed. This has been reported mainly from estuaries and close to the current coastline. However, peat has been reported from further offshore to the south of the Dogger Bank. The extent is uncertain.

3.1.3 Migration pathways

Once generated, gas rises towards the surface under the influence of buoyancy. The ability to rise is controlled by the nature of the overlying sediments and the availability of migration pathways. Generally, migration occurs most readily through coarse, permeable sediments. Where finer-grained sediments cap these, migration tends to be lateral and up-dip. Gas channelled into topographic highs within carrier beds will become trapped, escaping only when the spill-point is reached, or when a new migration pathway is opened by gas over-pressure.

Gas migration tends to be focussed:

- over gas accumulations,
- where permeable horizons crop-out,
- along faults,
- above the apices of folds
- where sediments are draped over buried topographic highs

Salt piercement structures (diapirs), which occur extensively in the North Sea, cause up-doming and create tension and thus faults, fractures and weaknesses in the fabric of the sediment. These enable gas to rise into the uppermost (Pliocene and Pleistocene) sediments producing a 'gas chimney' (see example in Figure 13). Gas migration is therefore commonly associated with salt diapirs, particularly those which penetrate the Palaeogene (Lower Tertiary) sediments and rise into the Neogene (Upper Tertiary). There are approximately 20 salt diapirs in the Central North Sea SEA2 area; their locations are shown in Figure 14.

Mud volcanoes and mud diapirs are responsible for the delivery of significant quantities of gas from deep within the sedimentary succession to the surface. However, there are none in the North Sea.

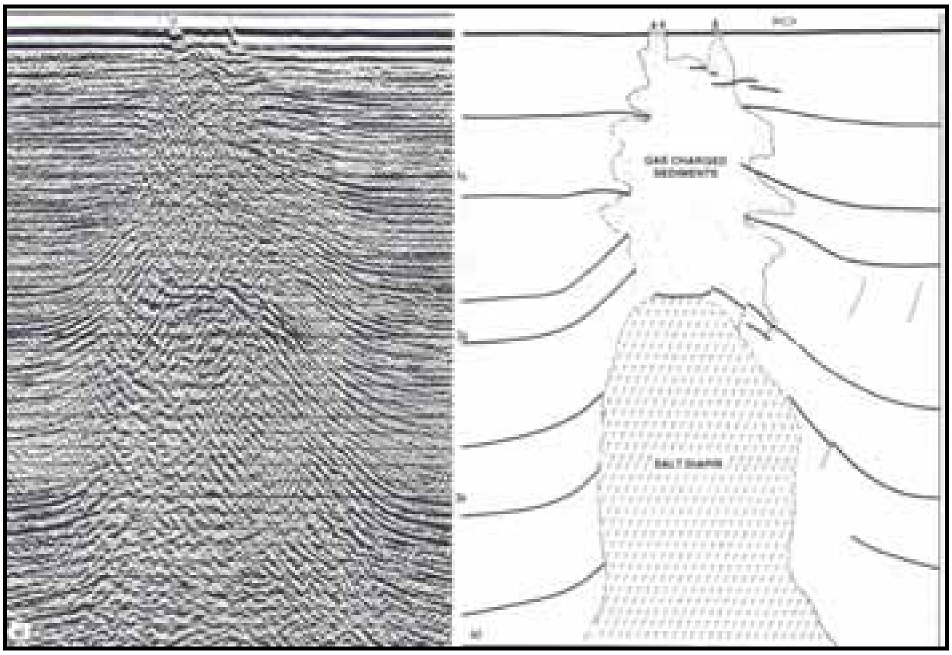


Figure 13: Gas chimney over the Tommeliten Delta salt diapir, Norwegian North Sea (after Hovland and Judd, 1988)

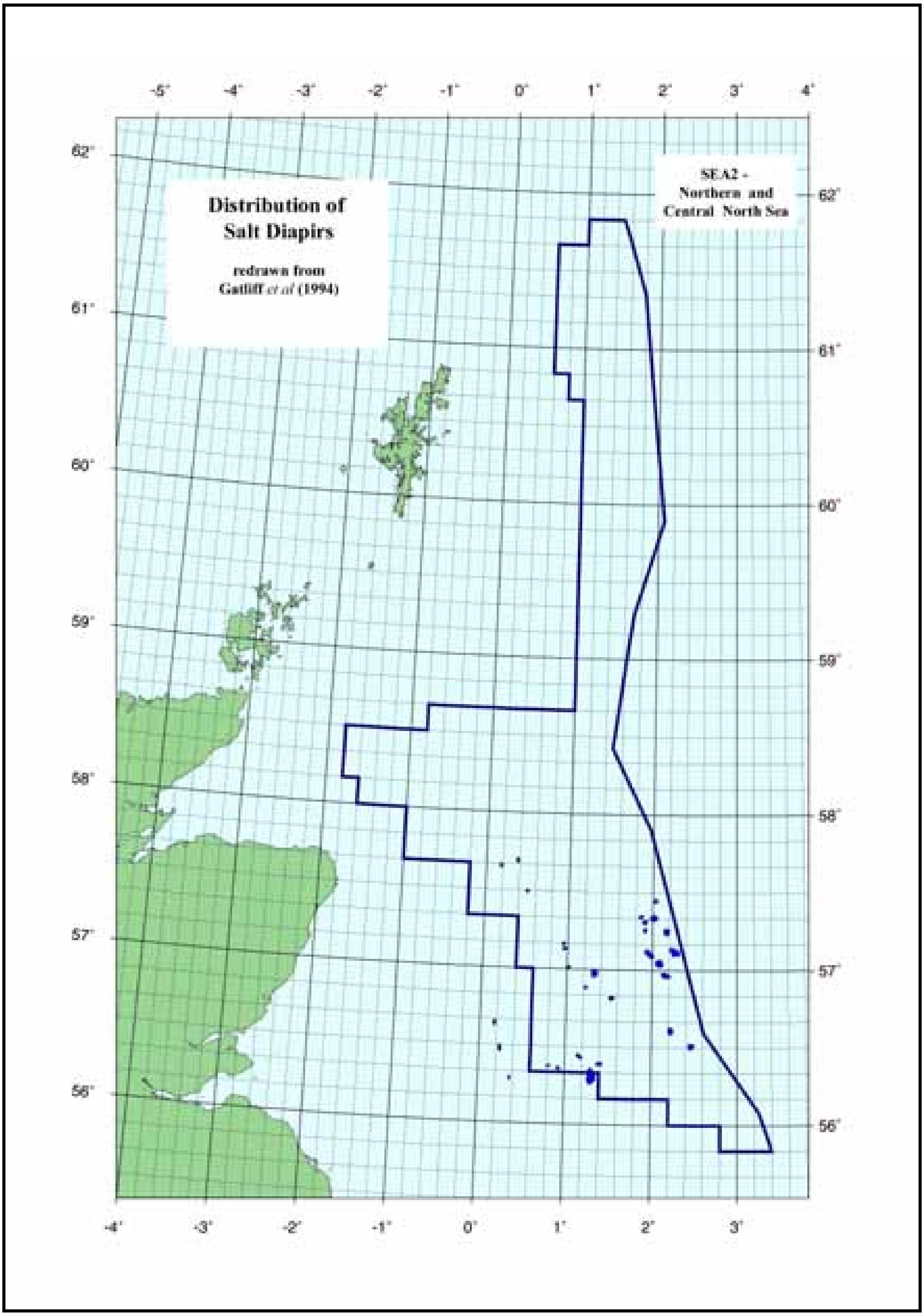


Figure 14: Distribution of salt diapirs in the Central North Sea

3.1.4 Gas accumulations

Gas accumulations are located according to the distribution of migration pathways and the three-dimensional configuration of the sediments. This is controlled by a combination of facies variation and structural features. In the present context only 'shallow gas' is of interest. This is variously defined, but in the oil industry it is generally regarded as gas accumulations occurring above the first casing point of petroleum wells (i. e. <1,000 m below seabed). Common locations for gas accumulations are in antiforms, adjacent to faults, and within laterally constrained coarse sediments (e.g. the infill of buried channels). It is not uncommon for shallow gas accumulations to occur in several layers at a single location, suggesting vertical gas migration from a deep source. Shallow gas accumulations may be identified from seismic data. Examples are shown in Figure 15.

In the North Sea shallow gas is commonly identified during drilling and site survey operations in the following horizons:

Witch Ground Basin

- Upper Tertiary (Pliocene to Eocene) lignite (source) and sands (reservoirs);
- The 'Basin Sands' near the base of the Aberdeen Ground Formation (Lower Pleistocene);
- Within coarse deposits in the Ling Bank Formation (Middle Pleistocene). This formation infills buried channels; gas is thus found on the flanks of buried channels;
- Within sediments at the top of buried channel infill;
- Close to the seabed, within the Witch Ground Formation (post-glacial - late-Pleistocene to Holocene).

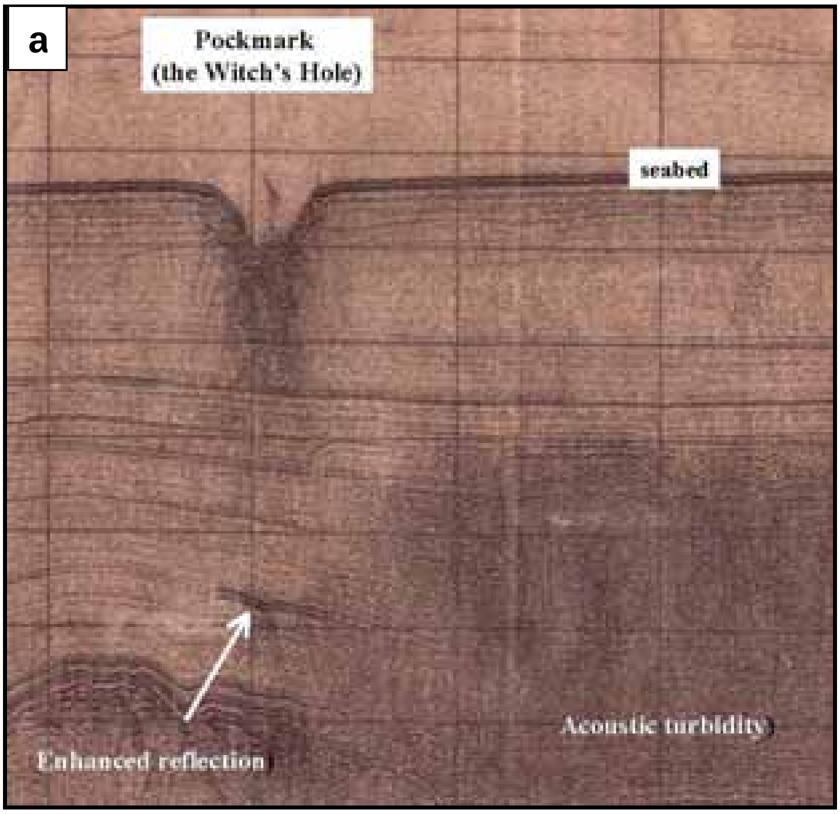
South of the Witch Ground Basin

- Within prodeltaic and prograding Pleistocene sediments.

Central North Sea

- In association with salt diapirs

The distribution of these shallow gas prone areas in the northern and central North Sea is shown in Figure 16. Figure 17 indicates areas of the UK continental shelf in which shallow gas has been reported by the British Geological Survey and industry sources either from seismic surveys or during drilling. Extensive acoustic turbidity has been reported (by Cameron *et al.*, 1984) in the Brown Bank Formation (late Eemian to early Weichselian) south of 53°N (i.e. south of the southern North Sea SEA2 area.



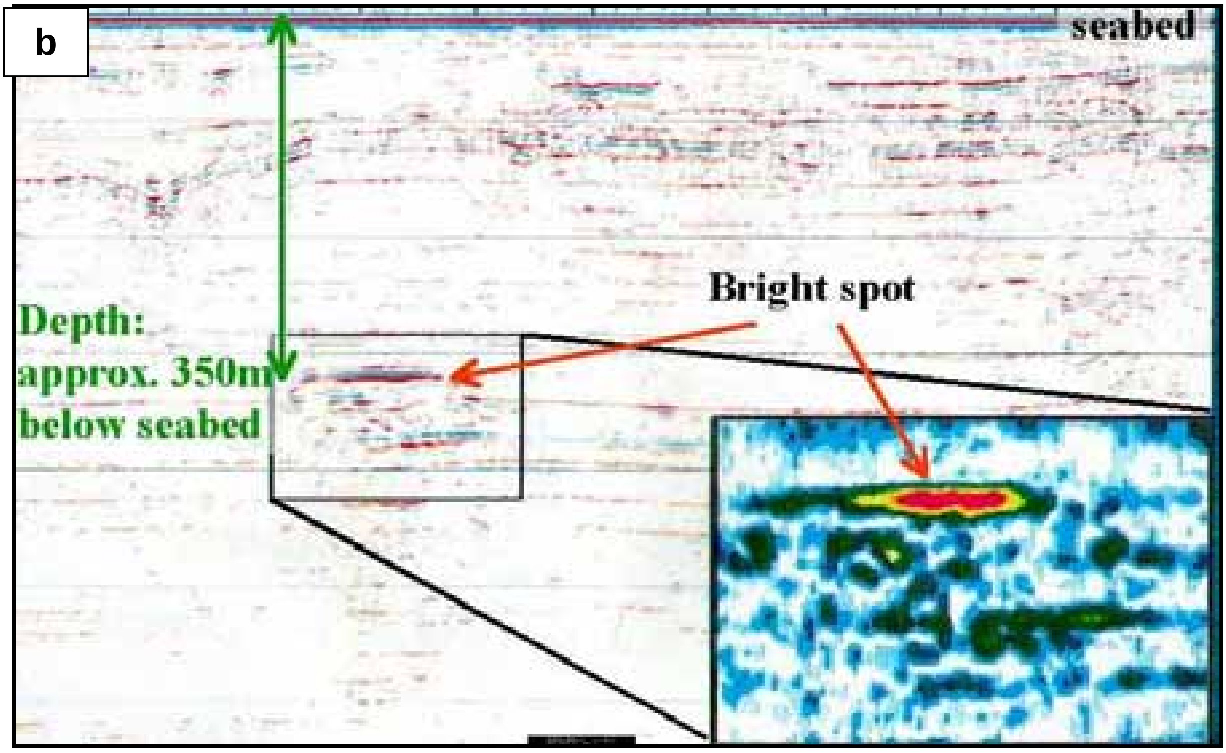


Figure 15: ***Seismic evidence of gas-charged sediment***
a) acoustic turbidity and enhanced reflection on an analogue (deep towed boomer) profile
b) bright spot on a digital (air gun) section [note the inset section which has been processed using different parameters]

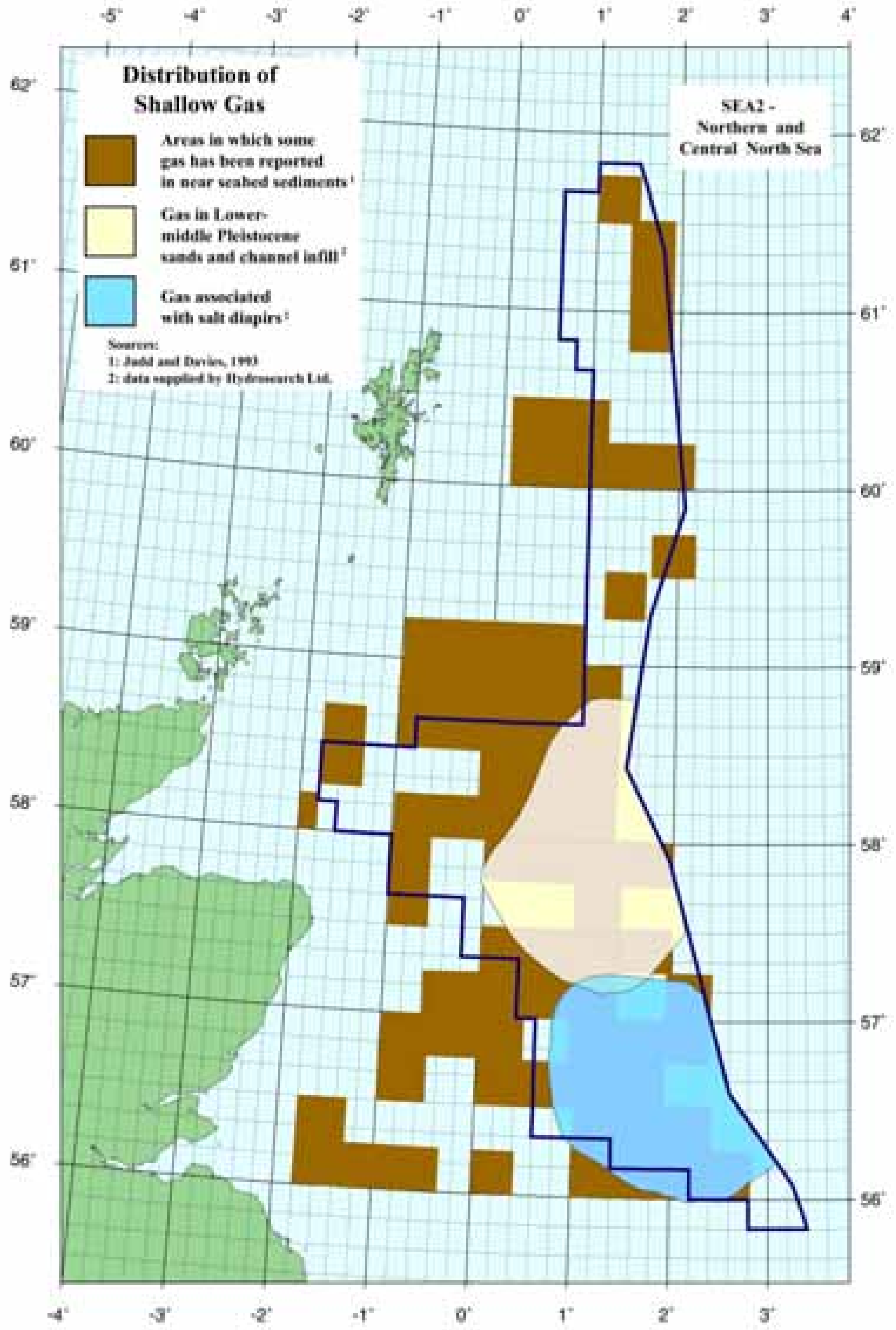


Figure 16: Distribution of shallow gas in the northern and central North Sea

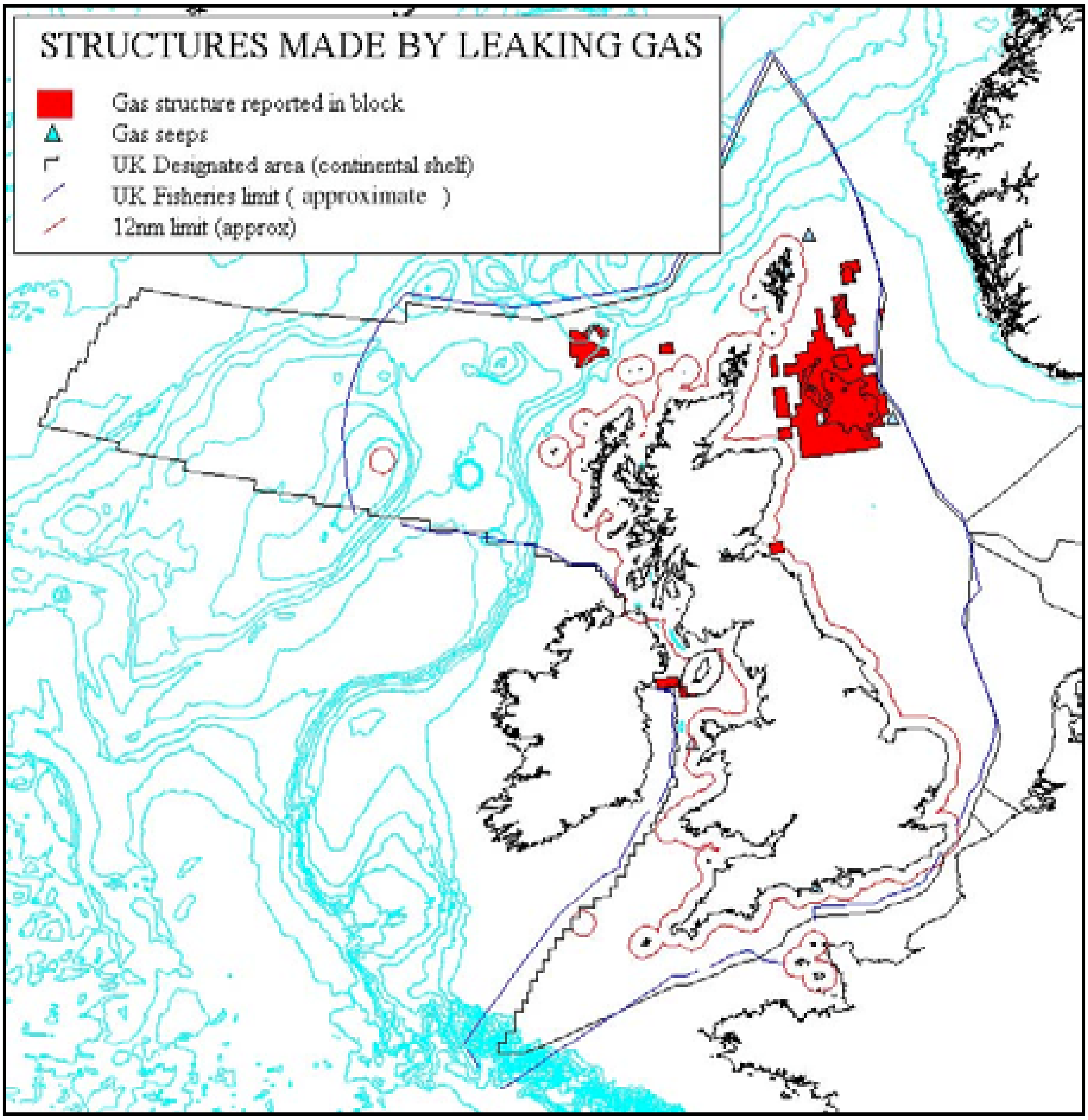


Figure 17: ***Distribution of shallow gas and related features on the United Kingdom continental shelf (compiled by C Graham, British Geological Survey, for the JNCC)***

3.1.5 Gas in seabed sediments

An indication of the distribution of gas sources was provided by Faber and Stahl (1984) who reported on an extensive survey of the gases in seabed sediment cores. Their survey area covered the majority of the Northern and Central North Sea SEA2 areas. They concluded that "*the bulk of the investigated sediment gases represent thermogenic gases which have been generated from deep source rocks and which have migrated to the surface*". Their results are summarised in Figure 18. However, it is possible that the thermogenic signatures Faber and Stahl reported may represent oxidised microbial methane. Whatever the source, this work indicates the widespread occurrence of methane in seabed sediments.

3.2 Seabed sediment type

Surveys and modelling studies have shown that the most readily pockmarked sediments are soft, silty muds. In the North Sea the majority of pockmarks have been found in the sediments of the Witch Ground Formation (in the Central / Northern North Sea depression known as the Witch Ground Basin) and their equivalents, the Flags Formation (which occupies hollows in the northern North Sea plateau). The distribution of these sediments is illustrated in Figure 19. They are also found in the Kleppe Senior Formation (in the Norwegian Trench).

Within the Witch Ground Basin the character of the Witch Ground Formation sediments varies. It is coarser and thinner towards the edges, finer and thicker in the deeper waters of the centre of the basin.

In the Southern North Sea SEA2 area, sediments suitable for pockmark formation are probably found only in the Well Hole Formation. This formation comprises "locally laminated, marine, fine-grained sands and sandy muds" (Cameron *et al.*, 1992). These sediments, which are normally 5 to 20 m thick, are confined to valleys cut into the underlying sediments.

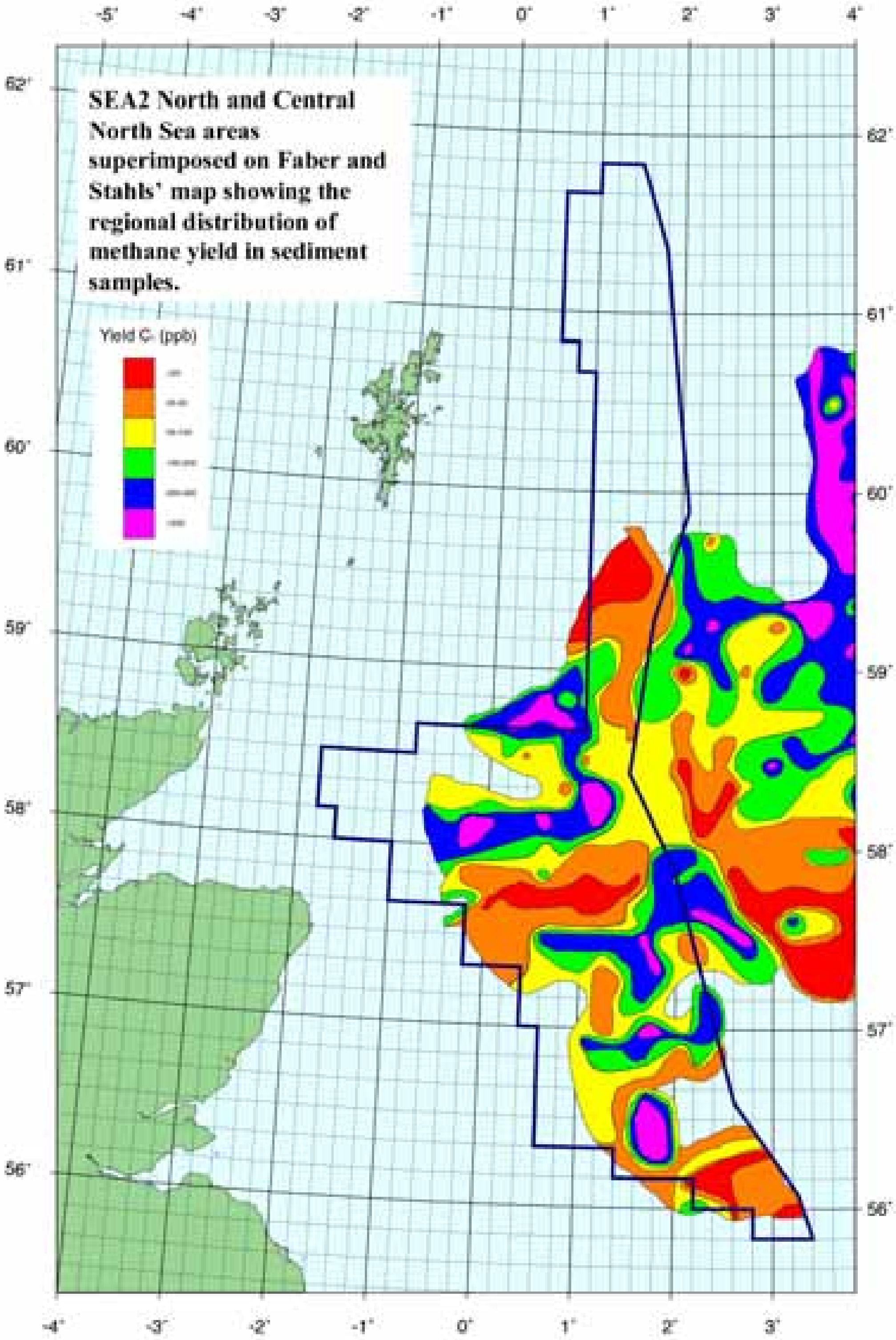


Figure 18: Methane in seabed sediments (modified from Faber and Stahl, 1984)

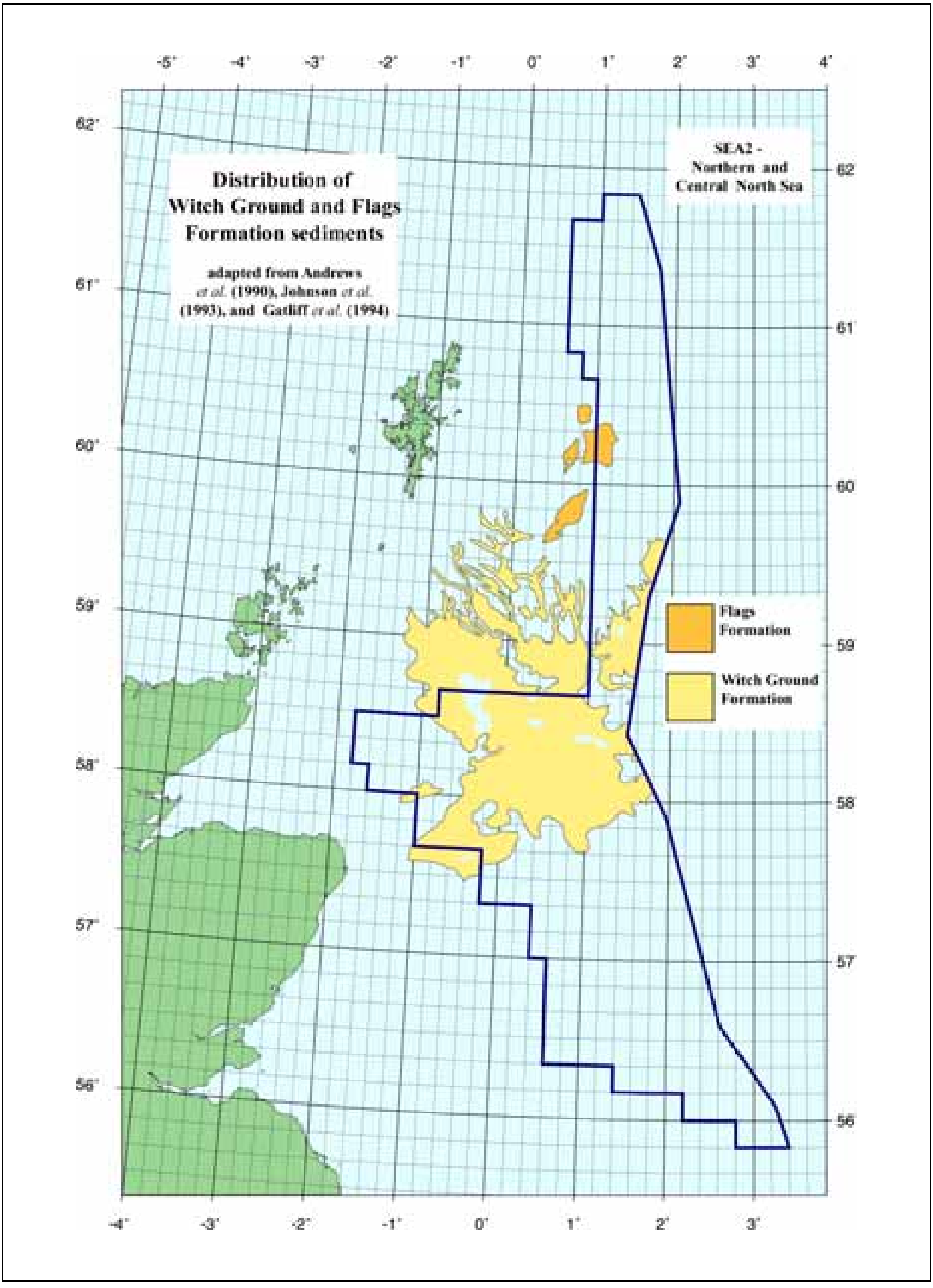


Figure 19: Distribution of the Witch Ground and Flags Formation

4. THE DISTRIBUTION AND CHARACTER OF NORTH SEA POCKMARKS

This section of the report has been prepared using data acquired from the K_Jack Survey undertaken specifically for SEA2, and data from offshore site survey reports (made available by the British Geological Survey with permission of the relevant oil companies), as well as published and publicly available material. The K_Jack Survey included nine pockmark survey areas in the Fladen Ground (Central North Sea SEA2 area). Their locations are shown in Figure 20. 3D seabed mages acquired during these surveys are presented in Appendix I.

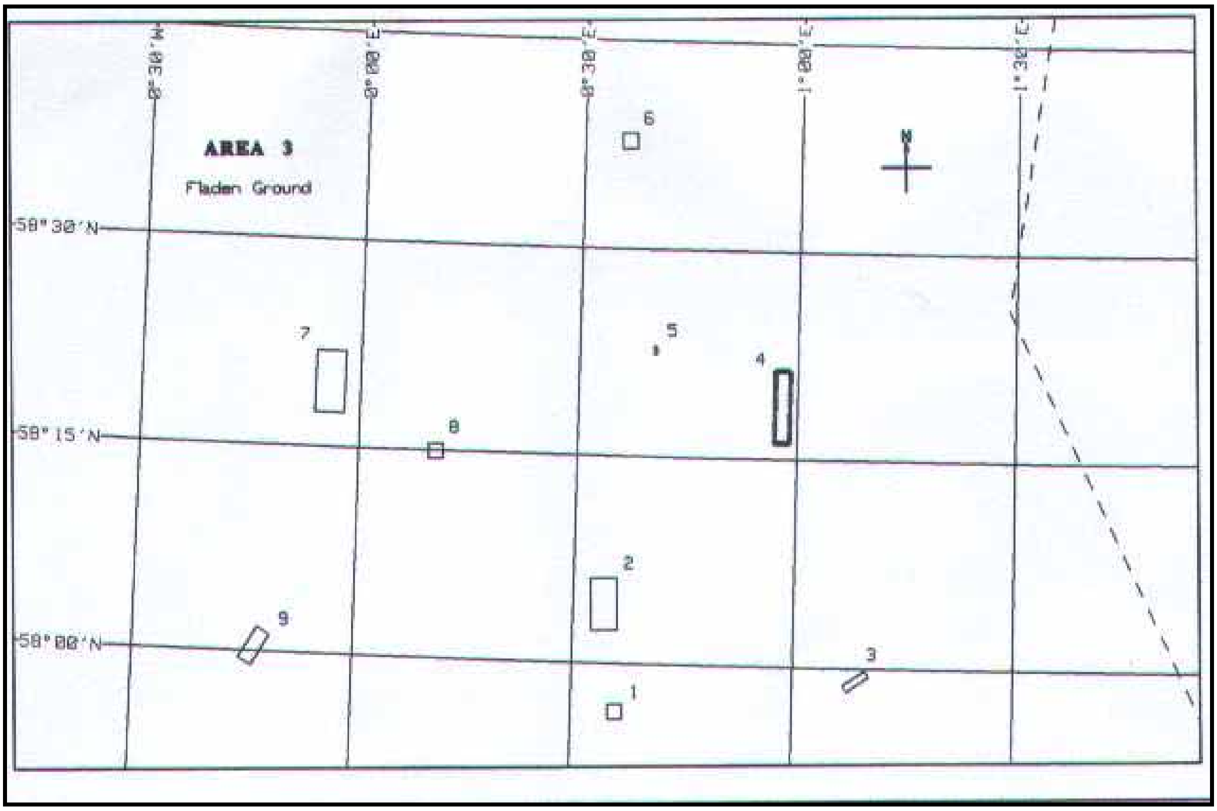


Figure 20: The K_Jack Survey areas: Fladen Ground

4.1 Appearance on geophysical records

Pockmarks were first identified on side scan sonar records. Until the introduction of multibeam echo sounders, side scan sonar remained the only technique capable of reliably demonstrating that depressions seen on echo sounder and seismic profiles were not channels.

The images in Appendix I clearly illustrate the suitability of multibeam echo sounders to identify pockmarks. On side scan sonar, pockmarks are identified as seabed depressions by the juxtaposition of an acoustic shadow (closest to the towfish) and a strong (dark) seabed reflection. The shadow represents an area of seabed facing away from the towfish, whilst the strong reflection is caused by seabed which slopes towards the towfish. An example is presented in Figure 21. [It is not difficult to misinterpret records of positive seabed features (domes, mud diapirs etc.) as pockmarks. An acoustic shadow and a strong reflection also represent these features, however, the strong reflection occurs closer to the towfish than the shadow.]

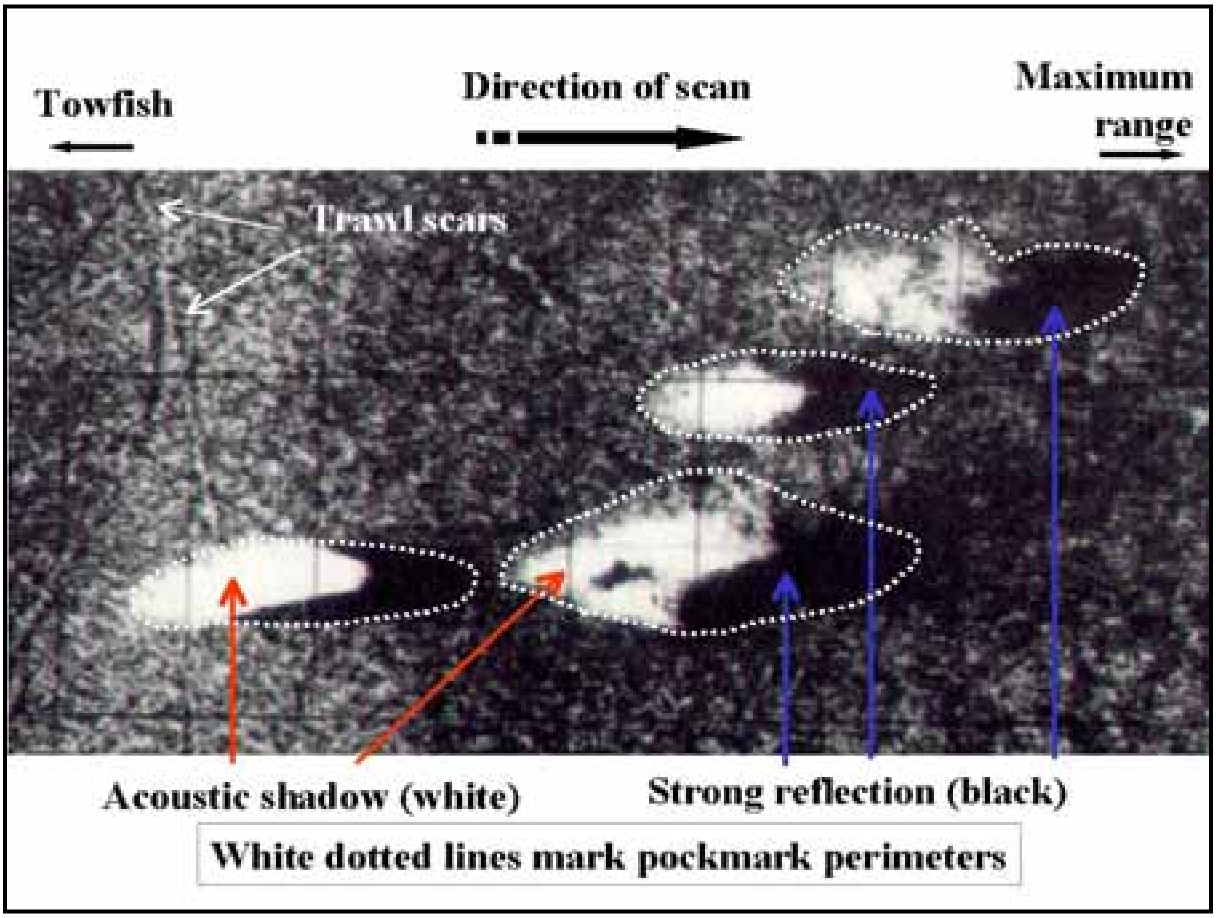


Figure 21: ***Pockmarks on a side scan sonar record (note: scale distortion has not been corrected)***

On echo sounder and shallow seismic reflection profiles pockmarks appear as notches in the seabed (see Figures 7 and 15a). Because profiles are normally displayed with a considerably exaggerated vertical scale, even quite subtle features can be identified. However, confirmation (by side scan sonar or multibeam echo sounder) is required before notches can be identified as pockmarks rather than elongated grooves, trenches or channels.

Because of its hardness relative to normal, uncemented seabed sediments, MDAC produces a strong acoustic reflection. This is represented by a dark signature on side scan sonar records (see Figure 22). It is possible that the strong seabed reflection from pockmarks indicates the presence of MDAC, however, ground truthing is required to confirm this interpretation.

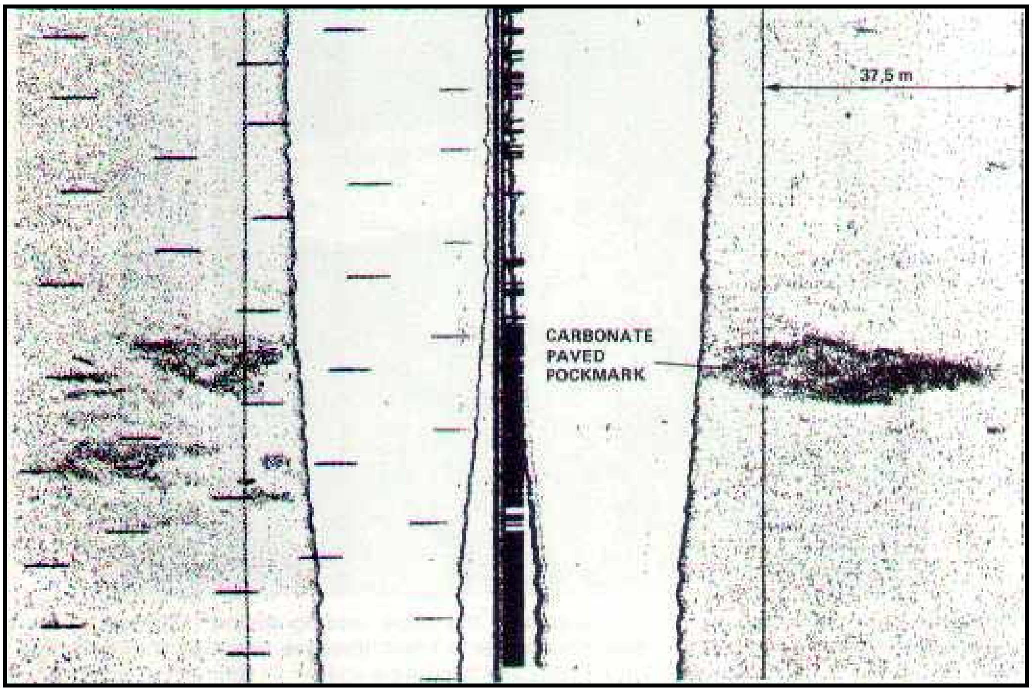


Figure 22: ***Highly reflective seabed on a side scan sonar record. This is indicative of the presence of methane-derived authigenic carbonate. This record shows the pockmark from which the MDAC shown in Appendix II photographs 2 to 4 were taken (after Hovland and Judd, 1988)***

4.2 Pockmark Distribution

The distribution of pockmarks in the UK North Sea is shown in Figure 23. It can be seen that this distribution is strongly correlated with that of the Witch Ground and Flags Formation sediments. However, there are large areas over which there are no pockmarks despite the presence of a gas source.

Within individual areas the pockmark size, density and distribution pattern are not uniform, as is shown by the results of the K_Jack survey (See Table 1). The density appears to vary with water depth (see Figure 24). However, this variation is actually caused by the coarseness of the Witch Ground Formation sediments, which fine towards the deeper, central part of the basin. Long (1986) reported that the highest densities (>30 km^{-2}) occur where the seabed sediments are sandy muds, whilst in the pure muds in the centre of the Basin densities are 10 - 15 km^{-2}. Towards the edges of the Basin, where the Witch Ground Formation sediments are coarser and thinner, pockmarks decrease in size until they are too small to identify acoustically. It is estimated that between 10 and 30% of the seabed is occupied by pockmarks.

Within individual areas the distribution of pockmarks may be random. However, commonly the pockmarks are preferentially organised into clusters or strings. For example, the pockmarks in K_Jack Survey Area 3 include six individuals arranged in a string (see Appendix I, Image 3). Such non-random distributions are determined either by sub-seabed fluid migration pathways, or by the influence of some external force acting on the seabed (for example, in the Barents Sea pockmarks are commonly found within iceberg scours).

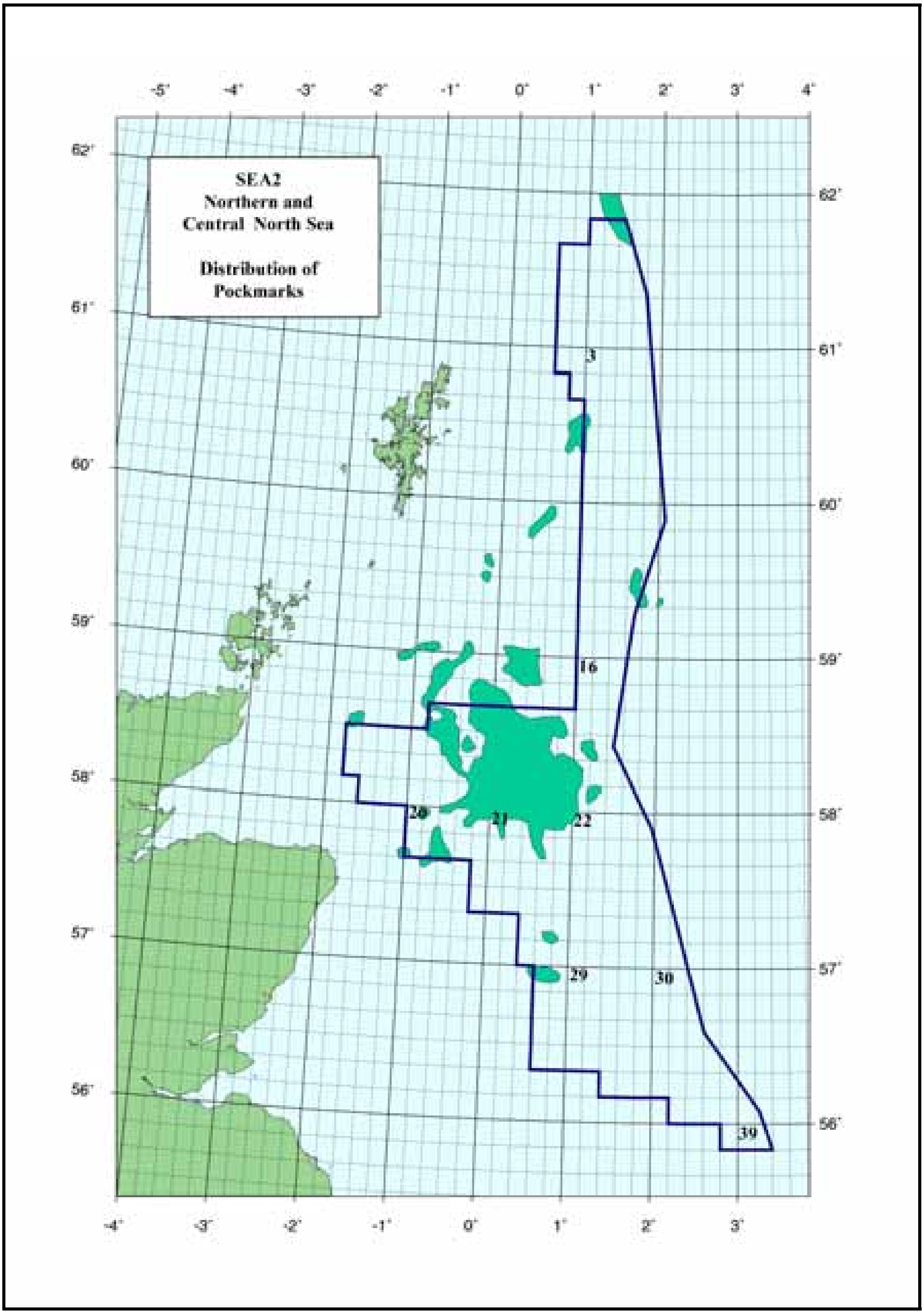


Figure 23: Distribution of pockmarks in the UK North Sea

Table 1 - Pockmark Density Variations [K_Jack Survey]

Survey Area	Size of Survey Area (Km^2)	Number of Pockmarks	Pockmark Density (Km^{-2})	Water depth (m)
1	6.8	42	6.2	142
2	24.5	437	17.8	148
3	5.6	17	3.0	130
4	19.5	213	11.1	150
5	0.6	6	10.7	145
6	6.8	40	5.9	145
7	18.7	30	1.6	130
8	4.9	23	4.7	138
9	10.8	29	2.7	120

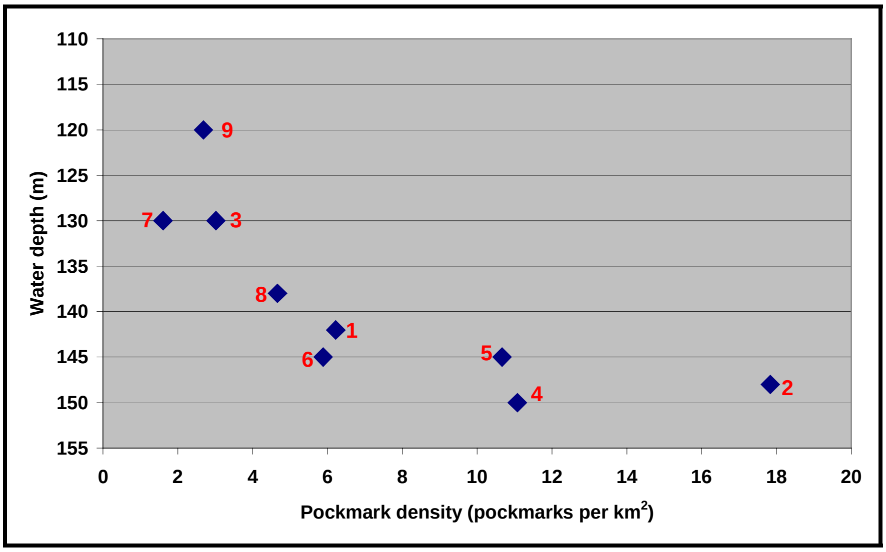


Figure 24: ***Variation of Pockmark Density with Water Depth. N.B. The density variation is actually caused by the coarseness of the Witch Ground Formation sediments, which fine towards the deeper, central part of the basin***

4.3 Pockmark Morphology

Pockmarks are commonly described as circular or elliptical seabed depressions occurring in an otherwise more or less flat and featureless seabed, as can be seen from the images in Appendix I. They occur either as single or as composite features. From seismic sections (Figures 7, 15a and 25 are examples) it can be seen that they are cut down through the seabed sediments.

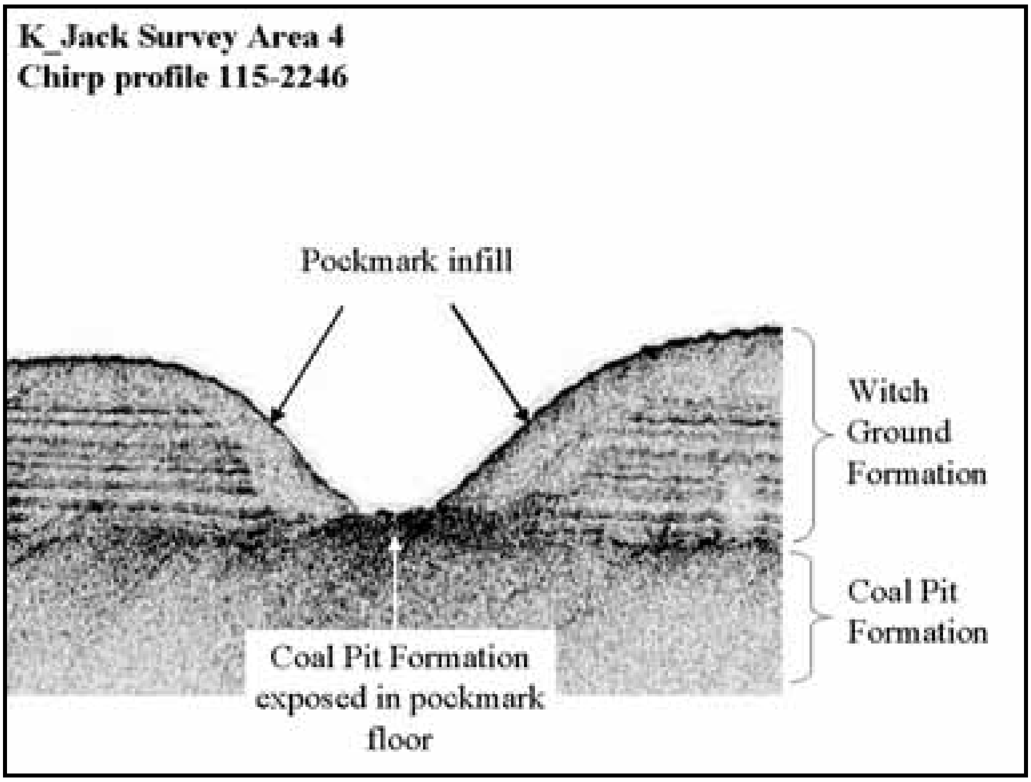


Figure 25: ***Witch Ground Formation sediments cut through to reveal the underlying sediments (Coal Pit Formation)***

4.3.1 Pockmark Sizes

Pockmark sizes are measured in terms of length and breadth, surface area, depth and the volume of displaced sediment. The results of the K_Jack Survey show that, within individual areas, there is a range of pockmark sizes (see Table 2). Generally, most lie within a limited size range, but in most areas there are a few anomalously large individuals (e.g. those seen on Appendix I, Images 6 to 10). The largest of these is 700 m across and has a maximum depth of about 22 metres (measured from previous ROV surveys), i.e. it is about the size of a large football stadium.

Many pockmarks, particularly the larger ones, are associated with small features (termed 'unit pockmarks' by Hovland and Judd, 1988). These unit pockmarks, which occur within and around the main features, are generally no more than a few metres in diameter.

There is a trend for pockmark sizes to be greater towards the centre of the Witch Ground Basin, and smaller towards the edges. Long (1986) noted that pockmarks tend to be about 50 m in diameter in the areas characterised by sandy muds (and a high pockmark density), and larger (100 - 100 m diameter) in the pure mud areas (with a lower pockmark density). That is, they tend to be larger where they are less dense, smaller where they are more dense. The smallest pockmarks occur close to the edge of the area occupied by the Witch Ground Formation. So, pockmark size may be a function of the either the coarseness of the seabed sediments or the thickness of the 'pockmarkable' sediment (or both).

Table 2 - Pockmark Size Variations [K_Jack Survey]

Survey Area	Number of Pock-marks	Diameter (m)		Depth (m)	
		Mean	Max.	Mean	Max.
1	42	30	125	2.6	6
2	437		180		7
3	17	140	220	3.9	6
4	213		700		16
5	6		400		5
6	40		100		6
7	30		250		4
8	23		110		1
9	29		300		6

In the largest pockmarks the underlying, stiffer sediment is exposed, suggesting that pockmark growth was inhibited once all the softer sediments had been removed (Figure 25). The stiffness (shear strength) of the sediment is therefore also a factor that determines whether or not pockmarks can be formed.

In other areas both larger and smaller pockmarks have been reported. In Belfast Bay, Maine (USA) depths of 35 m have been reported (Kelley *et al.*, 1994) in soft estuarine clays; in the Gullfaks field (Norwegian Block 34/10) very small pockmarks (identifiable only during ROV surveys) are present in coarse gravels (Hovland and Judd, 1988).

4.3.2 Pockmark Asymmetry

In parts of the Witch Ground Basin (e.g. Survey Areas 1,2,4,5,6 and 8) the length : breadth ratios of the pockmarks approximate to 1. However, many pockmarks are asymmetric. In Survey Area 3 the pockmarks are all elongate (length : breadth ratios between 3 and 5), and in every case the seabed is deepest at the eastern end (see Appendix I, Images 4 and 5; Figure 26). The pockmarks in Survey Area 9 are similar in shape and they also deepen to the east (see Appendix I, Images 14 and 15). The striking contrast between the pockmarks in Survey Areas 3 and 9 is the orientation of the strings of pockmarks. In Survey Area 3 these are aligned with the pockmark asymmetry, whilst in Survey Area 9 the strings are more or less normal to the asymmetry. Although the pockmarks in Survey Area 2 are apparently symmetrical, previous work (reported in Hovland and Judd, 1988) showed that in these too the deepest part of the pockmark generally lies towards the eastern side.

There is no complete explanation for this asymmetry. It has been suggested (see Hovland and Judd, 1988) that asymmetry is related to the direction of the dominant bottom water current. Further analysis of the K_Jack Survey data may lead to an explanation.

4.3.3 Seabed slopes

The seabed in the pockmarked areas of the Witch Ground Basin has a very gentle slope. Within the two largest K_Jack Survey Areas (2 and 4) the average seabed slope is less than 0.02°. In contrast the walls of some pockmarks have slopes (measured from bathymetric maps produced from multibeam echo sounder data) of >10°. In the soft sediments of the

Witch Ground Formation (undrained shear strength <10kPa) these slopes are probably unstable.

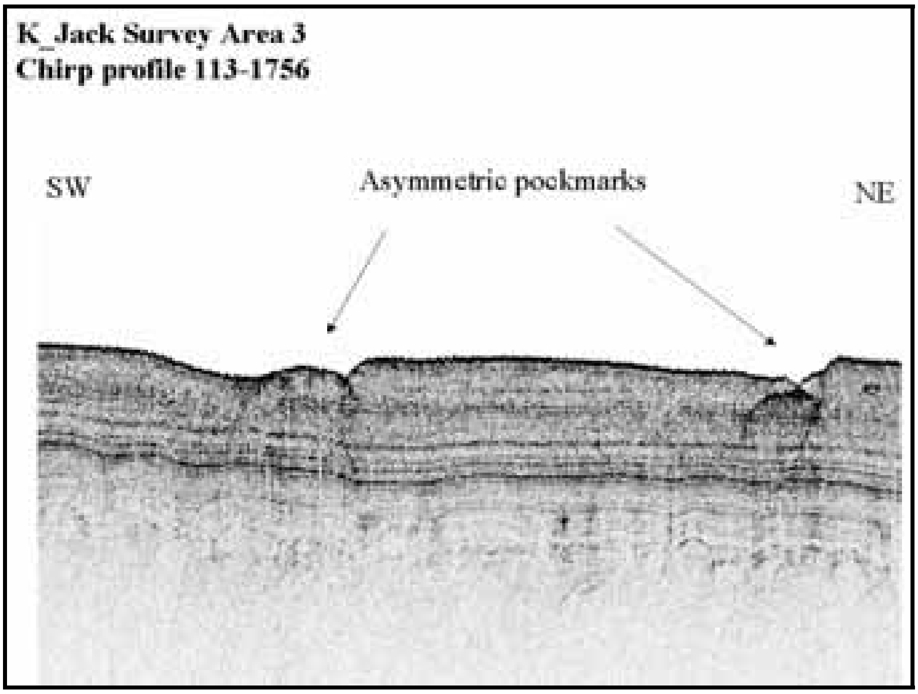


Figure 26: Asymmetric pockmarks in K_Jack Survey area 3

4.3.4 Infilling Sediment

The topmost unit of the Witch Ground Formation, the Glenn Member, comprises a thin layer of very well sorted silt. It is generally <0.5 m thick. In contrast, pockmark infill may be 2 m or more thick. The pockmark infill may be a lag deposit (the coarse material which remained in the pockmark during gas escape events) or post-formation sediments. As the Glenn Member is described as being formed by "*pockmark reworking of the underlying sediments*" (Andrews *et al.,* 1990) it is difficult to distinguish between the possible origins of the pockmark infill.

4.4 Appearance from visual observations

Reports of visual (ROV) surveys conducted in a large pockmark in Block 15/25, and in several pockmark and gas seep areas of the Norwegian sector of the North Sea were provided by Hovland and Judd (1988). These have shown that the perimeters of pockmarks may be quite distinct, with a pronounced change in slope (this can be seen in the foreground of Appendix II, photograph 8). The floors of pockmarks are not flat, but hummocky. Methane-derived authigenic carbonate (MDAC - described in section 1.1) occurs on the seabed; sometimes partially covered by sediment (e.g. Appendix II, photograph 10), but often blocks are to be found lying on the seabed (Appendix II, photograph 2).

Relative to the seabed outside the pockmarks (illustrated in Appendix II, photograph 1), the benthic fauna appears to be more prolific. However, it is very patchy, as can be seen from the photographs. There is a clear relationship between some of the fauna and the MDAC, the latter providing a hard substrate favourable to certain species. Bacterial mats (presumed to be the sulphur oxidiser, *Beggiatoa*) are present in places (see Appendix II, photographs 3 and 5).

It is noteworthy that, of the five sites illustrated in Appendix II, only two (UK Block 15/25 and Tommeliten in Norwegian Block 1/9) were identified from acoustic water column targets indicative of gas seeps. [N.B. At Tommeliten there are only very small (3 - 5 m wide) pockmarks. Gas seepage occurs in an area of stiff clays not suitable for the formation of larger pockmarks.] All these sites are characterised by an unusual fauna. MDAC was found at all but one of these sites; the exception (in Norwegian Block 26/9) was not surveyed in detail.

The data available to the author comes from surveys which have targeted pockmarks known to have active seepages. It is not known how these differ from 'normal' pockmarks.

5. EVIDENCE OF PRESENT DAY ACTIVITY

The seabed in the Witch Ground Basin has remained essentially unchanged by erosion or sedimentation since sea level stabilised after the last glaciation. Throughout this time gas generation (microbial and thermogenic) and migration has gone on uninterrupted. Consequently, the pockmarks present on the seabed represent the cumulative effects of gas escape activity over a period of at least 8,000 years [Judd *et al.*, 1994, showed that the anomalous pockmarks in UK Block 15/25, K_Jack Survey Area 4, were formed about 13,000 years before present, during climatic amelioration.] Given that gas migration may be cyclic (see Section 2 and Figure 6), it is unlikely that all pockmarks are actively seeping gas at present.

Evidence of gas escape comprises:

- Gas seepage: acoustic, geochemical and visual evidence of gas entering the water column;
- The presence of bacterial mats;
- The presence of methane-derived authigenic carbonate.

Bacterial mats and MDAC are thought to indicate seepage that has been continuous for a considerable period of time. Observations of actual seepage could be fortuitous, chancing upon an event that is part of an intermittent process, unless repeated observations are made at an individual site. Other indications of intermittent activity are:

- The appearance of new pockmarks, or the enlargement of existing ones;
- The appearance, disappearance, expansion, contraction or movement of shallow gas accumulations.

5.1 Gas seepage

5.1.1 Acoustic evidence

Both gas bubbles and the gas in the swim bladders of fish are detectable by high frequency acoustic systems: echo sounders, side scan sonars and high frequency sub-bottom profilers. Unlike fish shoals, gas bubbles tend to rise vertically from the seabed (with some deflection caused by water currents). So, more or less vertical acoustic targets may identify seeps. However, when bubble sizes vary as they rise through the water, they may present an acoustic target for only part of this time. Thus, hyperbolic targets may also provide evidence of gas seeps. Examples of presumed gas seeps are shown in Figure 27.

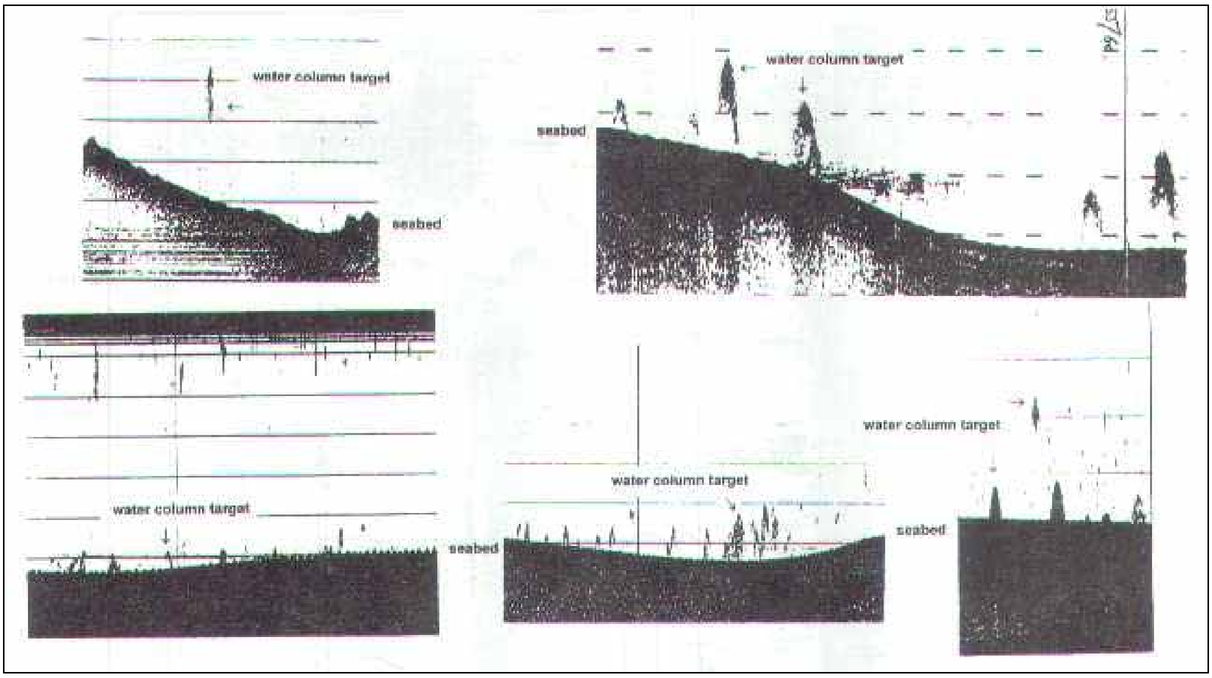


Figure 27: ***Examples of water column targets on 3.5kHz sub-bottom profiler records identified as gas seeps (after Judd*** **et al*****., 1997)***

Judd *et al.* (1997) estimated the density of gas seeps on the U.K continental shelf by considering the distribution of gas sources and shallow gas, and by reviewing more than 11,000 line kilometres of sub-bottom profiler data for evidence of bubble plumes. Their estimate of the distribution of seeps (presented here in Figure 29) suggests that seeps are quite common in the SEA2 areas.

Acoustic evidence of seeps in UK Block 15/25 (see Figure 28 for an example) has been provided by numerous surveys (reported by Hovland and Sommerville, 1985; and Dando *et al*, 1991). The seeps occur in anomalously large pockmarks which overlie an area of shallow gas (see Figure 30), and have been confirmed by visual surveys (Hovland and Judd, 1988). Consequently, the acoustic (side scan sonar) evidence of seepage at the same sites during the K_Jack Survey (Figure 31) is confidently interpreted as evidence that the gas seeps are still active. The seeps in Figure 31d seem to originate from dark (highly reflective patches of seabed. These patches may be indicative of MDAC.

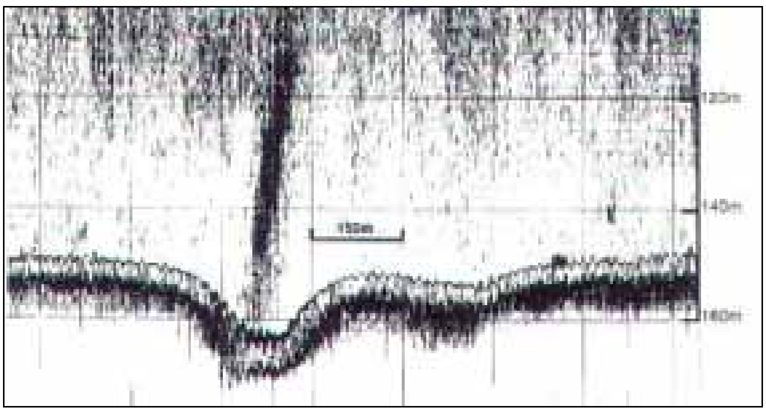


Figure 28: ***38kHz echo sounder profile of an active seep in UK Block 15/25***

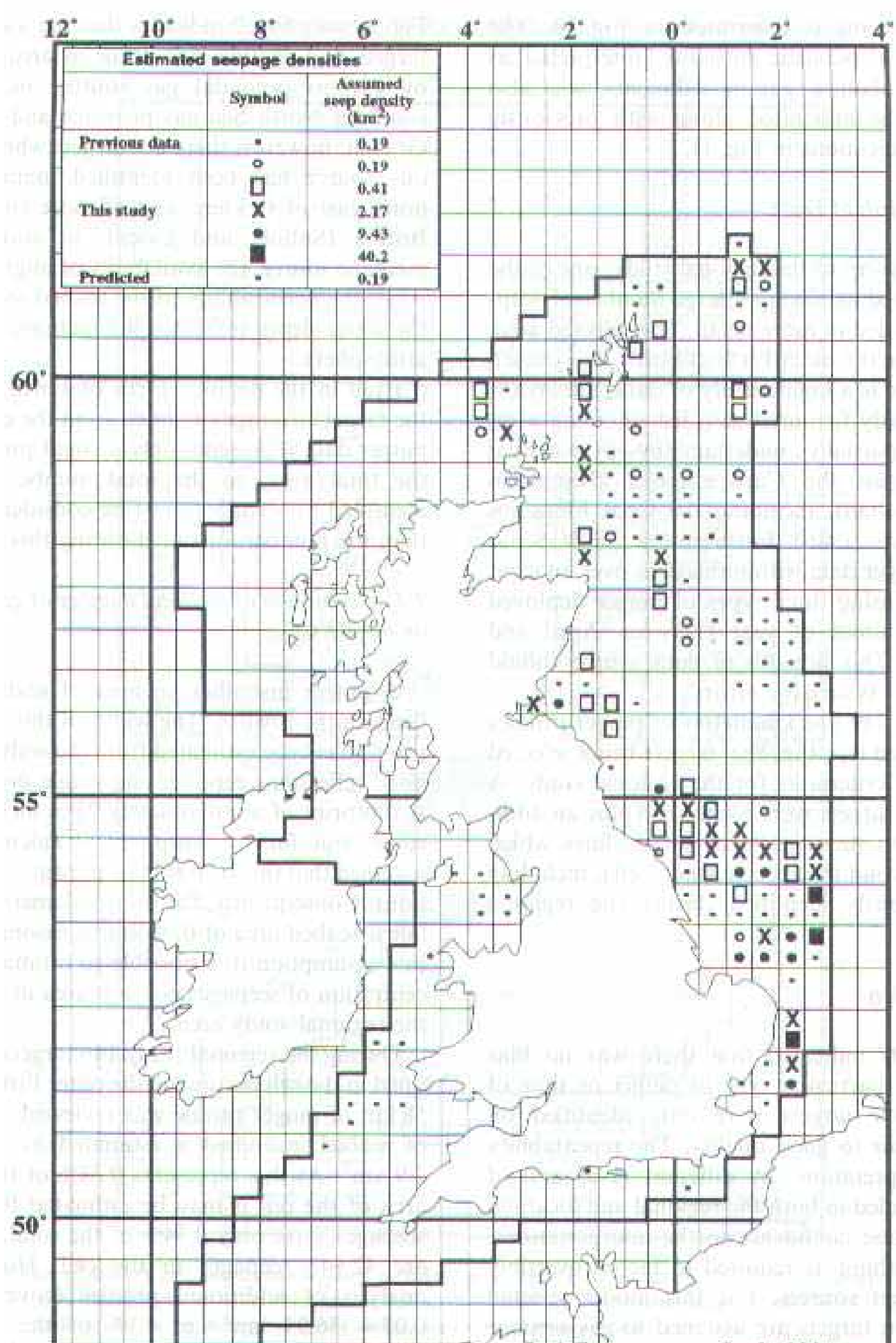


Figure 29: Distribution of gas seeps on the UK continental shelf (after Judd* et al.*, 1997)

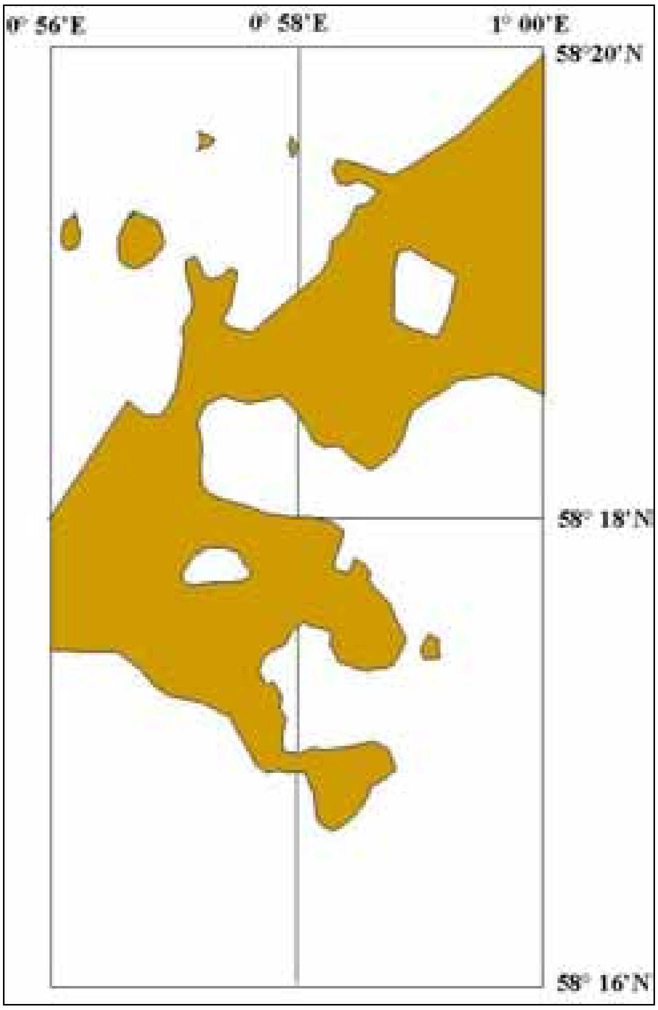


Figure 30: ***Extent of shallow gas trapped beneath the Coal Pit Formation; UK Block 15/25. (Modified after Judd* et al*, 1994)***

Whereas the majority of the seep plumes seem to represent single columns of bubbles, one (in Figure 31b) is much larger. This suggests a significant outburst of gas bubbles.

A review of the side scan sonar data from the other K_Jack Survey areas, using the same protocols as used above, revealed no other indications of gas plumes.

5.1.2 Geochemical evidence

In 1975 BP and the Institute of Geological Sciences (now the British Geological Survey) undertook a 'Sniffer' survey in a 340 km^2 area in the Witch Ground Basin. This provided geochemical analyses of the near-bottom seawater. Results indicated average total hydrocarbon concentrations of about 20 p.p.m., but values of up to 46p.p.m. were recorded. Methane comprised approximately 98% of the hydrocarbon.

The data from this survey were presented as contour maps which indicated considerable variation between individual measurements. One of the detailed surveys covers part of K_Jack Survey area 1. It suggests that gas may have been emanating from more than one pockmark in this area, including the Witch's Hole.

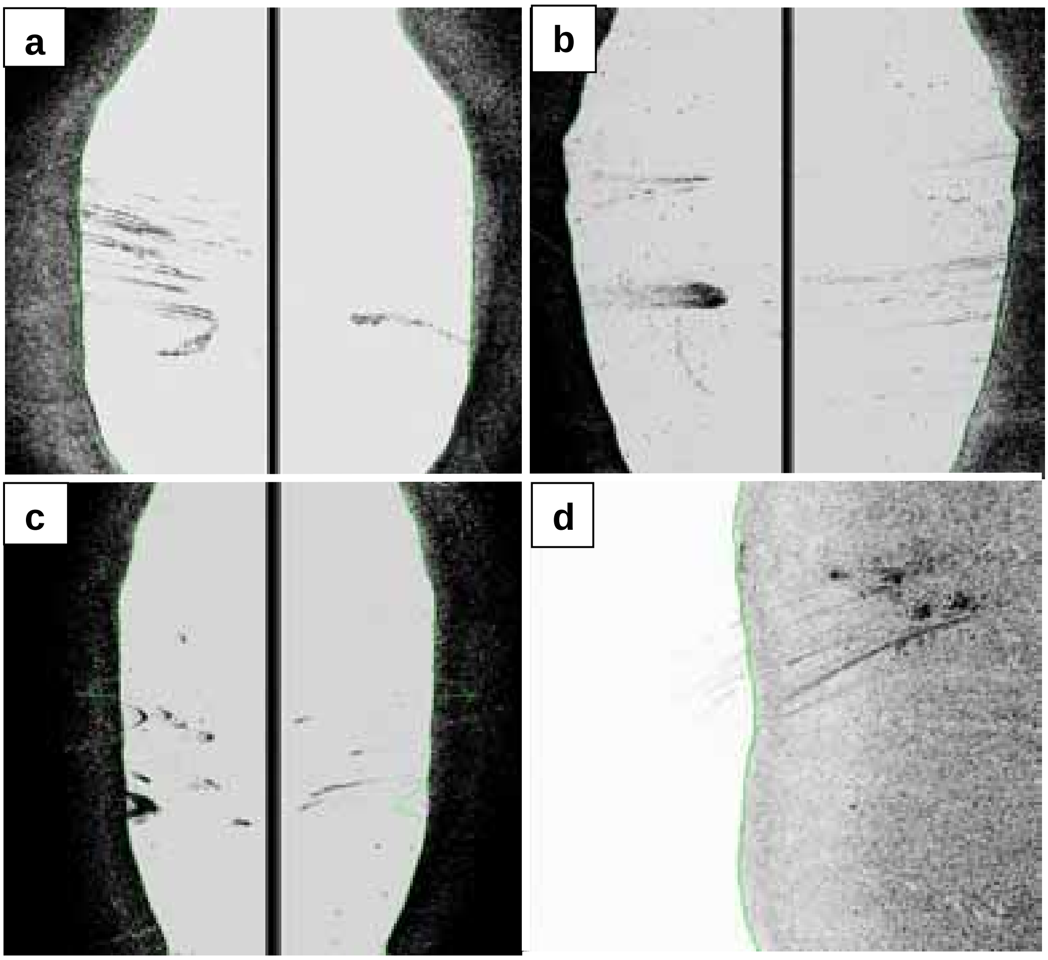


Figure 31: Gas seeps on K_Jack Survey side scan sonar data

In Block 15/25 gas samples collected at it seeped from the seabed was shown to be composed principally of methane which had a carbon isotope ratio (-70‰) consistent with a microbial source; this is probably Tertiary lignite. Water column sampling and analyses showed high concentrations of methane in the water above one of the pockmarks (see Figure 32).

5.1.3 Visual evidence

Visual surveys undertaken by ROV and manned submarine in the pockmarks of UK Block 15/25 provided unequivocal evidence of gas seeps. Bubbles were estimated to be 5 to 40 mm in diameter, and the gas flux rate was estimated at about 200 $l.hr^{-1}$ (Hovland and Judd, 1988).

None of the gas bubbles observed in this pockmark, or in pockmarks and seep sites in the Norwegian sector of the North Sea, was seen to lift sediment into the water.

5.2 Bacterial Mats

Bacterial mats are seen on the seabed at active seep sites as white patches (see Appendix II, Photographs 3, 5 and 12). These are generally believed to comprise communities of the sulphide oxidising bacterium *Beggiatoa*.

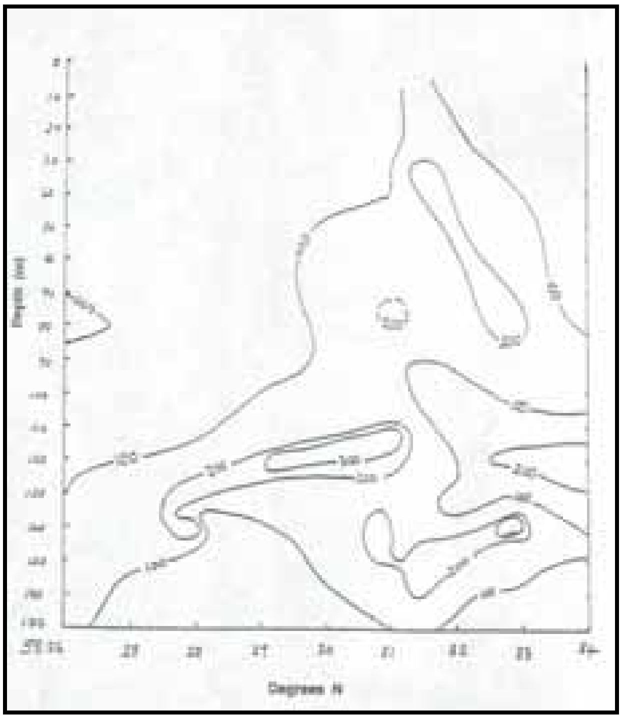


Figure 32: ***Methane concentration in the water column along a North - South transect in UK Block 15/25 (values are in nmoles methane; after Dando., 1992)***

It is only possible to detect bacterial mats by visual surveys, or by seabed sampling. As seabed sampling undertaken from a ship (as opposed to an ROV or submarine) has little control over the exact sample location, there is a very small probability of bacterial mats being sampled, even from active seeps.

In the UK sector of the North Sea the only published reports of bacterial mats associated with gas seeps relate to the pockmarks in UK Block 15/25. As can be seen from the seabed photographs (Appendix II, Photographs 9 to 12), the mats are not widespread.

5.3 Methane-derived Authigenic Carbonate (MDAC)

The presence of MDAC implies that methane seepage has persisted for some time. It is known to occur at seepage sites in the Norwegian sector of the North Sea (Appendix II, Photographs 2,4 and 5), and in the pockmarks of UK Block 15/25. (Appendix II, Photographs 9 to 12).

Being significantly harder than normal seabed sediment, MDAC is represented by a strong reflection on side scan sonar, echo sounder and sub-bottom profiler records. However, highly reflective seabed is not necessarily indicative of MDAC. Coarse sediment (e.g. gravel) and shell beds will also reflect acoustic energy well. However, when seen in conjunction with very shallow gas, highly reflective seabed may be regarded as evidence of MDAC. Side scan sonar data (Figure 21) indicates the presence of MDAC in the pockmark in which Appendix II Photographs 2 to 4 were taken. The seep site above one of the Tommeliten salt diapirs (Norwegian Block 1/9 - see Appendix II Photograph 6) was identified by similar side scan sonar evidence. Salisbury (1990) presented similar evidence (very shallow gas, highly reflective seabed and gas plumes in the water) from above another salt diapir in the Central North Sea (probably in the UK sector); it is probable that MDAC also occurs here (as well as gas seeps).

5.4 Evidence of Pockmark Formation

Evidence of the formation of new pockmarks has been reported from various places, for example:

- The Gulf of Patras, Greece where Hasiotis *et al*.(1997) reported that gas escape and pockmark formation were associated with earthquake activity;
- Belfast Bay, Maine (USA) where Gontz *et al.* (2001) demonstrated that new pockmarks were forming and older, less active pockmarks were being infilled over a two year time period.

5.4.1 Comparison of pockmark distribution from repeat surveys

Judd, 1982, compared the distribution of pockmarks in part of the Witch Ground Basin using data from British Geological Survey 1977 and 1978 surveys. No new features were identified. However, it was suggested that pockmark sizes might have increased, even over such a short time period.

5.4.2 Comparison of the distribution of shallow gas between repeat surveys

Judd, 1990, compared the distribution of gas within the sediments of the Witch Ground Formation close to the Witch's Hole between surveys conducted in 1975, 1977 and 1978 (see Figure 33). He concluded that there was a change. Data from the K_Jack Survey show that there is still shallow gas in this area. The extent has yet to be mapped.

5.4.3 Sediment Clouds

McQuillin *et al.*, 1979, described water column targets seen on deep-towed boomer and side scan sonar records during the British Geological Survey's 1978 pockmark survey (see Figure 34). They identified these targets as sediment clouds, lifted into the water by gas escape. Over a period of about eight hours they were seen to settle back to the seabed. Judd (1990) reported a similar sediment cloud seen close to the Witch's Hole on 1977 data.

This evidence suggests that gas escape events of sufficient magnitude to lift considerable volumes of sediment into the water occur at the present day.

5.5 Discussion

The evidence presented in this section suggests that:

- Gentle but continuous gas escape from pockmarks in the Witch Ground Basin is occurring at the present day;
- Visual evidence suggests that this gentle bubbling is not capable of lifting sediment into the water column, and therefore is not the cause of pockmark formation;
- Intermittent, more vigorous gas escape events are thought to occur. Such events are thought to have produced the sediment clouds described in Section 5.4.3. The large acoustic target seen in Figure 31b may be an example of such a gas escape.

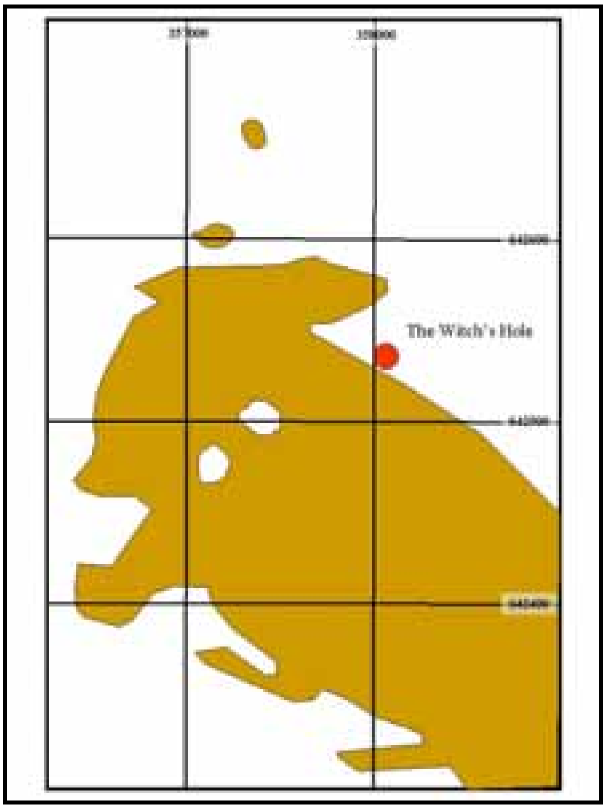


Figure 33: ***Distribution of gas in the Witch Ground Formation near the Witch's Hole; UK Block 21/04 (adapted from Judd, 1990)***

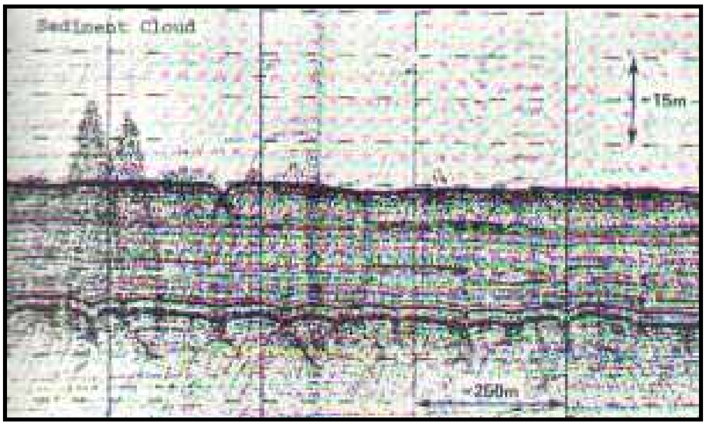


Figure 34: ***Sediment cloud near the Witch's Hole (British Geological Survey deep-towed boomer data)***

This evidence supports the model (Section 2 and Figure 6) which describes pockmark formation by intermittent vigorous gas escape events.

It has been surmised (Judd, 1990) that a large gas escape was responsible for the sinking of the ship that lies in the Witch's Hole (see Appendix I, Image 2). However, during the K_Jack Survey two more (probable) wrecks were discovered in pockmarks (see Figure 35). Like the Witch's Hole, both of these pockmarks are characterised by an unusual proliferation of 'unit' pockmarks in and around the main feature. This new evidence suggests that, rather than the ships being sunk by gas escapes (which seems extremely improbable), the impact of the ship hitting the seabed may have triggered the gas escapes and hence the formation of the pockmarks.

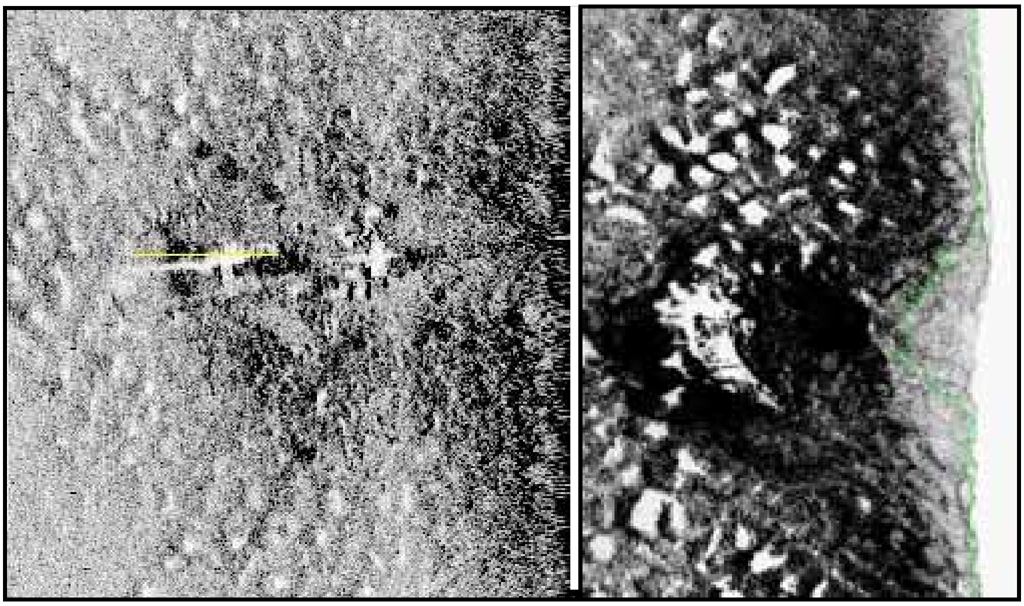


Figure 35: ***Sonar targets, possibly wrecks, lying in pockmarks. Data from the K_Jack Survey***

Recent modelling studies, described by Leifer and Judd (2001), suggest that many of the gas bubbles emitted from the anomalous pockmarks in UK Block 15/25 would dissolve at a about the same height above the seabed. This is consistent with measurements of the methane content of the seawater (see Figure 32). As microbes and nutrients adhere to bubble surfaces, it seems possible that there is a nutrient-rich layer where the bubbles dissolve above this pockmark. During coring operations it has been noticed that jelly-fish tentacles adhere to the corer cable at a point which reaches the same height above the seabed. It therefore seems possible that the ecological effects of gas seepage are not confined to the seabed.

6. GENERAL DISCUSSION AND CONCLUSIONS

6.1 Discussion

Pockmarks in the Witch Ground Basin show considerable variability with respect to their size and shape. Whilst it is evident that seabed sediment type influences their character, this alone does not explain the asymmetry of the pockmarks of several areas.

Clearly the large pockmarks in UK Block 15/25 (K_Jack Survey area 4) are anomalous. However, they are not unique. Several other pockmarks larger / deeper than the norm were identified in other areas (e.g. Appendix I, Image 9 - K_Jack Survey area 5). The new data, acquired during the K_Jack Survey, has revealed the true extent of the gas escapes that created these large features.

During the K_Jack Survey active gas seeps were identified only in UK Block 15/25 (Survey Area 4). However, gas seeps have been reported from several other locations in the Witch Ground Basin. Some of these reports are evidently erroneous; shipwrecks having been mistaken for gas seep plumes and 'carbonate reef' during at least two site surveys. Pockmarks are widespread in the North Sea, particularly in the Witch Ground Basin, but there is very little reliable evidence (in the public domain) of methane-derived authigenic carbonate (MDAC). This does not necessarily indicate that MDAC is very rare because of the difficulty in detecting MDAC remotely. The widespread availability of gas in the seabed, and evidence of gas seeps over much of the North Sea suggest that MDAC, and benthic communities associated with gas seeps and MDAC, are more widespread than has been realised hitherto. Certainly, gas seeps (and MDAC) are not confined to pockmarks; it is probable that, in addition to active pockmarks, further occurrences are present, particularly in the central North Sea associated with salt diapirs.

The identification of two possible shipwrecks in pockmarks, in addition to the previously known wreck in the Witch's Hole (UK Block 21/4), suggests that the pockmarks may have been formed by gas escape triggered when the ships hit the seabed. The probability that three ships have been sunk by major gas escapes seems very small. Until such time as the relationship between these wrecks and gas escape is established, there remains some doubt as to the risk to offshore operations of gas escapes. Generally, however, the risks associated with the presence of pockmarks and shallow gas are recognised and managed.

6.2 Conclusions

1. Pockmark formation processes are still not fully understood. In particular there is no adequate explanation for pockmark asymmetry. The data acquired during the K_Jack Survey may provide new evidence to explain the mechanism of formation more completely.

2. Notwithstanding (1), it is known that pockmarks are formed by fluid escape, therefore they occur only where there is a supply of fluid.

3. In the SEA2 areas, as in other areas of the North Sea and the UKCS, there are widespread sources of gas of various ages (Carboniferous to Holocene)

4. In the SEA2 areas, as in other areas of the North Sea and the UKCS, there is widespread evidence of shallow gas

5. Pockmarks are formed only where the seabed sediment is suitable (e.g. soft, silty clays). Where the sediment is not suitable there may be no morphological feature as evidence of fluid escape.

6. In the light of (2), (3) and (4), it is likely that seabed seeps occur in the SEA2 areas (as in other areas of the North Sea and the UKCS) outside the areas characterised by pockmarks. In particular it is thought likely that there are seeps associated with the salt diapirs of the Central North Sea.

7. Gas seepage is still on going in the anomalous pockmarks in UK Block 15/25. It is known that there is methane-derived authigenic carbonate in these pockmarks.

8. No other confirmed reports of gas seeps or methane-derived authigenic carbonate in the SEA2 areas have been identified in the literature.

9. During reviews of offshore site investigation reports and the K_Jack Survey no new positive evidence of active gas seeps or methane-derived authigenic carbonate was found.

10. The widespread distribution of gas sources and shallow gas suggest that other seeps do exist, and that they are not confined to either pockmarks or the Witch Ground Basin (nor to the SEA2 areas).

11. Risks (direct or indirect) to offshore activities associated with shallow gas and pockmarks are generally recognised and managed. However, the relationships between natural gas escapes and the sinking of ships, and between the impact of sinking ships (or other objects) on the seabed and the inducement of gas escapes (and pockmark formation) have yet to be established.

7. RECOMMENDATIONS FOR FURTHER WORK

- K_Jack Survey Areas 1 and 2 cover parts of the British Geological Survey's pockmark study area of 1977 / 1978. A detailed comparison of the BGS and K_Jack pockmark distributions should be undertaken to see if any new pockmarks formed during this 24 year time period. Differences in the equipment used, particularly the position fixing systems, mean that this will not be a trivial task. Nevertheless, the occurrence of a small (3.2M) earthquake within a few kilometres of the survey areas in the February 1995 suggests that this would be a worthwhile undertaking. Similar comparisons should be made between data from other K_Jack Survey areas and data from previous site surveys.

- The extent of gas within the Witch Ground Formation sediments around the Witch's Hole, as seen on the K_Jack Survey data, should be compared to the previously mapped extent.

- Reports and data from offshore site surveys of areas outside the Witch Ground Basin (especially those in the vicinity of salt diapirs) should be reviewed for evidence of gas seeps and MDAC.

- Seabed reflection strength should be mapped using the K_Jack Chirp data in order to compare areas of known MDAC (i.e. the pockmarks in UK Block 15/25) with other pockmark areas, particularly the large pockmarks mentioned in this report.

- Visual surveys should be undertaken of the (possible) wrecks located during the K_Jack Survey to see if there is any evidence for the cause of their sinking. In particular to test the hypothesis that they were sunk by gas escapes, and the alternative hypothesis that they triggered the release of gas that created the pockmarks.

In addition to these specific recommendations, it is recommended that maximum use be made of the valuable data set acquired during the K_Jack Survey. This could comprise a detailed academic study of pockmarks, their mode of formation, present-day activity, and the occurrence of methane-derived authigenic carbonate.

8. BIBLIOGRAPHY

Andrews, I J, D Long, P C Richards, A R Thomson, S Brown, J A Chesher, M McCormac, 1990, United Kingdom offshore regional report: the geology of the Moray Firth, HMSO for the British Geological Survey, 96p.

Andrews, J E, 1988, Methane-related Mg-calcite cements in recent tidal flat sediments from the Firth of Forth. Scottish Journal of Geology, 24, 233-244.

Boetius, A, K Ravensclag, C J Shubert, D Rickert, F Widdel, A Glieseke, R Amann, B B Jørgensen, U Witte and O Pfannkuche , 2000, A marine microbial consortium apparently mediating anaerobic methane oxidation, Nature, 407, 5 October 2000, 623-626.

Cameron, T D J, A Crosby, P S Balson, D H Jeffery, G K Lott, J Bulat, D J Harrison, 1992, United Kingdom offshore regional report: the geology of the southern North Sea, HMSO for the British Geological Survey, 152p.

Cameron, T D J, C Laban, R T E Schüttenhelm, 1984, Quaternary Geology: Flemish Bight Sheet 52°-02°E, British Geological Survey 1:250,000 Series.

Dando P R, M Hovland, 1992, Environmental effects of submarine seeping natural gas, Continental Shelf Research, 12, 10, 1197-1208.

Dando, P R, 1992, R R S Challenger Cruise 82 12 - 31 July 1991. Report, Marine Biological Association of the UK.

Dando, P R, M C Austen, R A Burke Jr, M A Kendall, M C Kennicutt II, A G Judd, D C Moore, S C M O'Hara, R Schmaljohann, A J Southward, 1991, Ecology of a North Sea pockmark with an active methane seep, Marine Ecology Progress Series, 70, 49-63.

Faber, E, W Stahl, 1984, Geochemical Surface Exploration for Hydrocarbons in North Sea, The American Association of Petroleum Geologists Bulletin, 68, 363-386.

Gatcliff, R W, P C Richards, K Smith, C C Graham, M McCormac, N J P Smith, D Long, T D J Cameron, D Evans, A G Stevenson, J Bulat, J D Ritchie with contributions by R Holmes, S Holloway, D H Jeffery, 1994, United Kingdom offshore regional report: the geology of the central North Sea, HMSO for the British Geological Survey, 118p.

Gontz., A M, D F Belknap, F Daniel, and J T Kelley, 2001, Evidence for changes in the Belfast Bay pockmark field, Maine. (Abstract), Geological Society of America, Northeast Section, 36th Annual Meeting.

Hasiotis, T, G Papatheodorou, N Kastanos, G Ferentinos, 1996, A pockmark field in the Patras Gulf (Greece) and its activation during the 14/7/93 seismic event. Marine Geology, 130, 333-344.

Hovland, M, 1990, Do carbonate reefs form due to fluid seepage?, Terra Nova, 2, , 8-18.

Hovland, M, 1993, Submarine gas seepage in the North Sea and adjacent areas, Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, 1333-1338.

Hovland, M, A G Judd, 1988, Seabed Pockmarks and Seepages, Graham and Trotman, publisher, London, 293p.

Hovland, M, A G Judd, L H King, 1984, Characteristic features of pockmarks on the North Sea Floor and Scotian Shelf, Sedimentology, 31, 471-480.

Hovland, M E Thomsen, 1989, Hydrocarbon-based communities in the North Sea?, Sarsia, 74, 29-42.

Hovland, M, J H Sommerville, 1985, Characteristics of two natural gas seepages in the North Sea, Marine and Petroleum Geology, 2, 319-326.

Hovland, M, M R Talbot, H Qvale, S Olaaussen, L Aarsberg, 1987, Methane-related carbonate cements in pockmarks of the North Sea, Journal of Sedimentary Petrology, 5, 881-892.

Johnson, H, P C Richards, D Long, C C Graham, 1993, United Kingdom offshore regional report: the geology of the northern North Sea, HMSO for the British Geological Survey, 110p.

Jørgensen, N O (Editor), 1994, Gas in marine sediments: proceedings of the 2nd conference on Gas in Marine Sediments held at the North Sea Centre, Hirtshals, Denmark, August 25-28 1992. Bulletin of the Geological Society of Denmark, 41, 1-109.

Judd A G, G D Floodgate, 1992, The origins of shallow gas, Continental Shelf Research, 12, 1145-1156.

Judd, A G, 1982, Computerised marine geophysical and geotechnical mapping techniques and their application to a study of pockmarks, Ph.D. thesis, University of Newcastle upon Tyne 233p.

Judd, A G, 1990, Shallow gas and gas seepages - a dynamic process?, Safety in Offshore Drilling: The Role of Shallow Gas Surveys (Ed. Ardus, D A and C D Green), 27-52.

Judd, A G, M Hovland, 1992, The evidence of shallow gas in marine sediments, Continental Shelf Research, 12, 1081-1096.

Judd, A G, D Long, M Sankey, 1994, Pockmark formation and activity, U K block 15/25, North Sea, Bulletin of the Geological Society of Denmark, 41, 34-49.

Judd, A G, G Davies, 1993, Potential Contribution to Atmospheric Methane by Natural Seepages, Report to the Department of trade and Industry, ETSU Report Number ETSU/ENI/R002.

Judd, A G, G Davies, 1994, Potential Contribution to Atmospheric Methane by Natural Seepages, Report to the Department of trade and Industry, ETSU Report Number ETSU/NI/01/00024/REP.

Judd, A G, G Davies, J Wilson, R Holmes, G Baron, I Bryden, 1997, Contributions to atmospheric methane by natural seepages on the U K continental shelf, Marine Geology, 140, 427-455.

Judd, A G, R Sim, P Kingston, J McNally (Submitted) Gas seepage on an inter-tidal site: Torry Bay, Firth of Forth, Scotland. Submitted to Continental Shelf Research.

Kelley, J T, S M Dickinson, D F Belknap, W A Barnhardt, M Henderson, 1994, Giant sea-bed pockmarks: evidence for gas escape in Belfast Bay, Maine. Geology, 22, 59-62.

Leifer, I, A G Judd, 2001, Seep bubble layer deposition due to sharp bubble dissolution. European Union of Geosciences conference (EUG XI), Strasbourg, France, April 2001.

Long, D, 1986, Seabed Sediments: Fladen Sheet 58°N-00°, British Geological Survey 1:250,000 Series.

Long, D, 1992, Devensian Late-glacial gas escape in the central North Sea, Continental Shelf Research, 12, 1097-1110.

McQuillin, R, N Fannin, 1979, Explaining the North Sea's lunar floor, New Scientist, 1163, 90-92.

McQuillin, R, N G T Fannin, A G Judd, 1979, IGS Pockmark Investigations 1974-1978, Institute of Geological Sciences, Continental Shelf Division, UC/097, 38p.

Pegrum, R M, A M Spencer, 1990, Hydrocarbon plays in the northern North Sea. IN Brooks J (Ed.) Classic Petroleum Provinces, Special Publication of the Geological Society of London, No 50, 441-470.

Salisbury, R S K, 1990, Shallow gas reservoirs and migration paths over a Central North Sea diapir, Safety in Offshore Drilling: The Role of Shallow Gas Surveys (Ed. Ardus, D A and C D Green), 167-180.

Ziegler P A, 1990, Geological Atlas of Western and Central Europe 1990, Shell Internationale Petroleum Maatschappij b.v., 238p

9. GLOSSARY OF TECHNICAL TERMS

Acoustic turbidity	Sub-bottom profiler feature representing a gas charged sediment
Authigenic	Developed in situ
Bacterial gas	Generated by bacteria
Biogenic gas	*See microbial*
Bright spot	Digital seismic feature representing a gas accumulation
Carboniferous	Period of geological time (345 - 280 mya)
Chemosynthesis	The use of chemical energy (as opposed to sunlight - photosynthesis)
Enhanced reflection	Sub-bottom profiler feature representing a gas charged sediment layer
Eocene	Period of geological time (54 - 38 mya)
Gas chimney	Vertical column of gas charged sediment
Holocene	Period of geological time (10,000 ya to present) (also known as the 'Recent'
Jurassic	Period of geological time (190 - 136 mya)
MDAC	Methane-derived authigenic carbonate
Microbial gas	Generated by microbes: includes bacterial gas and gas generated by arachaea
Miocene	Period of geological time (26 - 7 mya)
Neogene	Period of geological time (26 - 7 mya) incorporates the Miocene to Pliocene epochs
Oligocene	Period of geological time (38 - 26 mya)
Palaeocene	Period of geological time (56 - 54 mya)
Palaeogene	Period of geological time (65 - 26 mya) - incorporates the Palaeocene to Oligocene epochs
Pleistocene	Period of geological time (2 - 0.01 mya) - the glacial period
Pliocene	Period of geological time (7 - 2 mya)
Pockmark	Seabed crater formed by the expulsion of fluids (liquid or gas) from the seabed
Quaternary	Period of geological time (2 mya to present) - incorporates the Pleistocene and Holocene epochs
ROV	Remotely Operated Vehicle
Salt diapir	Geological structure formed when salt rises under buoyancy, piercing the overlying sediment layers
Tertiary	Period of geological time (65 - 2 mya)
Thermogenic gas	Gas produced by thermocatalytic processes at high temperatures and pressures deep below the seabed

APPENDIX I

3D Seabed Images acquired during the K_Jack Survey

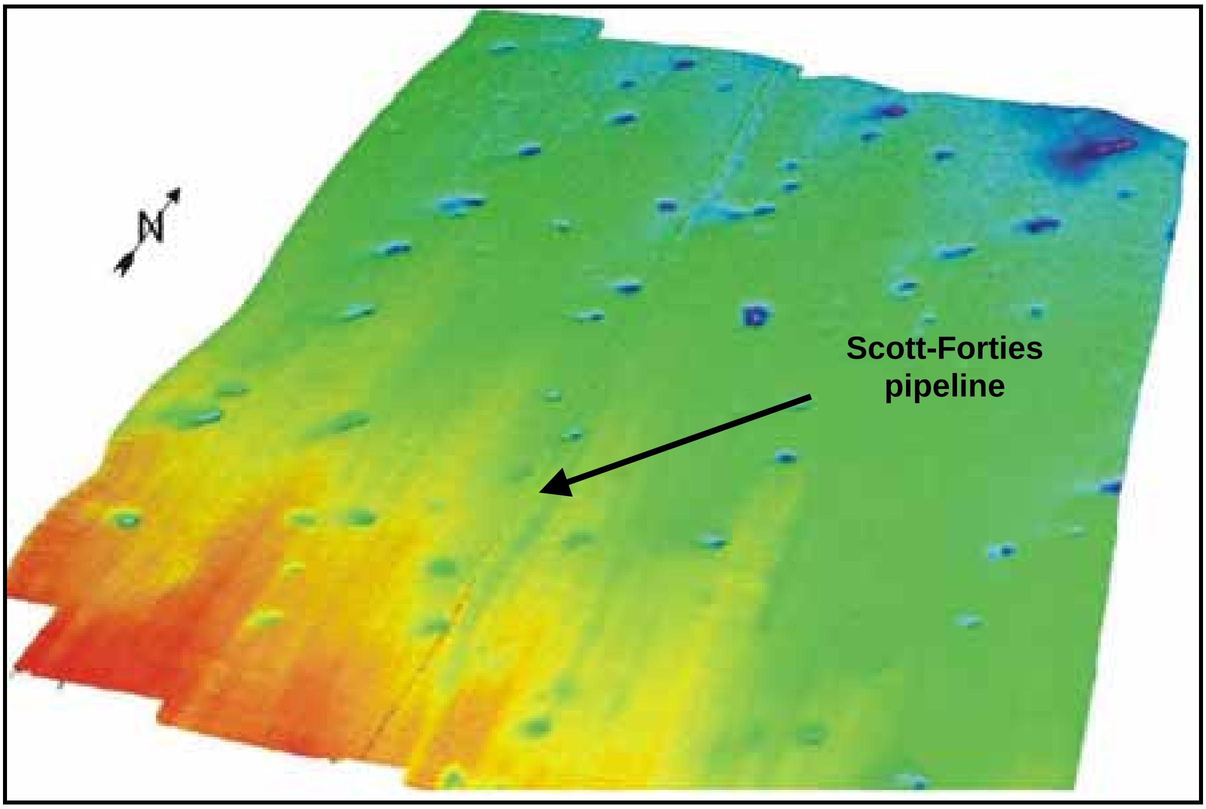


Image 1. Survey Area 1

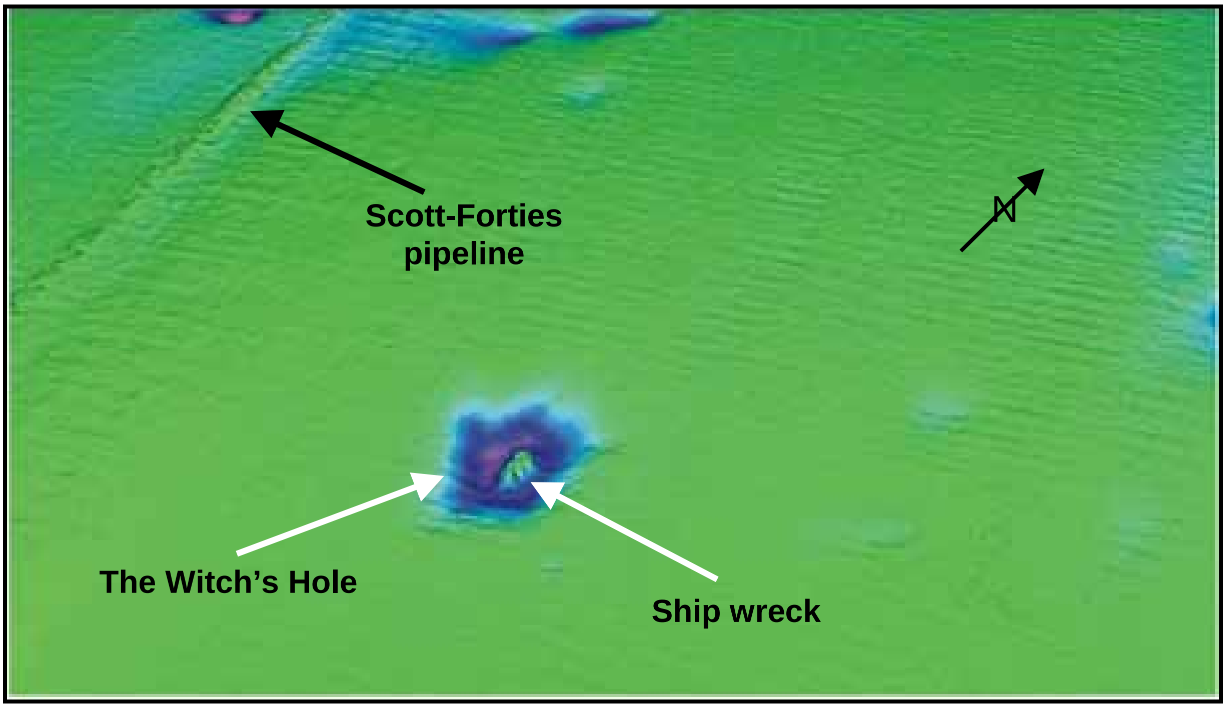


Image 2. Detail from Survey Area 1

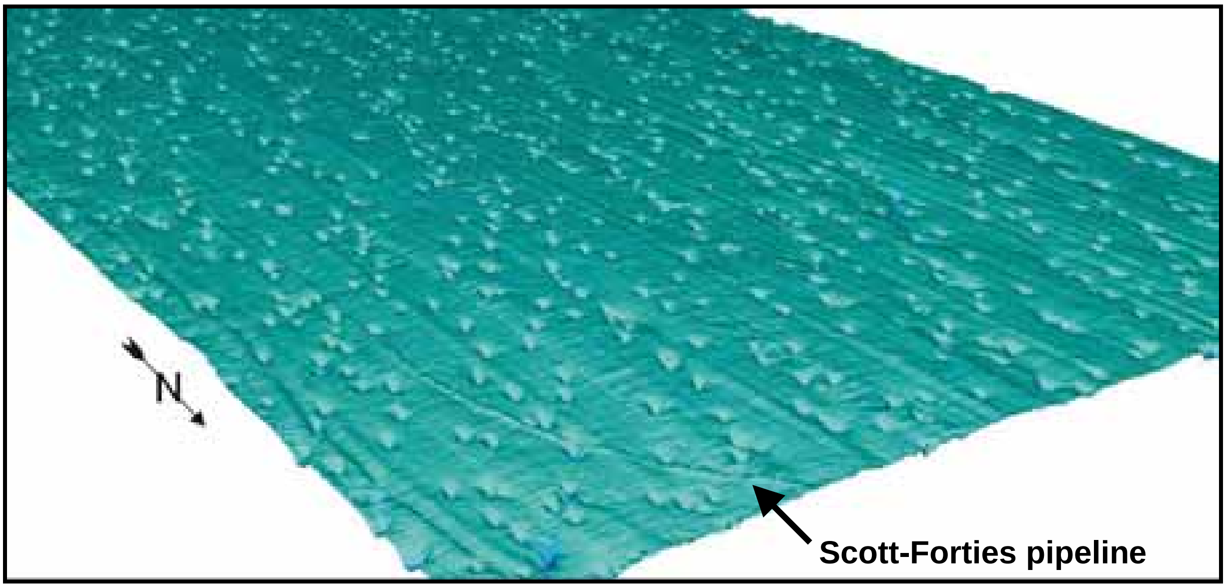


Image 3. Survey Area 2

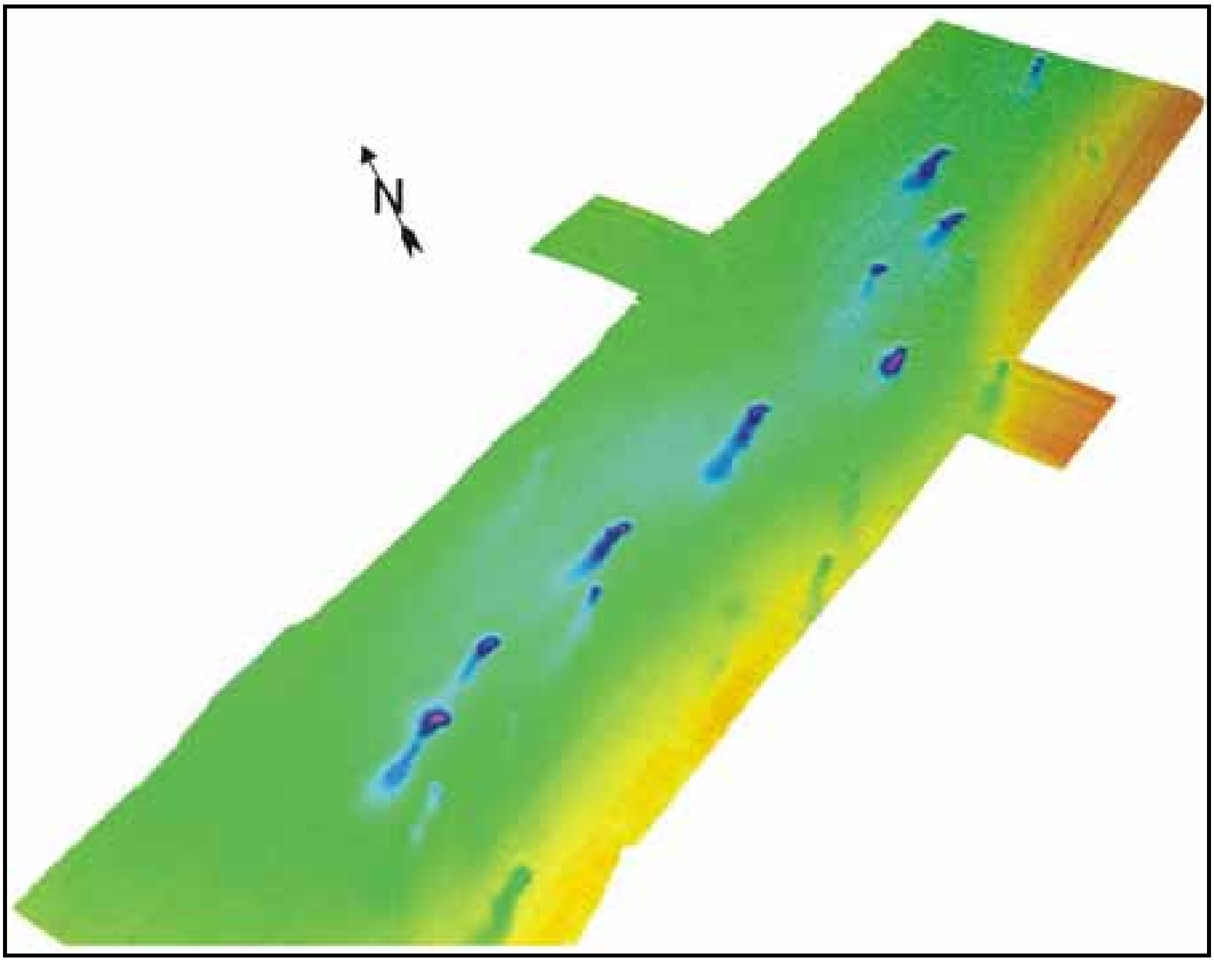


Image 4. Survey Area 3

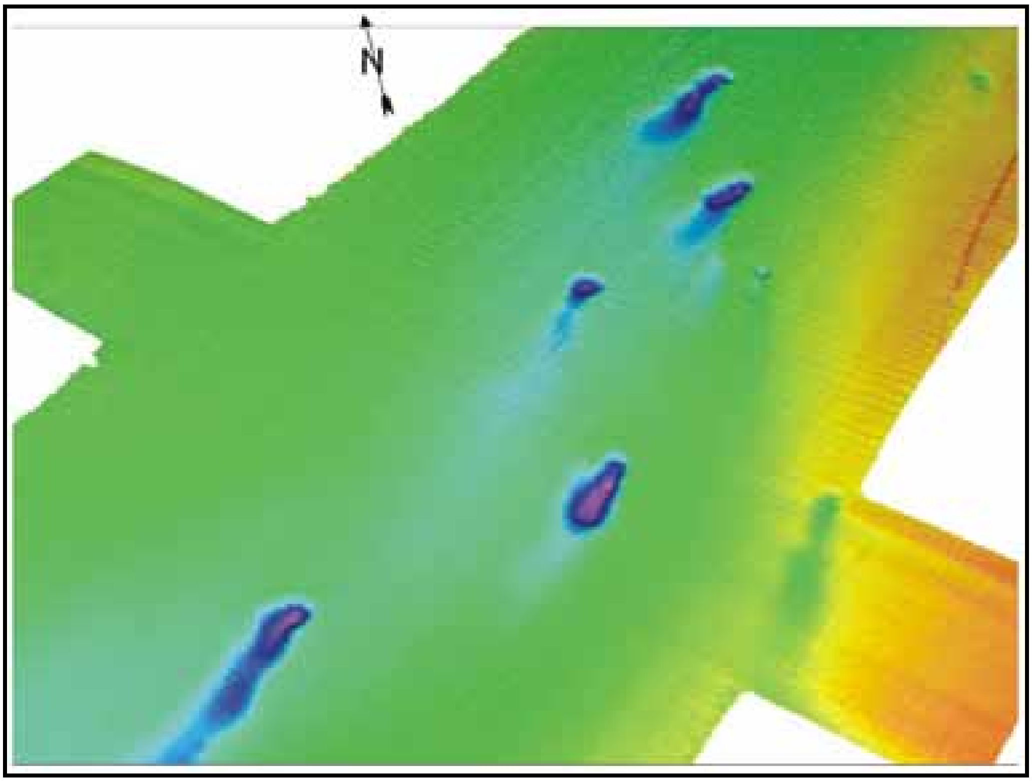


Image 5. Detail from Survey Area 3

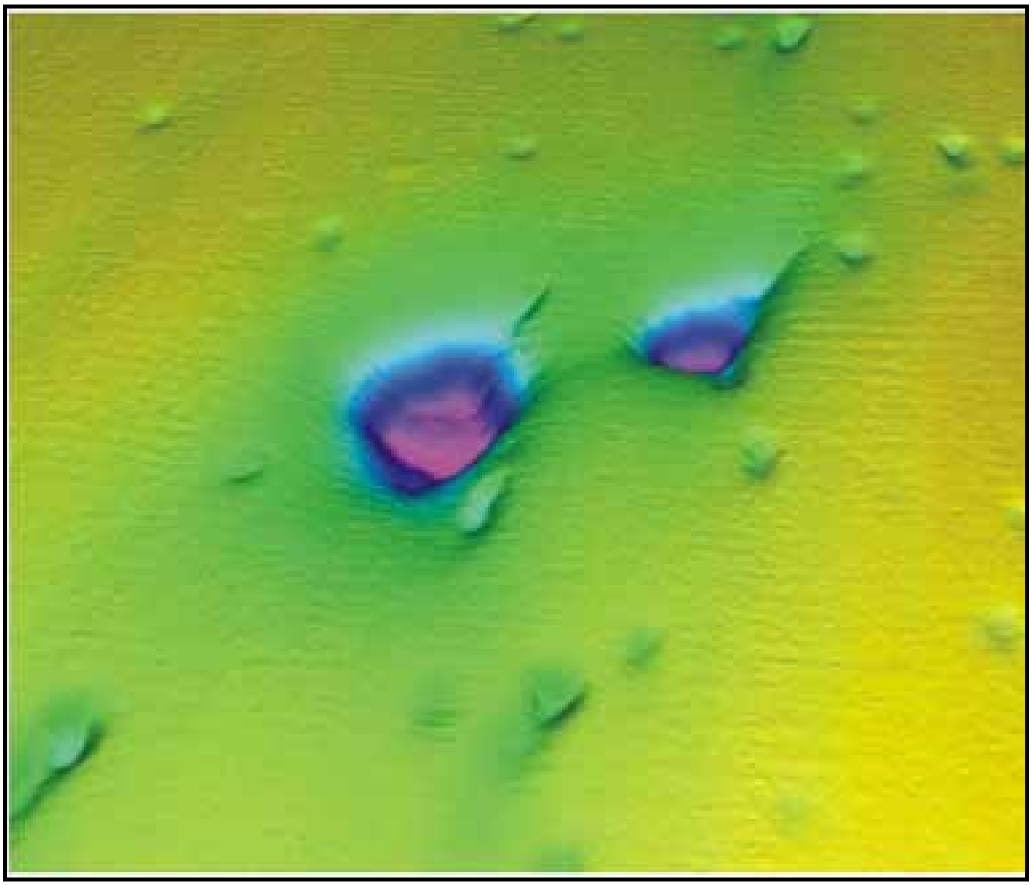


Image 6. Detail from Survey Area 4

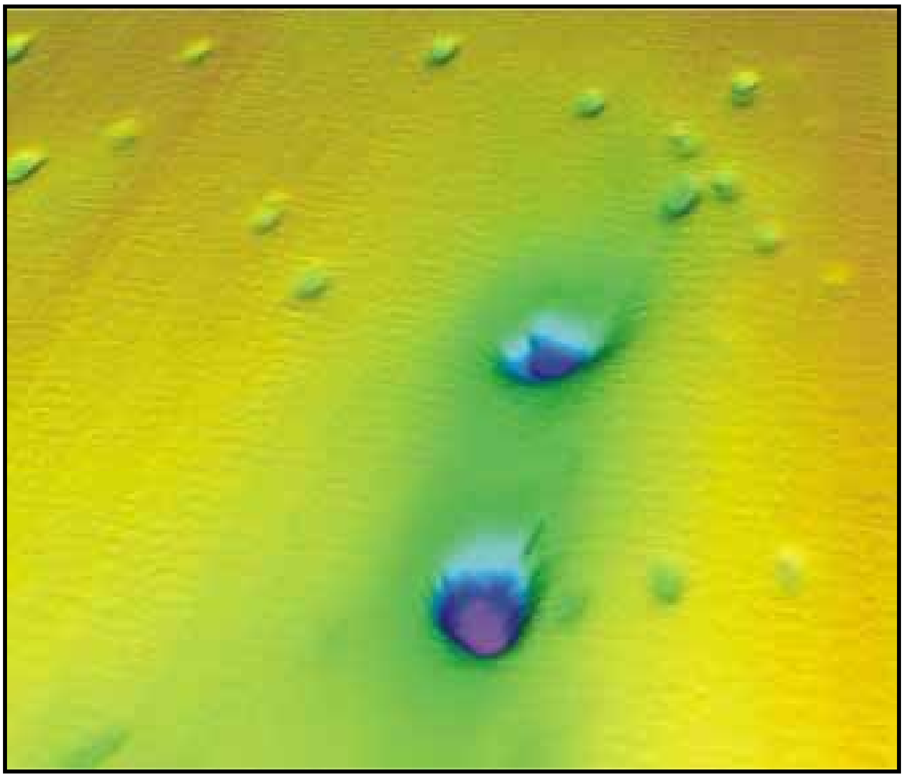


Image 7. Detail from Survey Area 4

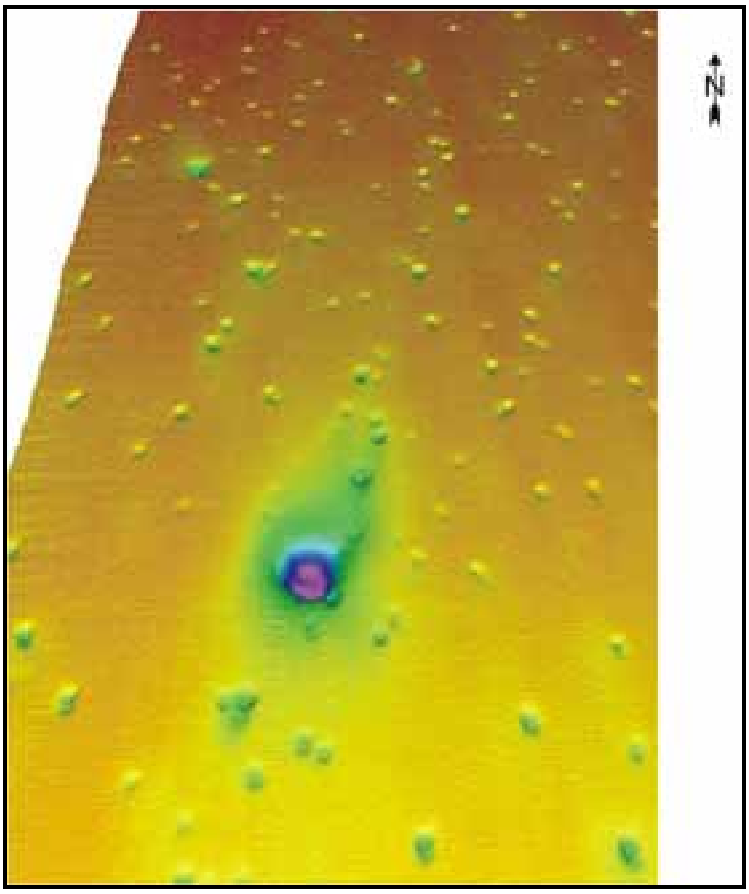


Image 8. Detail from Survey Area 4

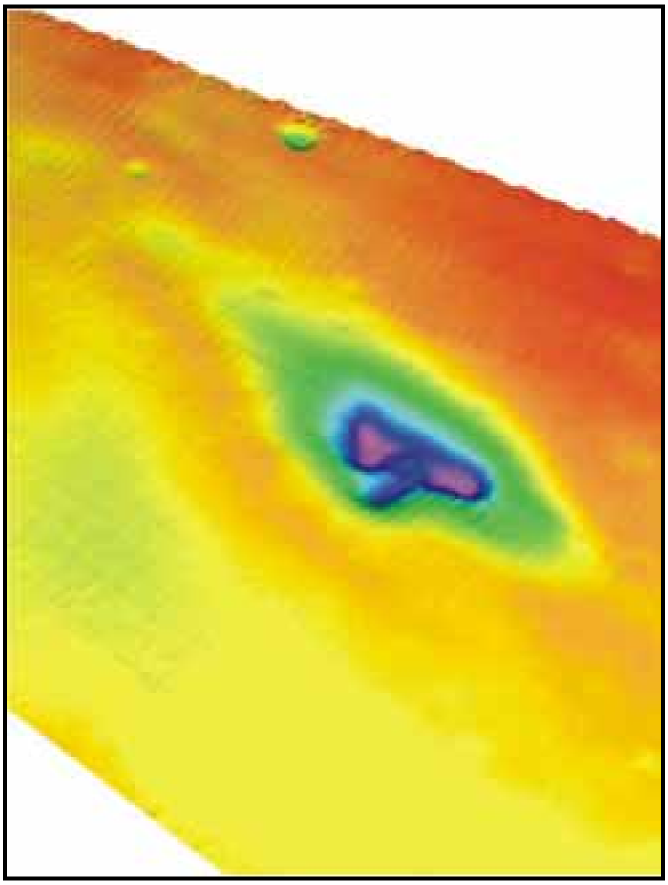


Image 9. Detail from Survey Area 5

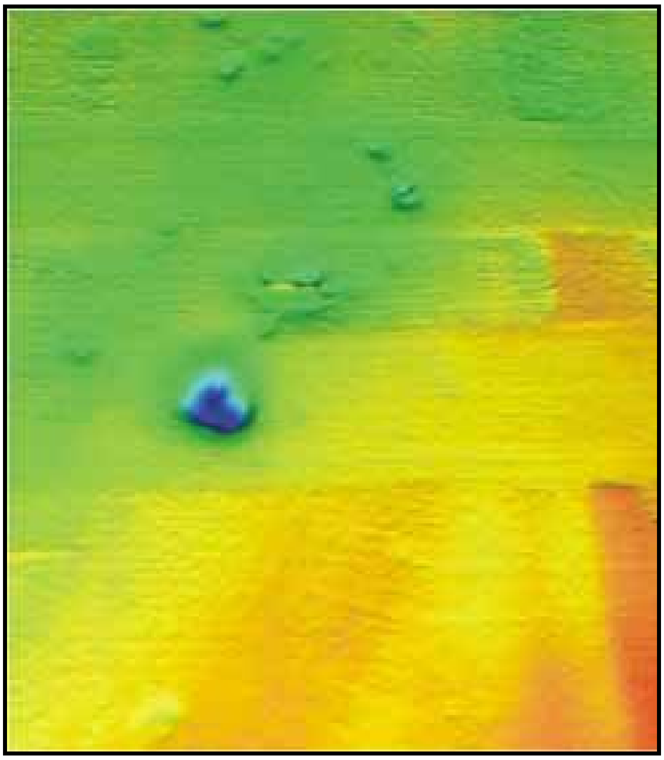


Image 10. Detail from Survey Area 6

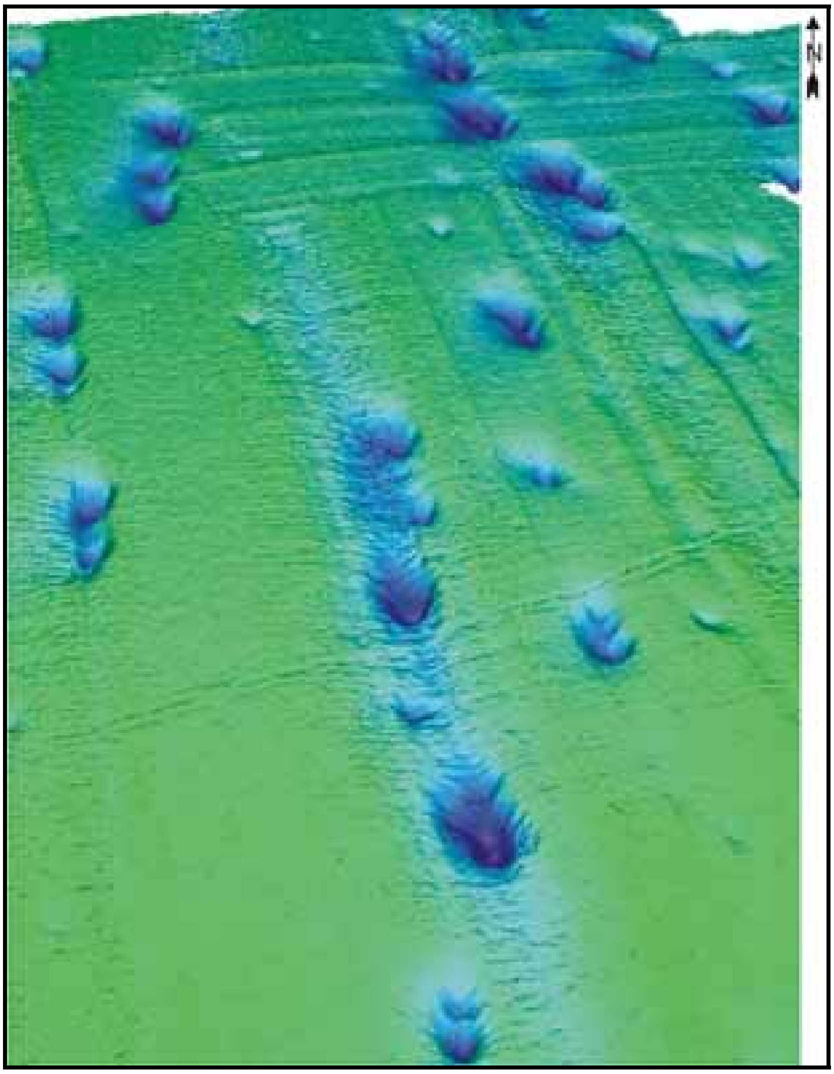


Image 11. Detail from Survey Area 7

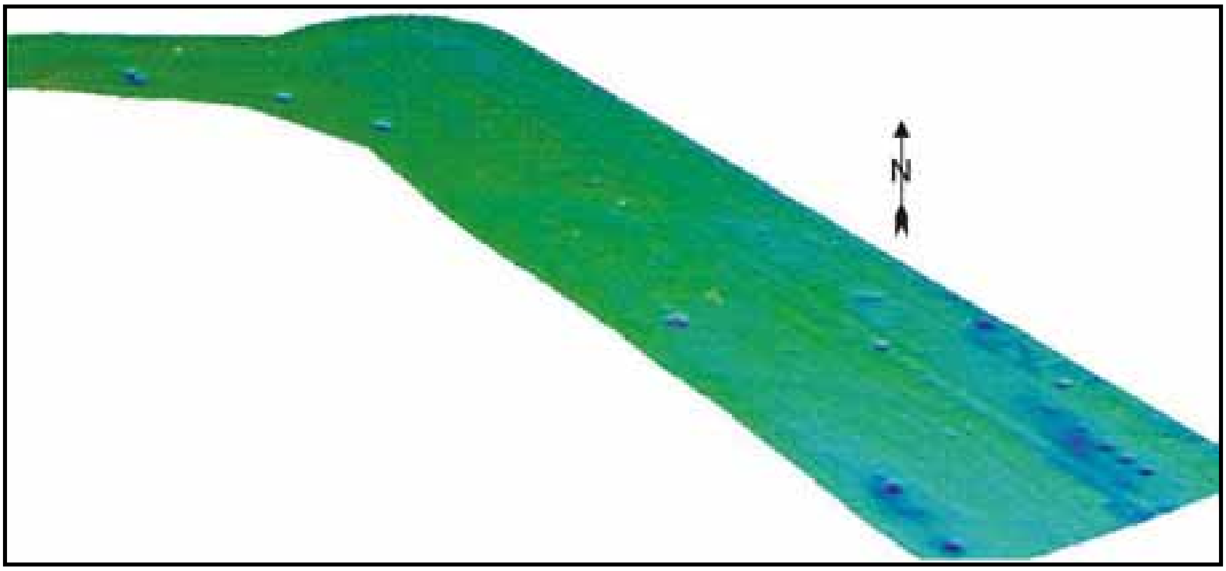


Image 12. Survey Area 8

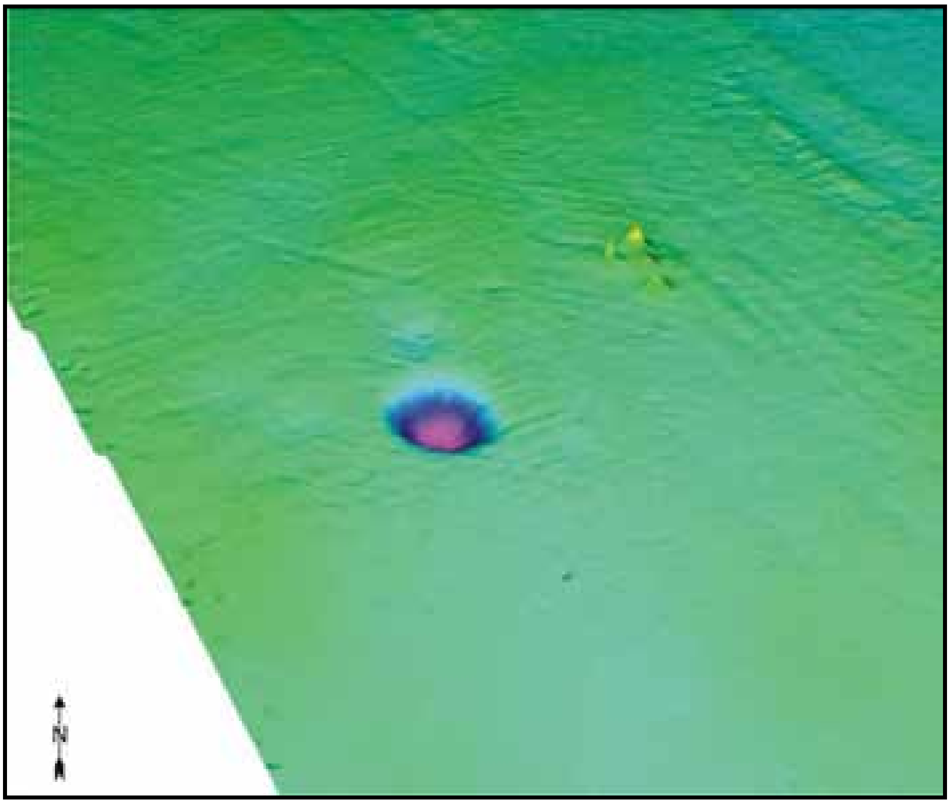


Image 13. Detail from Survey Area 8

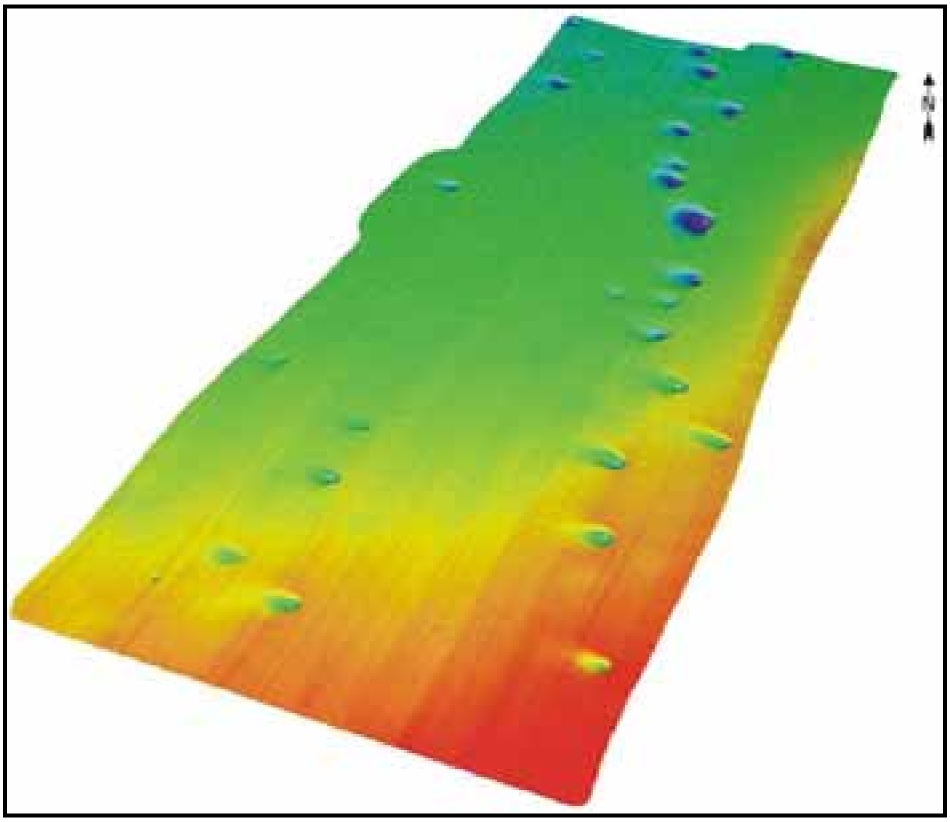


Image 14. Survey Area 9

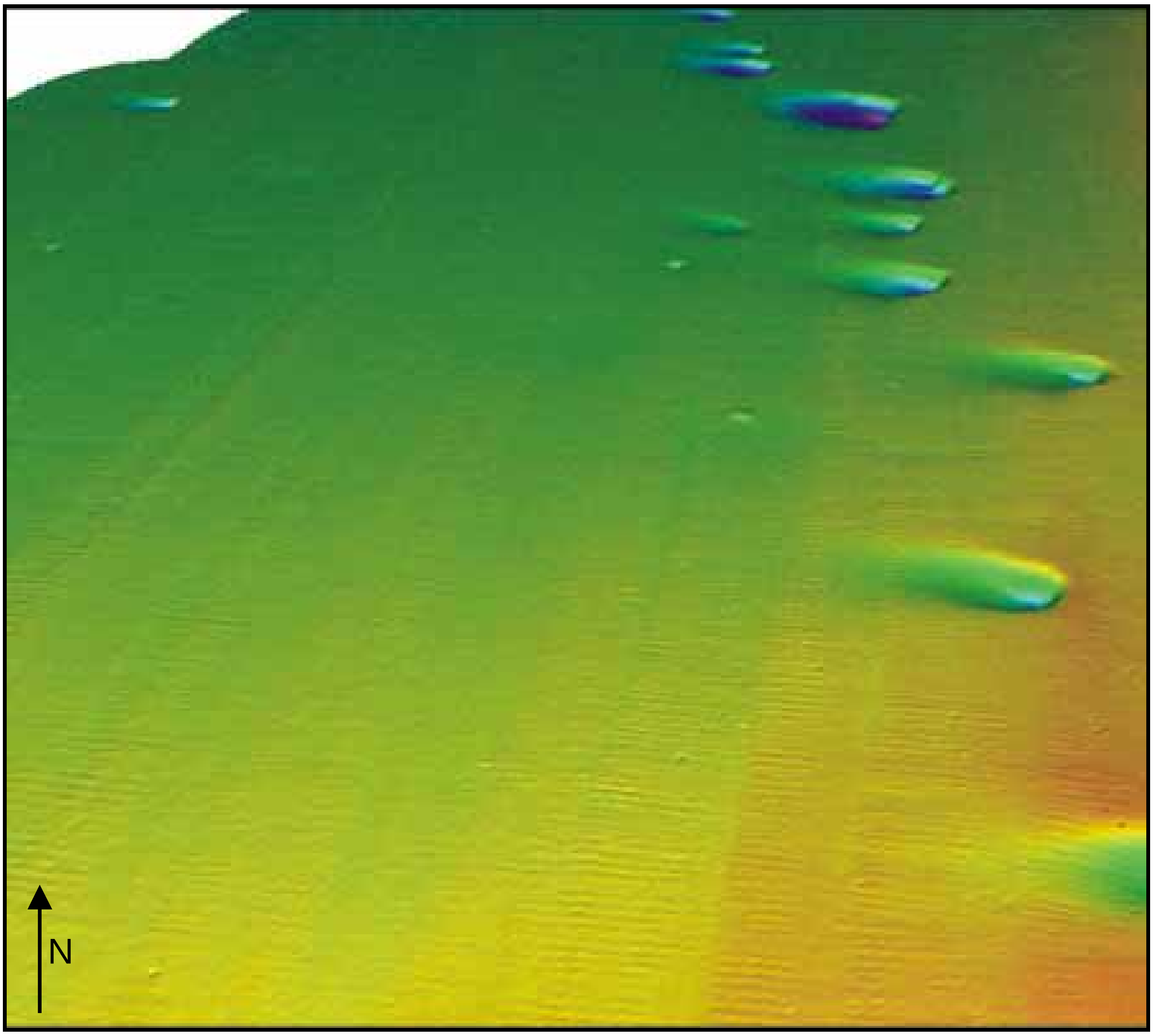
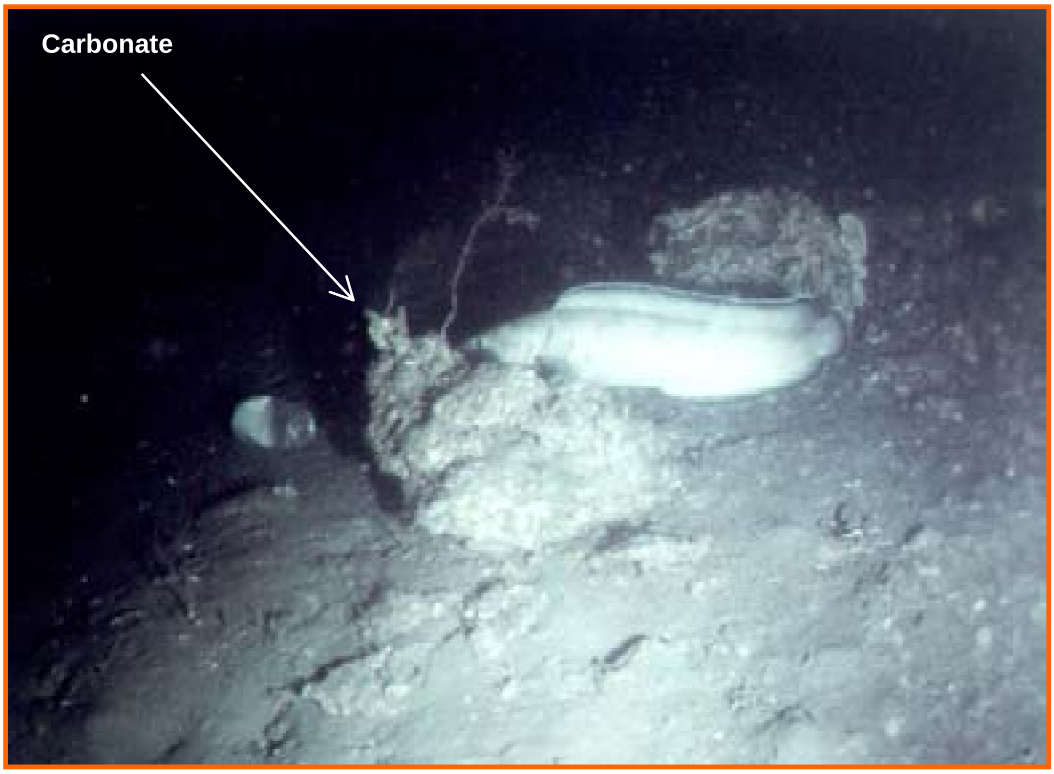


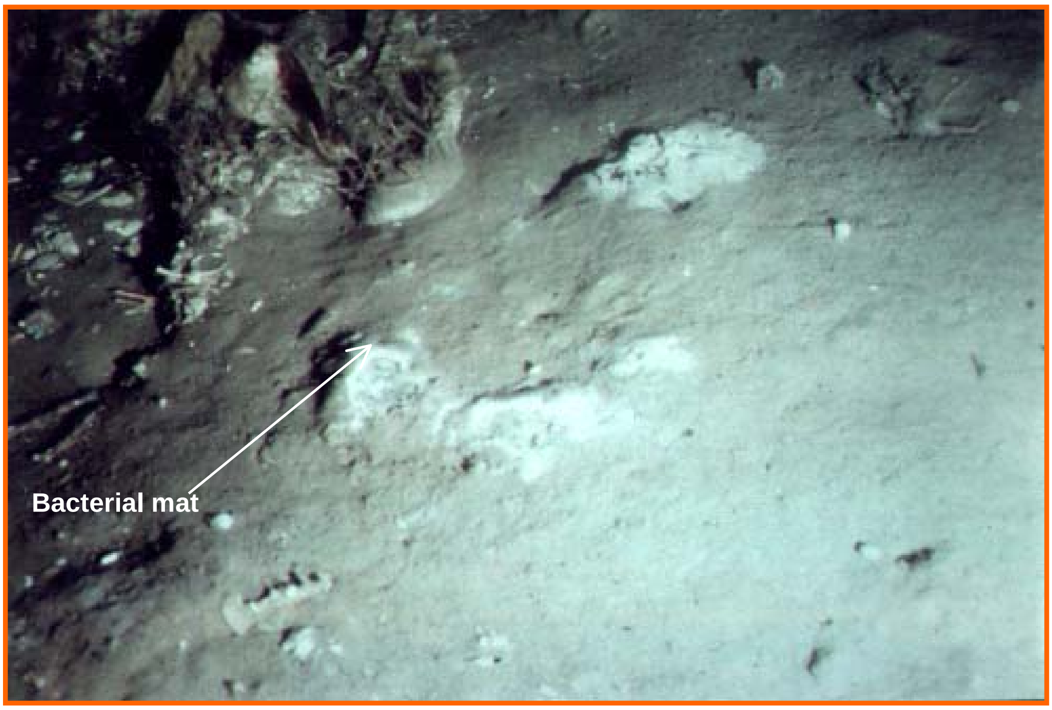
Image 15. Detail from Survey Area 9

APPENDIX II
Seabed Photographs (courtesy of Statoil)

Photograph 1 ***NO Block 25/7***

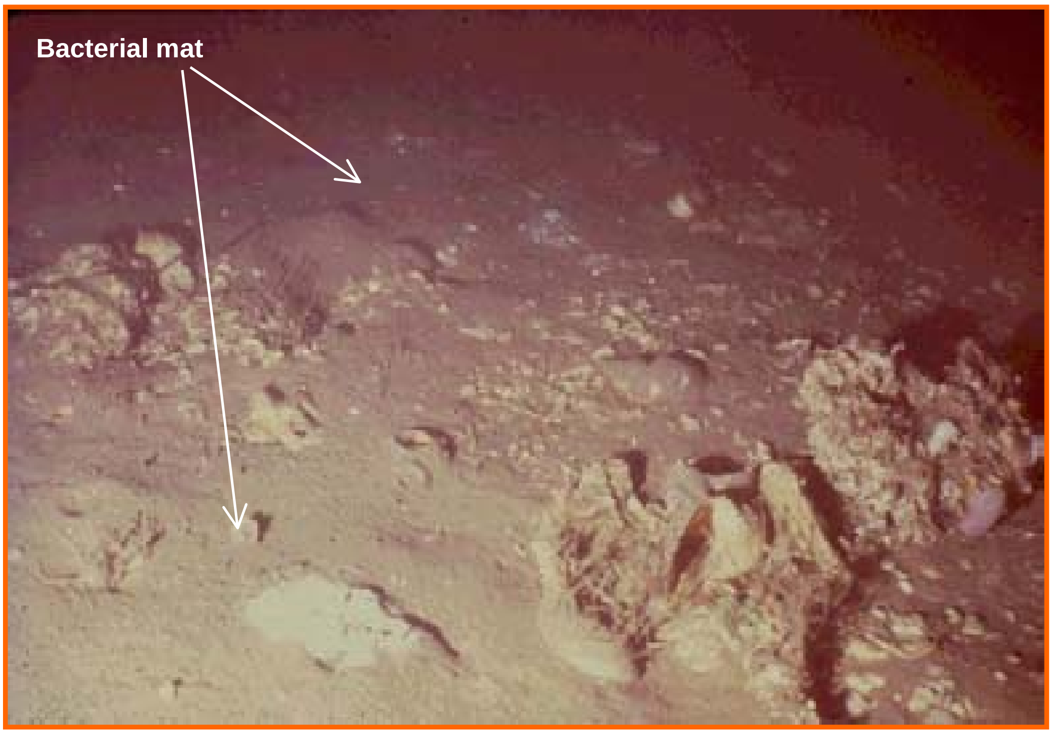


Photograph 2 ***NO Block 25/7***



Photograph 3 ***NO Block 25/7***

Photograph 4 ***NO Block 25/7***

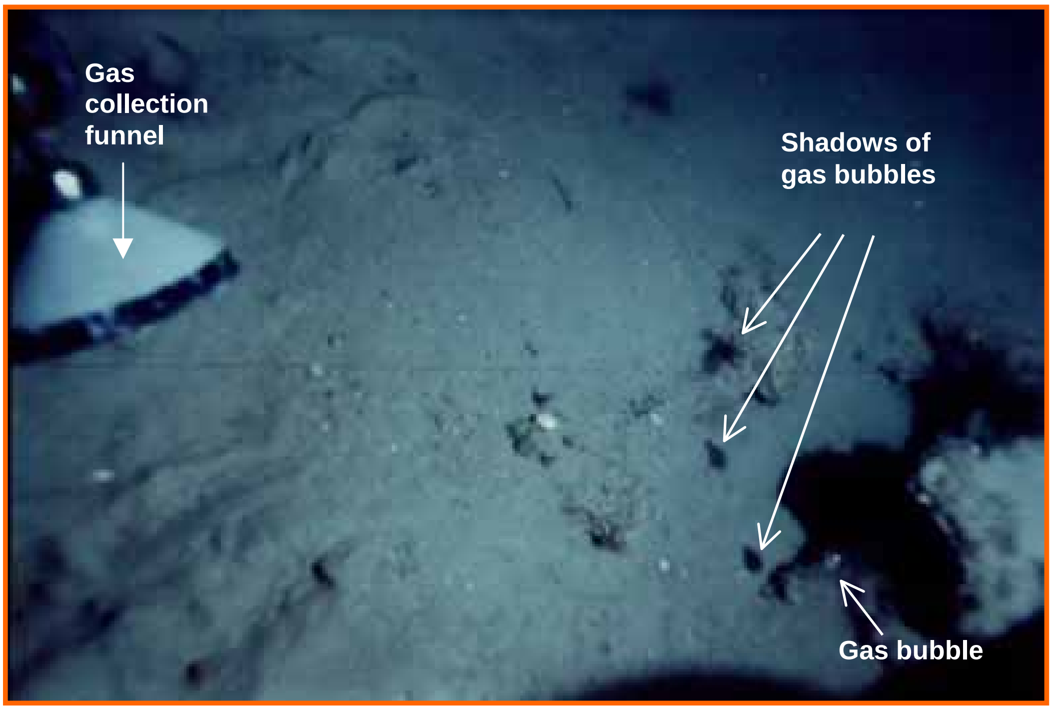


Photograph 5 ***NO Block 25/7***

Photograph 6 ***NO Block 1/9 - Tommeliten***

Photograph 7 ***NO Block 34/10 - Gullfaks***

Photograph 8 ***NO Block 26/9***



Photograph 9 ***UK Block 15/25***

Photograph 10 ***UK Block 15/25***

Photograph 11 ***UK Block 15/25***

Photograph 12 ***UK Block 15/25***

APPENDIX III
Survey Operations in the Fladen Ground

INTRODUCTION

This appendix summarises the methods during the K_Jack Pockmark Survey for undertaken for SEA2 in April 2001.

METHODS

Instrumentation

Geophysical surveying has been undertaken using the following equipment (operated by OSAE from the survey vessel '*Kommandor Jack*'):

Swath Bathymetry:	Simrad EM1002
Side scan sonar:	Geoacoustics 159
Sub-bottom profiling:	Datasonics Chirp profiler
Positioning:	DGPS

SURVEY OBJECTIVES

To acquire data from a several pockmark sites that will:

- enable pockmark characteristics to be determined
- shed light on pockmark ages and formation processes
- distinguish between active and inactive pockmarks
- identify pockmarks from which gas is actively seeping, and in which there is a probability of methane-derived authigenic carbonate and associated benthic communities.

SITE SELECTION CRITERIA

- Location: must be inside SEA2 area
- Targets must enable survey objectives to be achieved – collectively providing a range of information (rather than visiting several sites which all seem to offer the same 'information')
- Probability of locating a suitable target: dependent upon reliability of description available from previous data
- Possibility of acquiring additional data (from previous future or surveys)
- Location logistics - requiring minimum transit time between sites

Sites have been selected on the basis of available data, including advice from BGS who trawled through their archive of site survey reports for Quadrants 14, 15 and 16. The advantage of surveying sites that have already been covered by commercial surveys is that it may be possible to access additional data (e.g. seismic profiles providing greater penetration than the Chirp profiler).

SELECTED SITES

Survey Area 1: Witch's Hole - blocks 21/3 – 21/4

Data source: BGS surveys 1977/78
Objectives:

- map the pockmark
- map surrounding area to compare Witch's Hole with other pockmarks in the area (is it unusually large?)
- map shallow gas distribution (has it migrated since 1978?)

Survey Area 2: South Fladen Pockmark study area (northern part) – Block 15/28

Data source: BGS survey 1977/78
Objectives:

- to test the hypothesis that pockmarks are 'fossil' features by comparing pockmark distribution with those mapped in 1977/78 (by BGS)
- to use this well documented area as a 'standard' with which to compare other parts of the Witch Ground.

Survey Area 3: Block 22/1

Data source: seabed features chart of rig site survey – 22/1b – J (by Geoteam –Wimpol for Amoco, Nov. 1995) supplied by BGS.
Objectives:

- to investigate 3.5km long string of large (2 of which >400m by 100m by >4m deep)

Transit Area 3/4: Block 16/26

Data source: Site survey report for well 16/21a-8 held by BGS.
Objectives: to survey an unusually large pockmark.

Survey Area 4: Block 15/25

Data source: several previous surveys, including by ROV.
Objectives:

- to provide detailed side scan and swath bathymetry coverage of pockmarks to aid interpretation of existing video and therefore the extent of gas seeps and methane-derived authigenic carbonates
- to find out whether or not gas seeps are still active, and if so, to provide standard seep plume signatures against which data from other sites may be compared.

- to provide a map backscatter strength at a pockmark known to have methane-derived carbonates (a 'standard' for use with the other sites)

Transit Area 4/5: Block 15/19

Data source: site survey reports held by BGS (Ref. SO/93/57)
Objectives: to survey an unusually large pockmark that appears (from deep towed boomer a profile supplied by BGS) to be comparable to those in Block 15/25.

Survey Area 5: Blocks 15/19 & 15/24

Data sources: site survey reports held by BGS (SO/89/314; SO/91/52 & SO/92/31)
Objectives:

- to cover two (or three) locations in one
- one location appears on side scan sonar data (provided by BGS) to be a pockmark with a hard target in the centre.
- one location appears on side scan sonar data (provided by BGS) to be a pockmark with a positive target in the centre

Survey Area 6: Block 15/14

Data source: site survey report held by BGS (SO/92/68)
Objective: to investigate a site described as "*active gas seepage on mound 3.5m high; numerous mini pockmarks on mound*"; a contrast to other sites.

Survey Area 7: Blocks 14/20 and 14/25

Data source: seabed features chart of rig site survey – 14/25a-B (by Geoteam for Shell Expro, 1991) supplied by BGS, plus personal data.
Objective: to investigate an area in which a significant number of 'active' pockmarks was reported.

Survey Area 8: Block 15/21

Data source: site survey report held by BGS (SO/92/61)
Objective: to investigate a pockmark reported to contain a 20m diameter area of carbonate; it appears on side scan sonar data (supplied by BGS) as a pockmark with a large hard target in the centre.

Survey Area 9: Block 14/29 and 20/4

Data source: seabed features chart of rig site survey – 14/29a -G (by Fugro-Geoteam for Shell Expro, June-July 1997) supplied by BGS.
Objectives: to investigate a string of pockmarks – including 2 >500m long, of which one is 7m deep

SYNOPSIS OF RESULTS

Introduction

The following is intended as nothing more than a preliminary review of the results of the surveys conducted in Area 3. A more detailed analysis is required.

As the most obvious indications of the presence of 'structures associated with leaking gas' are pockmarks, high reflective seabed and gas seepage plumes, preliminary reviews of the data have been largely focussed on looking for evidence of these.

Survey Area 1: Witch's Hole - Blocks 21/3 – 21/4

Data confirm that the Witch's Hole is remarkably different from all other pockmarks in Survey Area 1 (SA1). Indeed, very few pockmarks with this character (i.e. a central depression surrounded by a dense scattering of small 'unit' pockmarks) have been seen during the Area 3 surveys.

3D images show that the wreck (previously documented) lies in the centre of this pockmark.

A detailed comparison of these data with the BGS data acquired in 1977/78 is required in order to ascertain whether or not lateral migration of shallow gas has occurred in the intervening 23 years. This will provide a valuable indication of whether or not gas migration occurs on a time scale relevant to the offshore operations of the oil industry.

Survey Area 2: South Fladen Pockmark study area (northern part) – Block 15/28

Complete coverage of SA2 has been acquired. Initial inspection shows that, although there is some variation in size, there are no unusually large pockmarks in this area.

The data from this area provides a standard against which other 'normal' pockmark areas can be compared.

A detailed comparison of these data with the BGS data acquired in 1977/78 is required in order to ascertain whether or not any new pockmarks have been formed in the intervening 23 years. This will provide a valuable indication of whether or not pockmark formation occurs on a time scale relevant to the offshore operations of the oil industry.

Survey Area 3: Block 22/1

A string of large (90 – 315m long, 40 – 100m wide), deep (5 – 6m) pockmarks is aligned approximately SW-NE in the centre of this survey area. They all deepen towards the NE end. The string does not extend to the west of the original site survey area, but does extend to the east (beyond the present survey).

Transit Area 3/4: Block 16/26

This was a limited search – using swathe bathymetry and Chirp profiler only – for 'anomalous' pockmarks at a site identified by BGS. As no large / deep or unusual pockmarks where found the site was abandoned without deploying the side scan sonar.

Survey Area 4: Block 15/25

An extensive survey of this SA was conducted, and then detailed cross lines of selected pockmarks were added in order to provide the best possible detail of these pockmarks, and to assess whether or not it is possible to use multibeam backscatter mapping to identify areas with methane-derived carbonate.

Although much of this area has been surveyed before, and detailed studies (including visual seabed surveys) have been conducted on one of the pockmarks, this survey has provided invaluable data. Firstly, the detailed bathymetric mapping has provided the best maps, and some excellent 3D images. Secondly, the uncorrected side scan sonar images of gas plumes rising from the pockmarks are excellent.

Backscatter mapping was attempted. However, the natural variability in the data was such that no reliable conclusions can be drawn from the 2 m by 2 m grid data.

Another approach to backscatter mapping to identify carbonate distribution is to map the amplitude of the seabed return from the Chirp data. This would be possible as a post-cruise exercise using the SEGY data on a seismic workstation.

A protocol was established for identifying water column gas plumes.

The bathymetric data from these pockmarks provide a standard against which other pockmarks, thought to be active, can be compared.

Finally, the most northerly cross lines were run in order to investigate a pockmark which has the same speckled appearance as the Witch's Hole. From the two side scan sonar lines crossing this feature it is clear that there is an object in it. However, it is not very clear what it is (possibly a wreck?).

Transit Area 4/5: Block 15/19

A short survey was made of a single pockmark.

Survey Area 5: Blocks 15/19 & 15/24

The presence of a drilling rig and an FPSO at one end of the proposed survey area meant that the survey had to be restricted to one of the sites of interest, at the north end of the proposed survey area.

The reduced survey identified a single pockmark with the following approximate dimensions: 400m long by 170m wide by 7m deep. This feature is aligned approximately North-South. There were no indications on the uncorrected side scan sonar of gas bubble plumes in the water above this feature.

Survey Area 6: Block 15/14

This area has numerous small (<50m across, <2m deep) pockmarks. Also, there is a much larger pockmark: approximately 120m long, 90m across and 5 – 6 m deep. In appearance this feature resembles the Witch's Hole – and in the centre there is a sonar target which includes items standing <7m above the seabed. This may be a wreck approximately 58m long and 16m broad. Using less discriminating sonar and echo sounding equipment this object may appear as a mound (as was described on the site survey report).

Survey Area 7: Blocks 14/20 and 14/25

Active pockmarks had been reported from the north, but not the south of SA7. In this survey it was hoped that any differences between the north and south could be identified, and pockmark activity confirmed.

In the south of this area is a plateau (water depth <130m) on which there are no pockmarks. To the north of this plateau pockmarks are present (generally <100m by <300m by 2 – 4m). They tend to deepen towards the north. The underlying reasons for this will be investigated by examining the bathymetric and chirp data after the survey.

Detailed reviews of the uncorrected side scan sonar data revealed no indications of gas in the water column.

A seabed feature, probably a well head, apparently leaking gas was located at 58°22'00" N 0°00'52"W.

Survey Area 8: Block 15/21

A single pockmark, reported to have an exposure (20m in diameter) of carbonate, was the target for this survey. A few pockmarks were located. No unequivocal evidence of 'hard ground' was identified, but a target, probably the pockmark identified in the site survey) was selected for sampling.

A seabed feature, probably a well head, apparently leaking gas was located at 58°16'15" N 0°09'44"E, and the survey area includes a seabed well head (template).

Survey Area 9: Blocks 14/29 and 20/4

The large, deep pockmarks shown on the site investigation seabed features chart are remarkable in that they are virtually impossible to detect on the side scan sonar because of the gentle topography. The nature of the seabed has yet to be confirmed by inspecting the chirp profiles.

Transit Lines

During transits between survey areas the chirp profiler and swath bathymetry systems have been kept running and recording. It is hoped that the resultant data will provide valuable information about the context of the detailed surveys.

OVERVIEW

During the survey a great deal of high quality data was acquired. No direct evidence of new gas seeps and associated 'structures' was located, however the understanding of the distribution of sites at which such structures are likely to occur has been greatly improved. The following 'highlights' are noted:

- Whilst it is clear that the active pockmarks in SA4 are exceptional. It is also apparent that most areas have a few anomalous large / deep pockmarks. It seems that pockmarks can be divided into two categories: 'normal' – the vast majority [relatively small, apparently inactive]; and 'anomalous' – the interesting majority [large and deep]. At least some are actively seeping gas and (probably) contain methane-derived carbonates.
- The orientations of pockmarks seem to vary from place to place. This may be indicative of the pockmark formation process.
- Shallow gas (i.e. *very* shallow gas – as the penetration of the chirp profiler is effectively limited to the Witch Ground Formation) was seen only in the vicinity of the Witch's Hole (SA1).
- Numerous features which may affect fluid migration, and hence seepage activity, have been noted for future analysis. The possibility that the seabed reflection amplitude is indicative of the presence of carbonates requires some investigation.

The possible discovery of one or maybe two other wrecks in the middle of pockmarks is quite remarkable. Does this suggest that seeping pockmarks sink ships, or that sinking ships cause pockmarks?