5 PHYSICAL AND CHEMICAL ENVIRONMENT

5.1 Regional overview

The physical and chemical environment of the SEA 5 area has been shaped largely by the complex interaction of past geological and glacial processes with more recent hydrological and meteorological conditions. Generally, direct anthropogenic contamination is low and restricted largely to industrialised coastal areas.

The overall topography of the SEA 5 area is characterised by a relatively flat seabed which deepens to the north and east with localised depressions and topographic highs. It is bounded to the west by the continental shelves of Shetland, Orkney and the Scottish mainland and to the north and east by the deeper basins of the Viking and Central Grabens. The coastal boundary is dominated by the large scale firths and estuaries which cut into the east coast and the numerous islands of the Orkney and Shetland archipelagos.

The smaller scale seabed landscape is a relic of several glacial periods when large volumes of material were eroded from the adjacent mainlands and from the continental shelf itself. The bulk of modern seabed sediments comprise substrates that are more than 10,000 years old and have been reworked by tidal currents and waves. These typically form large areas of seabed sand and gravel, and may also form large scale sandbanks and ridges and smaller sand waves. Finer silts and muds are restricted largely to bathymetric deeps and very sheltered coastal areas.

A number of significant seabed features and bedforms present within the SEA 5 area were investigated by the DTI 2003 seabed survey programme, including Pobie Bank, Fair Isle, the Sandy Riddle, Smith Bank and the Southern Trench. Significant new information regarding the topography and substrates of these areas was collected.

The climate and hydrology of the area is strongly influenced by weather systems and water flow from the North Atlantic. Large scale westerly air circulation, frequently containing low pressure systems predominates in the area. This influence is variable and long-term changes in the strength and persistence of westerly winds are influenced by the winter North Atlantic Oscillation (NAO), a pressure gradient between Iceland and the Azores.

Water circulation is dominated by significant inflows of Atlantic water across the SEA 5's north west boundary where it mixes with North Sea and coastal waters. Inflow variability associated with NAO related atmospheric forcing can result in significant seasonal and annual changes to circulation patterns and water masses with profound implications for the circulation of nutrients and contaminants, and for the supply of oceanic planktonic species and fish larvae.

Maximum surface tidal streams which vary from 0.25 to 0.5m/s over much of the offshore area are strongest in shallow coastal areas and in excess of 1.0m/s on the Orkney-Shetland Platform. Density stratification is well developed throughout much of the SEA 5 area in the summer months, breaking down in autumn due to increased frequency and severity of storms and seasonal cooling at the surface.

In general, coastal and offshore waters of SEA 5 do not show significant anthropogenic contamination. The offshore area has been subject to lower historical and current inputs of hydrocarbons than the mature oilfield areas considered in SEA 2, and the heavily industrialised coastal areas of SEA 3. Other contaminants including heavy metals and persistent compounds such as PCBs are also generally at low levels, although particular areas may display localised elevations associated with historical inputs.

5.2 Geology, substrates and coastal geomorphology

5.2.1 Overview

Technical reports produced by British Geological Survey (BGS) for previous SEAs provided information on the deep geology of the North Sea (BGS 2001, 2002). Information was also provided by the relevant BGS UK offshore regional reports (Andrews *et al.* 1990, Gatliff *et al.* 1994, Johnson *et al.*1993). To support the SEA 5 process, a survey programme was commissioned by the DTI to investigate particular seabed features within the SEA 5 area. Further information on the surficial geology and processes was also provided by a BGS report commissioned for SEA 5 (Holmes *et al*. 2004).

The North Sea Oil Province is one of the world's major oil-producing regions. Commercial petroleum reservoirs occur in almost every sedimentary succession ranging in age from approximately 410-360 million years (BGS 2001). The geological history of the oil province was dominated by an episode of late Jurassic to earliest Cretaceous crustal extension, which developed the Viking Graben, Moray Firth and Central Graben rift systems. Organic-rich marine mudstones (Kimmeridge Clay Formation) are the source rocks for virtually all of the region's hydrocarbons (DTI 2003).

The overall modern topography of the North Sea seabed originates from the influences of the deep geological structure on the patterns of basin subsidence, uplift and climate on sediment input. The smaller scale seabed landscape is a relic of several glacial periods when large volumes of material were eroded from the adjacent mainlands and from the continental shelf itself. This material was then re-deposited on the shelf or in the deeper waters on the adjacent continental slope. The modern sedimentary environment of offshore areas of the North Sea continental shelf is now dominated by very low sediment input and the reworking of the seabed by near-bottom currents (BGS 2001).

5.2.2 Deep geology

The configuration of crystalline and metamorphic basement rocks that underlie the North Sea sedimentary basins was assembled during the Caledonian Orogeny (about 420-390 million years ago) to form the Caledonian basement. Many of the major faults within the Caledonian basement formed lines of weakness that experienced significant reactivation during subsequent phases of earth movements. The major geological events that have affected the central and northern North Sea area since the Caledonian Orogeny are described in Table 5.1.

Table 5.1 – Major geological events since the Caledonian Orogeny	
Devonian (410-360Ma)	Major phase of faulting took place 388-362Ma forming basins, including the Orcadian Basin extending what is now the Moray Firth, Caithness and the Orkney Islands and the Forth Approaches Basin. The Orcadian Basin was filled by non-marine, red sandstone (Old Red Sandstone) and lacustrine (lake-filling) sandstone and mudstone. Some of the mudstones have been considered as potential hydrocarbon source rocks.
Early Carboniferous (360-325Ma)	In the Forth Approaches and Outer Moray Firth basins sedimentation continued into the Carboniferous (<360Ma) and included deposition of deltaic coal-bearing and shallow marine strata.

Table 5.1 – Major geological events since the Caledonian Orogeny	
Permian (290-248Ma)	During the early Permian (290-256Ma) the East Fair Isle, East Orkney, Inner Moray Firth and Forth Approaches basins were filled by non-marine, red sediment (New Red Sandstone). By the late Permian (256–248Ma), following a marine transgression, marginal and shallow marine sediments covered most of the SEA 5 area. In the farthest offshore areas salts were deposited from seawater that was evaporating in an arid environment. These rocks have been deformed by halokinesis (salt processes) intermittently since mid-Triassic times, leading to the widespread growth of salt pillows and salt diapirs, especially in the central North Sea.
Triassic (248-205Ma)	Rejuvenation of faulting and a return to non-marine sedimentation over much of the area.
Jurassic (205-145Ma)	During the Early Jurassic (205-180Ma), spread of marine deposits over much of the North Sea during a phase of thermal subsidence following Permo-Triassic rifting. In the mid-Jurassic (180–160Ma) continuing transgression led to non-marine, then coastal and then marine sediments being deposited in the northern North Sea and Moray Firth areas. In the late Jurassic (160–142Ma) major phase of extensional faulting resulted in formation of the main North Sea sedimentary depocentres, the Viking Graben, Moray Firth Basin and Central Graben, all of which contain significant hydrocarbon reserves.
Cretaceous (145-65Ma)	Period of local strike-slip faulting and salt diapirism.
Cenozoic (65Ma-present)	Thermal subsidence in response to Late Jurassic rifting, dominated much of the Cenozoic. In the early Paleogene (approximately 65-50 million years ago), huge volumes of sediments were shed from the uplands of northern Scotland and the Orkney-Shetland Platform, which were undergoing thermal uplift, into North Sea basins. Later these uplifted areas became centres of ice accumulation and facilitated the expansion of the major ice sheets into the North Sea.

Source: Holmes et al. (2004), Andrews et al. (1990), Gatliff et al. (1994), Johnson et al. (1993).

Petroleum geology

The Kimmeridge Clay Formation (more than approximately 140Ma old) is the principal hydrocarbon source rock of the central and northern North Sea. The majority of oil and gas fields in the hydrocarbon provinces to the east and adjacent to SEA 5 were charged from this prolific source (Cornford 1998, cited by Holmes *et al.* 2004).

Producing fields in the East Shetland Basin and the Beryl Embayment have reservoirs of Lower-Middle Jurassic age. In the Viking Graben, the producing reservoirs are dominantly Upper Jurassic deep-marine sandstones. Paleogene reservoirs are also developed in the East Shetland Basin, Beryl Embayment and South Viking Graben. The Paleogene play remains highly prospective and extends into basin-marginal areas such as the East Shetland Platform, where Middle Devonian lacustrine sediments may provide an additional source of oil (DTI 2003).

The Beatrice Field in the Inner Moray Firth is the only reservoir in the SEA 5 area currently producing oil. The field is producing oil from uppermost Triassic to uppermost Jurassic sandstones but the main reservoir sands are mid-Jurassic in age (Holmes *et al*. 2004). The main reservoir is sealed by shaly mudstone and the trap is a northeast- trending, tilted fault block that formed as a result of Upper Jurassic faulting (Thomson & Underhill 1993, Davies *et al.* 2001, cited by Holmes *et al.* 2004).

Within the Central Graben, producing fields with reservoirs of Triassic to Lower Jurassic age are typically thick, highly feldspathic, fluvial channel and sheetflood sandstones. The pinch-out of Upper Jurassic shallow marine sandstones at the margins of the Central Graben continues to provide an attractive exploration target (e.g. Buzzard discovery). Paleogene reservoirs in the Central Graben occur in both structural and stratigraphic traps (DTI 2003).

5.2.3 Seabed topography

The present day seabed around Shetland slopes steeply from coastal cliffs down to shelf depths of approximately 80m. Water depths then deepen northwards and eastwards across the North Sea plateau. Banks or topographic highs such as Pobie Bank (see Section 5.2.5), to the east of Shetland are generally restricted to a zone of 80-100m water depth. Sea floor depressions occur locally to about 160m depth and include a number of small basins east of Pobie Bank (Johnson *et al.* 1993).

The channels between the islands of Orkney are relatively shallow, often less than 20m depth. To the north and east of the islands, the seabed slopes gently down to approximately 50-60m depth, gradually deepening to 100-120m further out on the Orkney-Shetland platform. In the Pentland Firth, the seabed reaches approximately 60m and is scoured of surface sediments by strong tidal currents. At the eastern entrance of the Firth, a large sand bank, the Sandy Riddle, rises to 60m above the seabed (see Section 5.2.5).

The seabed of the Moray Firth is generally smooth, with water depths in the western part reaching some 50-70m, and deepening eastwards to about 150m over the Witch Ground. A series of deeps occur from the north Aberdeenshire coast out into the northern North Sea; these vary in orientation and are cut to more than 200m below sea level. The largest of these, the Southern Trench (see Section 5.2.5), runs parallel to the coast. There are a number of banks, including Smith Bank (see Section 5.2.5) which rises to over 30m above the surrounding seabed (Andrews *et al.* 1990).

Nearshore areas off the Scottish east coast slope gently to an extensive and generally flat platform. Water depths across the platform range from 70-100m, but the area is cut by many unfilled incisions, notably the Devil's Hole which is over 220m deep. A number of banks are found within 50km of the coast (Gatliff *et al.* 1994).

5.2.4 Seabed substrates

This section broadly describes the sediment types and their distribution in the SEA 5 area; the potential conservation importance of a number of associated offshore habitats, and the substrate distributions found in the major firths and estuaries of the area.

Broadscale seabed sediment distribution in the SEA 5 area is shown in Figure 5.1. The bulk of modern seabed sediments comprise substrates that are more than 10,000 years old and have been reworked from strata by currents generated by tides and waves. The reworked sediments typically form large areas of seabed sand and gravel, and may also form large-scale sandbanks and ridges and smaller sand waves.

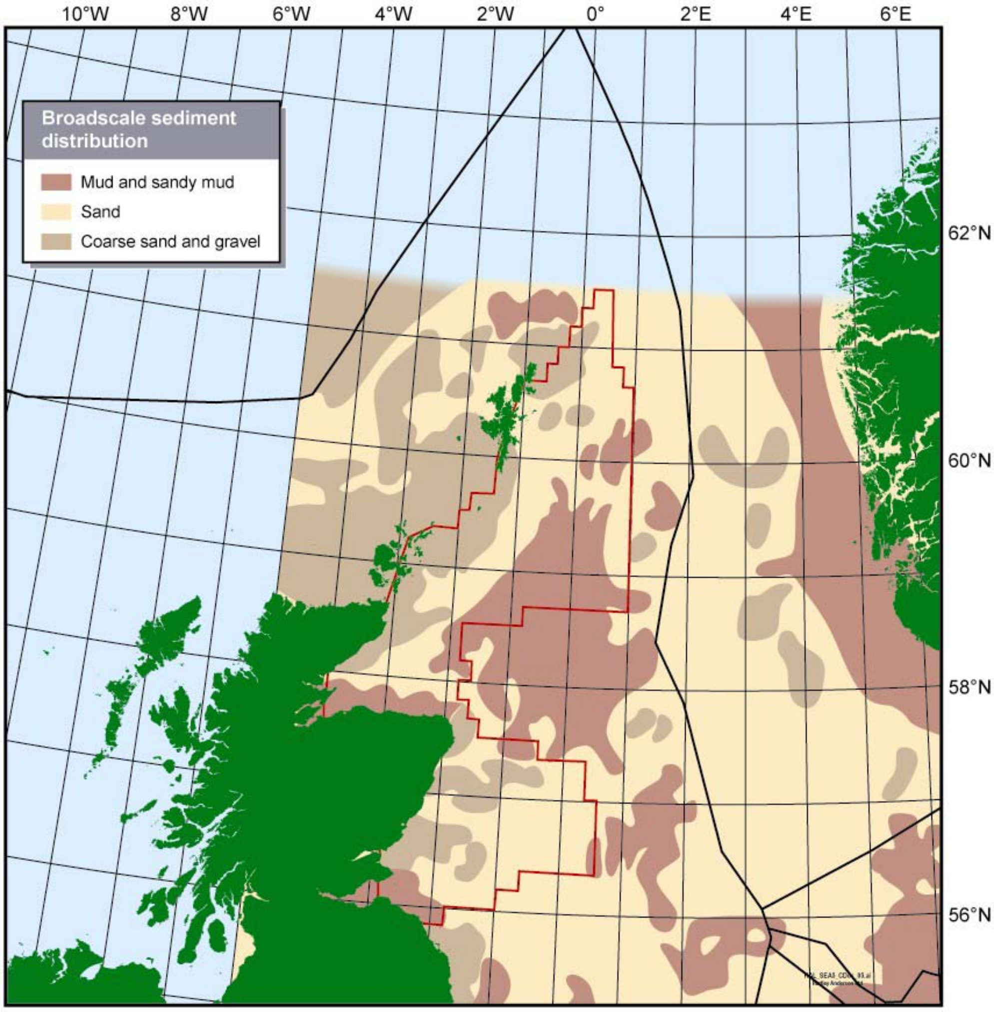
Gravel

Gravel spreads mostly occur in nearshore areas of Shetland and Orkney with very strong tidal and wave driven near-bottom currents. Granular to pebble size classes of gravel are probably mobile during peak tidal currents and storm waves but are virtually static in areas below wave-base (Pantin 1991). In the Moray Firth, there is a large area (greater than 100km^2) of gravel off the mouth of the River Spey at Lossiemouth which fines eastwards; smaller patches are also present along the northwest coast of the firth (Andrews *et al.* 1990).

Gravelly sand and sandy gravel occur extensively to the north of Shetland, on the Orkney-Shetland Platform, and on upstanding areas to the east of Shetland; isolated patches are found on Bressay Bank and Halibut Bank. The DTI 2003 survey found sediments around Fair Isle comprised typically coarse to very coarse calcareous sand and gravel with a mean gravel content of approximately 40%. The gravel content of sediments collected from the Sandy Riddle commonly exceed 50%, and comprised broken as well as whole shells (Black 2004). Sandy gravel also occurs on Smith Bank where the gravel is predominantly biogenic. A tongue of well sorted sandy gravel extends northeast from Rattray Head and further south, gravelly sediments are restricted mainly to offshore banks, notably the Marr and Aberdeen Banks (Gatliff *et al*. 1994).

Areas of 'gravel', according to the BGS modified Folk classification, include any solid particles from 2mm diameter to greater than 256mm diameter. In terms of the Wentworth classification, this category includes 'cobbles' and 'boulders', which would be included within the UK interpretation of definition of reef, but also includes 'pebbles' and 'granules' which do not fall within the definition. Potential Annex I reef habitat in offshore waters has been mapped using the areas of gravel and rock identified from BGS seabed sediment maps (Johnston *et al*. 2002).

Figure 5.1 – Broadscale seabed sediment distribution in the SEA 5 area



Source: OSPAR 2000 (after Eisma 1981)

Sand

Sand deposits in the northern North Sea exhibit significant regional variations in grain size, sorting and carbonate content. These reflect the spectrum of environments, from relatively high energy around Orkney and Shetland where there are sources of carbonate material to low energy further offshore where there is relatively little sediment input.

To the east of Shetland, a sand zone 40-60km wide occurs in water depths ranging from 100m to over 120m. The sand is mainly fine grained and well sorted, becoming moderately sorted northwards (Johnson *et al.* 1993). A broad, irregular swath of sand extends from 50km east of Fair Isle to 50km east of Peterhead. Sand and slightly gravelly sand covers much of the central North Sea and occurs within a wide range of water depths from the shallow coastal zone to 110m in the north and to below 120m in isolated deeps in the south and west (Andrews *et al.* 1990).

Mobile sandwaves and sandbanks occur throughout the SEA 5 area. Sandwaves and megaripples with maximum crest heights of between 3.5-7.3m occur between Orkney and Shetland (Flinn 1973, cited by Johnson *et al.* 1993), with their orientation around Orkney indicating a clockwise net sediment movement around the islands (Farrow *et al.* 1984). Sandwaves have also been mapped off Rattray Head (Belderson *et al.* 1971) and in the inner Moray Firth (Reid 1988, cited by Andrews *et al.* 1990). Off the northeast coast, areas of sandy sediment are characterised by sand ribbons, elongated sand patches and sand waves. Large sandwaves with average wavelengths of 200m and heights of up to 17m occur along the eastern coast of Aberdeenshire, where maximum tidal currents range from 0.6-1.3m/s. Further offshore, three large fields of sandwaves with wavelengths of between 160 and 270m and up to 8m in height have been mapped in areas to the north and west of Devil's Hole (Holmes *et al.* 2004).

Mud

In the northern North Sea, muddy sand occurs mainly as very large patches up to 50km across in water depths between 120-160m. There are also a number of smaller, isolated areas of muddy sediment within local bathymetric deeps and in the voes of Shetland (Johnson *et al*. 1993). Further south, sandy muds and muds occur chiefly in the outer Moray Firth where water depths exceed 120m. Muddy sediments are also found in the approaches to the innermost firths (Andrews *et al*.1990). In the Witch Ground Basin, to the east of the SEA 5 area, sediments grade with increasing water depth from muddy sand to sandy mud and then mud. In the central North Sea, muddy sand occurs within isolated, linear deeps such as those in the vicinity of the Devil's Hole (Gatliff *et al.*1994).

Firths and estuaries

In general, the coastal zone of the Moray Firth is covered with coarse sands and fine gravels which also dominate the entrance to the inner firths between Tarbat Ness and Culbin. Fine sands cover most of the offshore seabed down to a depth of about 50m, with muddy sands and sandy muds characterising the bathymetric depressions off the south coast. Muddy sediments are also found in shallower waters near the head of the firth (Hansom & Black 1996). Detrital carbonate sediments, mainly shell fragments derived from around Shetland and Orkney contribute to sediment deposits; contours of sediment carbonate content decrease from the north with localised tongues entering the Dornoch Firth and inner Moray Firth (Stapleton & Pethick 1996).

The present Tay Estuary is dominated by sands (Al-Dabbas & McManus 1987). From the Road Bridge eastwards to Broughty Ferry the north flank of the main channel consists of mainly well sorted fine sands with irregular patches of sands and gravels on the southern shore. Off the south coast, the coarse sand and fine gravel of the Newcome Shoal forms sand waves and dunes which reach to within 2.5m of the water surface at low tide (McManus *et al.* 1980). Coarse and medium sands dominate the main channel, with mussel *(Mytilus edulis)* beds to each side, shoreward of which are finer silts (McManus 1972). Medium to fine sands characterise the outer reaches of the estuary with gravels and clays on the channel floor. The channel shallows as the estuary mouth spits join to form the 'bar', with gravel giving way to coarse and medium sands (McManus *et al.* 1980).

Silts and clays predominate in the Forth Estuary, with coarser sands and gravels occurring where the estuary is constricted (Grangemouth Docks, Kincardine Bridge, Rosyth) and near the main channel close to the north shore. Large areas of fine material extend from the Kinneil and Skinflats mudflats. Within the Firth, mud and muddy sands predominate in eastern and central areas particularly off Edinburgh and between Inchkeith and Aberlady Bay. Deeper areas such as Mortimer's Deep contain muddy gravels. Much of the outer coast is underlain by clean sands (Firth *et al.* 1997).

5.2.5 DTI survey of specific seabed features

The DTI undertook an environmental survey of a number of seabed features in the SEA 5 area in the summer/autumn of 2003. Features investigated included Pobie Bank, Fair Isle, Sandy Riddle, Smith Bank and the Southern Trench. Data collected included multibeam bathymetry, sidescan sonar, reflection profiles, seafloor photographs and sediment samples. St. Magnus Bay and Braer West, areas off the Shetland coast affected by the *Braer* oil spill in 1993, were also surveyed to confirm the geology of these areas.

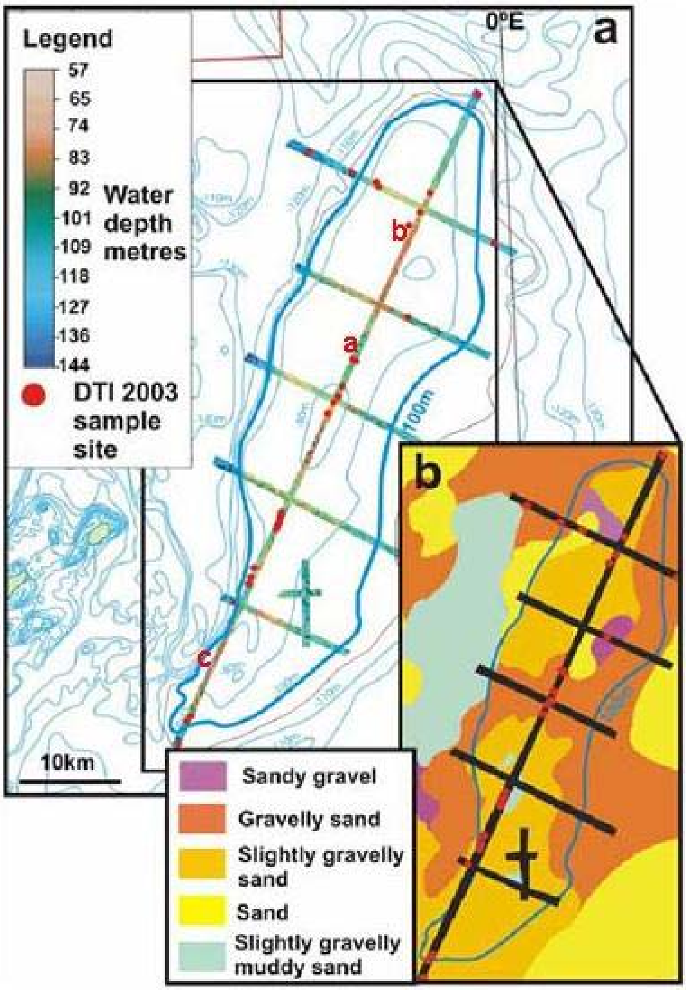
Pobie Bank

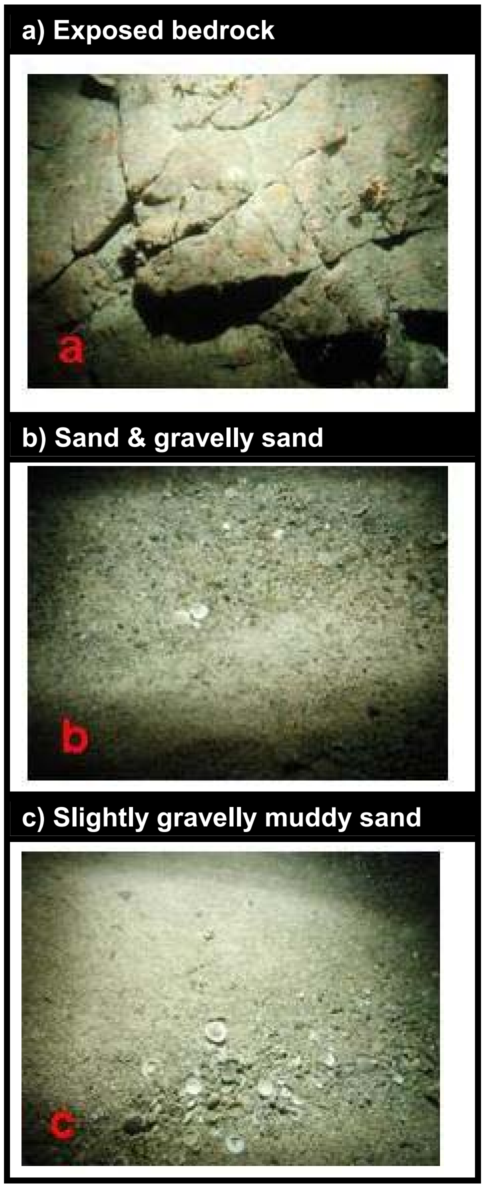
Pobie Bank is located 25-30km east of Shetland, is approximately 70km long and up to 20km wide, and rises from approximately 110m below sea level to less than 80m water depth along the crest. The area was identified by the Joint Nature Conservation Committee (JNCC) (using BGS substrate maps) as containing potential Annex I reef habitat and has been classified in Group 2 indicating that more information is required before the site can be properly assessed (Johnston *et al.* 2003).

Swath bathymetry (Figure 5.2a) indicated a bank crest with features interpreted as bedrock outcrops (Figure 5.2a, photograph a). Seabed sediments comprised sand and gravelly sand with patches of sandy gravel located on the northern and eastern margins of the bank (Figure 5.2b, photograph b) and slightly gravelly muddy sand on the southern and western margins and southern bank crest (Figure 5.2b, photograph c).

Overall, the patterns of sediment distribution indicate the impact of winnowing by higher energy near-bed currents on the north and east flanks. These patterns are consistent with the predictions for the mean peak spring-tide near-bed currents in stormy conditions and peak near-bed orbital currents having the greatest impact on the northern flanks in stormy conditions.

Figures 5.2 – Pobie Bank swath bathymetry and seabed sediments





Notes: a) Swath bathymetry colour shaded image with DTI sample locations including photograph sites, b) BGS model of seabed sediment classes.
Source: DTI 2003 survey, Holmes et al. (2004)

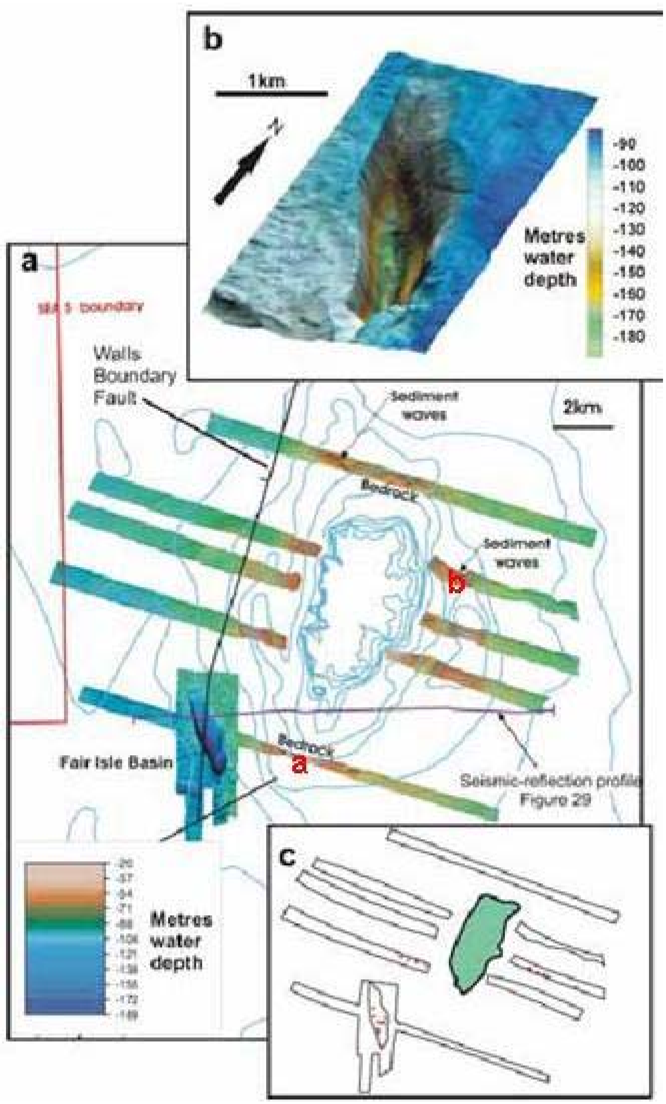
Fair Isle

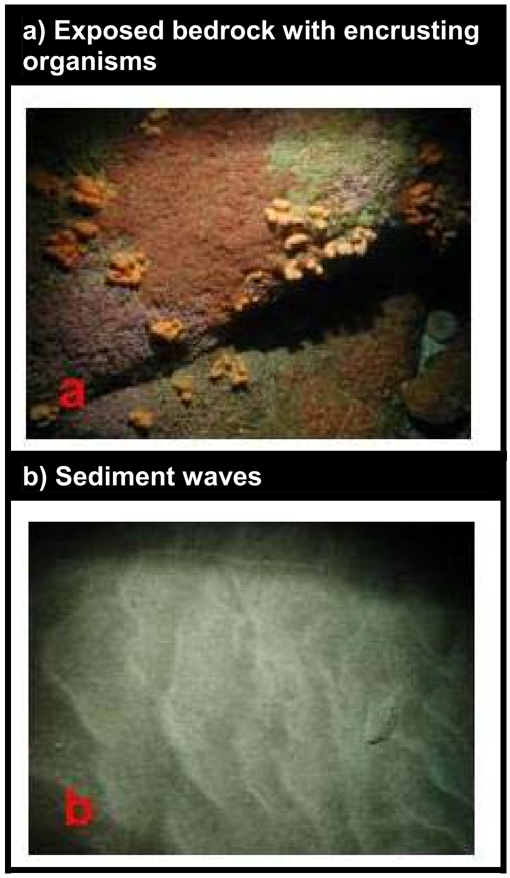
The Fair Isle Channel in which Fair Isle sits is one of the major gateways for North Atlantic Surface Water flowing eastwards into the North Sea. Mean peak spring-tide near-bed current speeds are predicted to exceed 0.5m/s when flowing to the northwest around Fair Isle in calm weather. They are forced to the southeast in stormy weather (Holmes *et al.* 2004).

The DTI 2003 survey investigated the seabed around Fair Isle and identified a number of previously unknown features. The seabed deepens away from the shore to a depth of approximately 100 metres below sea level. Bedrock ridges crop at the seabed in a northeast to southwest orientation (Figure 5.3a, photograph a). The Fair Isle Basin, a 160m deep basin lies to the southwest of the island (Figure 5.3b and 5.4).

The basin is approximately 3km long and 900m wide and is sited over the location of the Walls Boundary Fault. The west flank has a seabed slope of up to 50° and on the east flank, a maximum slope of approximately 25°. The basin probably originated as the result of glacial processes at the margin of an ice sheet and appears to be a sink for mobile sediments that have spilled over into it from sediments mobilised on the surrounding seabed. The lack of fine grained sediments in samples taken from the basin (Figure 5.4, photograph b) suggests that the sediments have been reworked by current-related processes (Holmes *et al*. 2004).

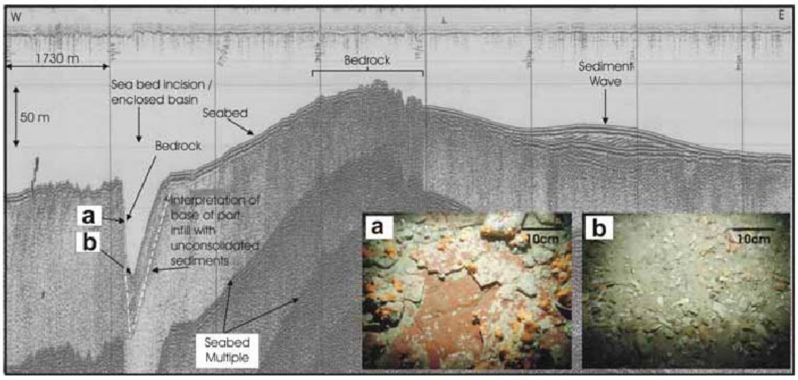
Figures 5.3 – Fair Isle swath bathymetry and image of Fair Isle Basin





Notes: a) Swath bathymetry and interpreted seabed solid geology indicating photograph sites b) Perspective elevated terrain model of the enclosed Fair Isle Basin c) Sediment sample locations.
Source: DTI 2003 survey, Holmes et al. (2004)

Figure 5.4 – Fair Isle seismic profile of enclosed basin and seabed images



Notes: Photographs a and b were taken at the locations indicated on the seismic-reflection profile a) bedrock exposed on seabed with approximately 50° slope b) very poorly sorted sandy gravel deposited within the basin axis. The gravel fraction mainly consists of shell fragments.
Source: DTI 2003 survey, Holmes et al. (2004).

To the south of Fair Isle a very large-scale sediment wave appears to be prograding towards shallower water. It is disconnected from the shallower bedrock adjacent to Fair Isle and appears to be part of a large shoal area in the east lee of Fair Isle. Sediment waves (Figure 5.3a, photograph b) migrate from the northern margin of Fair Isle onto the bank with sediment accumulation occurring during periods of the strongest near-bed currents. These findings are important as they lead to a prediction that the headlands and the islands and skerries that are exposed to strong tides will be coupled to stable banks formed from sediments that have accumulated in their shelter. In this setting the banks are one form of sediment sink.

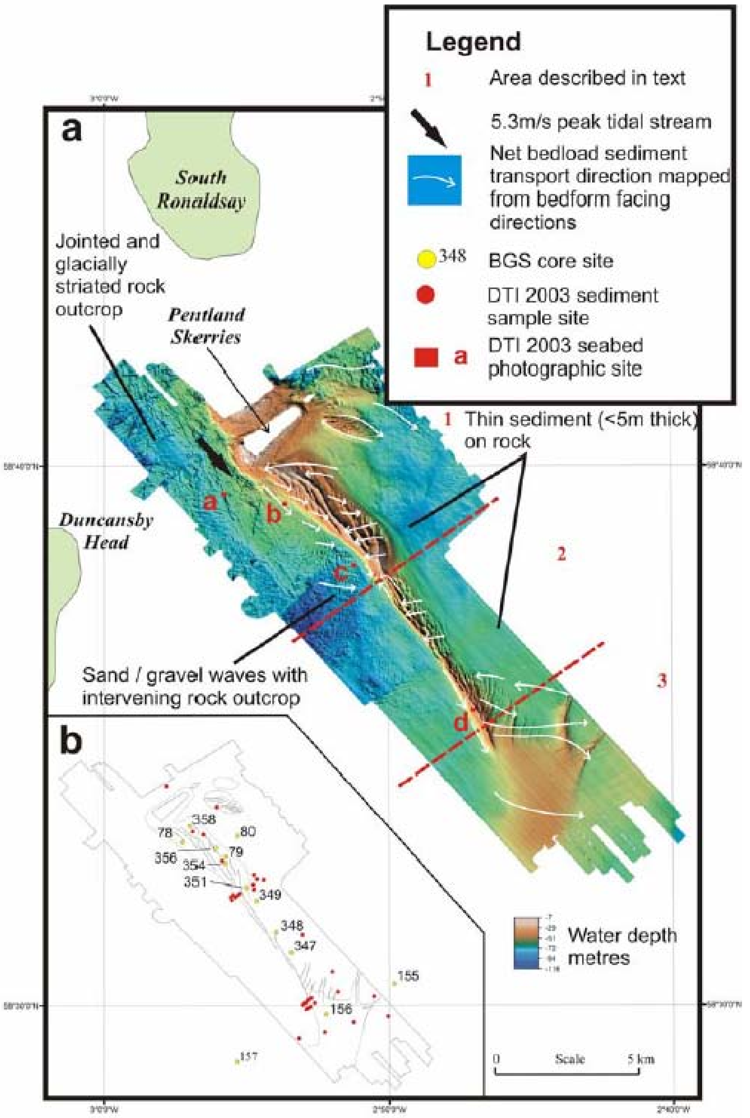
Sandy Riddle

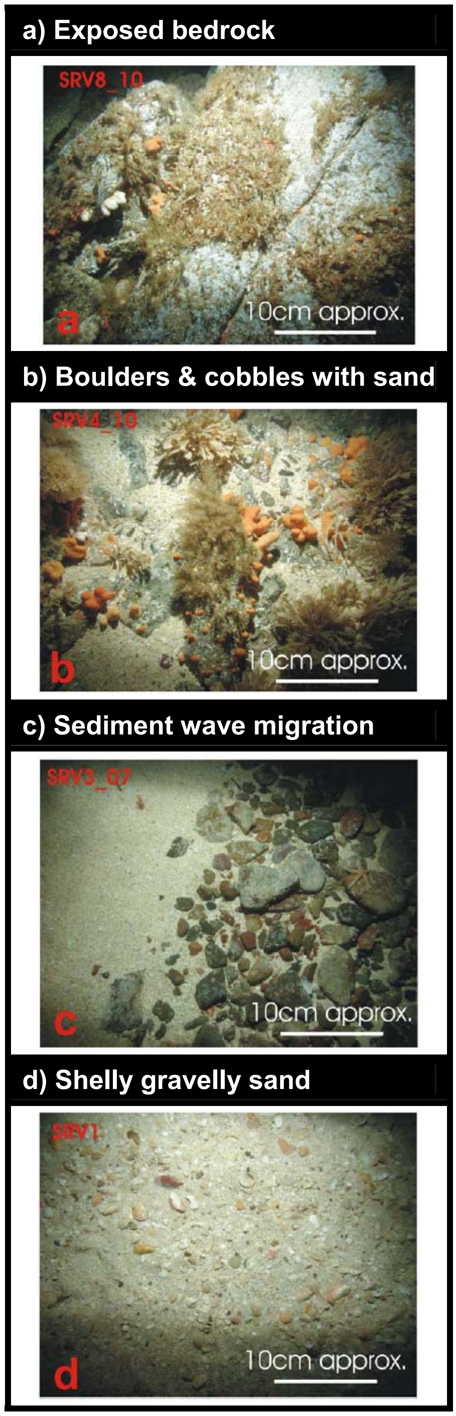
The Sandy Riddle is a large gravel and sand bank set at the east end of the Pentland Firth in one of the major northern gateways of influx of NE Atlantic waters into the North Sea. The area is characterised by high current velocities generated from tidal streams which have profoundly affected the regional distribution and composition of seabed sediments

Sediment transport and the resulting geomorphology of the Sandy Riddle (Figure 5.5a) are determined by the complex pattern of eddies generated over the area under the influence of tidal and wave-induced currents. Maximum east-going surface tidal streams of 5.3m/s are recorded on the west margin of the Pentland Skerries, at which time a strong tidal eddy extends some 3.2km to the south east. Near-bed spring tide currents are more than 2.75m/s near the head of the Sandy Riddle and decrease rapidly to around 0.875m/s further to the south east (Holmes *et al*. 2004).

To the north and west of the Sandy Riddle, the areas with the strongest tides are swept clean of sediments exposing bedrock (Figure 5.5a, photograph a). Areas with strong currents and cobbles and boulders are also largely swept clean of sandy sediments except in the spaces between the rocks. In this sediment-starved environment the surfaces of the pebbles and cobbles are characterised by abundant attached biota (Figure 5.5a, photograph b). In areas of weaker currents the seabed is characterised by cobbles and pebbles but also by mobile bedforms with coarse-grained sands. The mobile sands are thick enough to migrate as sediment waves over the seabed and periodically bury the underlying pavement of cobbles and pebbles. This process appears to prevent the establishment of abundant permanently attached biota on the pebbles and cobbles (Figure 5.5a, photograph c). Sand and gravel carbonates accumulate in areas of weak or convergent currents (Figure 5.5a, photograph d).

Figure 5.5 – Sandy Riddle swath bathymetry and seabed sediments





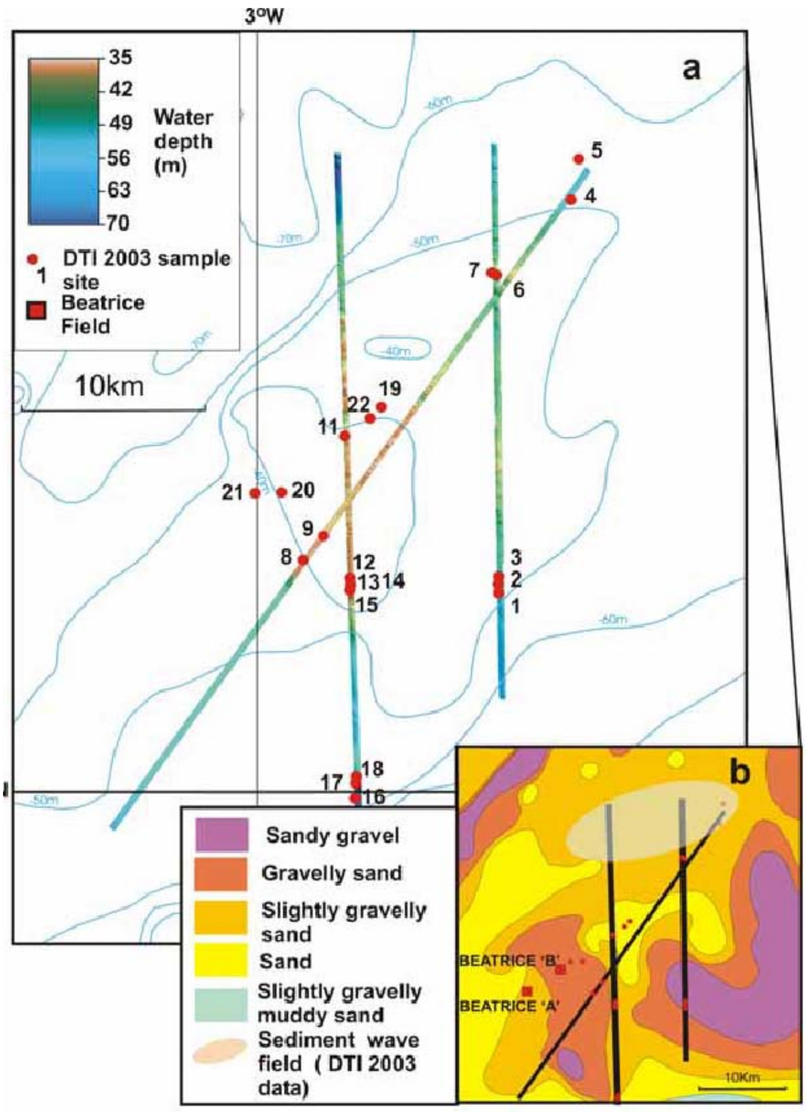
Notes: a) Swath bathymetry colour shaded image of Sandy Riddle indicating net sediment transport directions and locations of photographic images b) DTI sediment sampling sites.
Source: DTI 2003 survey, Holmes et al. (2004)

Smith Bank

Smith Bank lies in the northwest area of the Moray Firth, approximately 25km southeast of the Caithness coast. The bank is approximately 35km long from southwest to northeast and 20km wide. It rises from a base level of between 50 and 60m below sea level to less than 35m (Figure 5.6a). Estimates from the BGS regional data indicate that the seabed area of the bank in less than 50m depth of water is approximately 40km^2 (Holmes *et al*. 2004).

Seabed sediments on Smith Bank show an asymmetry with the coarsest sediments (sandy gravels) distributed on the north and east flanks (Figure 5.6b). There is evidence of sand patches and sheets with sediment waves of approximately 0.5-1.5m height and wavelengths of approximately 50m on the north flanks. These sediment waves are in approximately 45 to 60m water depth migrating to the south and west in a direction that is consistent with the direction of flow of mean peak spring-tide near-bed currents (Holmes *et al.* 2004). As with Pobie Bank, storm conditions are an important influence on the regional and local variability of seabed composition over Smith Bank.

Figure 5.6 – Smith Bank swath bathymetry and seabed sediments



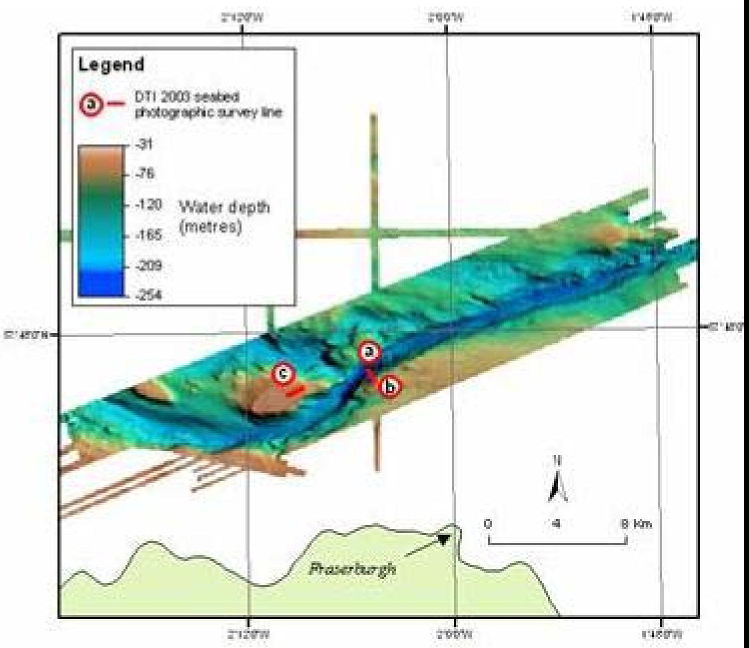
Southern Trench

The Southern Trench lies in the south-eastern part of the Moray Firth, 10km north of the Fraserburgh–Banff coastline. At more than 120km long and with a total seabed area below 100m water depth of 550km^2, the trench is the longest of a series of closed seabed incisions in the Moray Firth created by glacial processes (Figure 5.7).

The trench is 1-4km wide with a relief of up to 160m relative to the surrounding seabed, which is approximately 100 metres below sea level. The flank of the trench slopes from less than 2° to more than 50°, although average gradients vary locally in the range of 6-22°. On the south wall, areas of seabed slumping were identified where seabed gradients were more than 40°.

Sediment samples collected from the trench floor as part of the DTI survey comprised well sorted, slightly muddy, fine to medium sand with a mud fraction typically <5% (Figure 5.7, photograph a), with mainly muddy fine sand (mud fraction typically <10%) on the trench flanks (Figure 5.7, photograph b). The well sorted sediments found over much of the trench floor suggest that constricted parts of the trench system are swept by faster currents (>0.7m/s) than other areas. Finer sediments may accumulate on the trench flanks or less constricted areas of the trench floor (Holmes *et al*. 2004).

Figure 5.7 – Southern Trench swath bathymetry and seabed sediments



Notes: Swath bathymetry colour shaded image of Southern Trench indicating photographic survey line and images from areas within the trench system.
Source: DTI 2003 survey

a) Well sorted, slightly muddy, fine to medium sand

b) Muddy fine sand

c) Pebble, cobble & boulder armour, coarse sand

Seabed photography of the isolated plateau occurring to the north of the Southern Trench found that much of the area was characterised by well-rounded pebbles, cobbles and boulders forming a seabed ‘armour’ with relatively small areas of coarse-grained sand (Figure 5.7, photograph c). These observations are contrary to the blanket of muddy seabed sands mapped on the top of the plateau by the BGS and are thought to reflect a mixed origin from former beach processes, isolation from bedload transport from the adjacent regions and exposure to extreme storm waves prior to survey.

Pockmarks

In the central and northern North Sea, spreads of soft muds are locally characterised by small depressions or 'pockmarks', most of which appear to have been formed at times of fluid/gas escape at seabed. The largest areas of pockmarks occur outside the SEA 5 area in the Witch Ground Basin (Figure 5.8). In some cases, where these are associated with modern fluid/gas escape, they may contain distinctive biota of conservation interest (DTI 2001).

Whilst the DTI 2003 survey did not investigate pockmarks, a survey programme carried out for SEA 2 in June-July 2001 collected extensive data on pockmarks in the central and northern North Sea including multi-beam bathymetry, photography and seabed sampling (DTI 2001).

Within individual areas the pockmark size, density and distribution pattern are not uniform. This variation is 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 (>30km^2) occur where the seabed sediments are sandy muds, whilst in the pure muds in the centre of the Basin densities are 10-15km^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 (Judd 2001).

Pockmarks with carbonate structures formed by leaking gases are the only features known to occur in UK offshore waters which may conform to the Annex I habitat, *Submarine structures made by leaking gases.* In the northern North Sea, two examples of this habitat; the *Scanner* pockmark in Block 15/25 and a series of pockmarks near the Braemar oil field (Block 16/03) (both outwith the SEA 5 area) have been identified as Group 1 sites (i.e. the presence of Annex I habitat has been confirmed; sufficient biological information is available, and sites of this character do not occur in territorial waters) (Johnston *et al*. 2003).

Johnston *et al.* (2002) identified potential areas to the east of Shetland and an extensive area centred on the Fladen and Witch Grounds which, based on BGS seabed sediment maps, may contain the Annex I habitat and may fall within the SEA 5 area (Figure 5.8).

St. Magnus Bay and Braer West surveys

Reconnaissance sidescan sonar and multi-beam swath bathymetry surveys were completed by the DTI in areas to the southwest of Shetland affected by an oil spill originating when the oil tanker *M.V. Braer* ran aground in January 1993. The purpose of the surveys was to verify the geological setting of the spillage region which had been surveyed by the BGS 24 years previously.

St. Magnus Bay

St. Magnus Bay is a former glacially over-deepened basin in approximately 170m water depth. Seabed sediments are mainly gravelly sands with 40-100% shell carbonate (BGS 1998). Net seabed sediment transport is driven by tidal currents and is towards the north across the western approaches to the bay and anti-clockwise in nearshore areas within the bay. The survey indicated that bedrock probably crops at seabed which had not been previously resolved by the previous BGS survey.

Braer West

The Braer West surveys were completed over a former glaciated enclosed basin, up to approximately 120m deep. Seabed sediments consist of sands, gravelly sands and sandy gravels with 40-100% shell carbonate. The seabed is also characterised by patches of bedrock crop at or just below seabed (BGS 1998). Net sediment transport is driven by tidal currents and is towards the northwest on the outer approaches and anti-clockwise around the coastal margins of the bay.

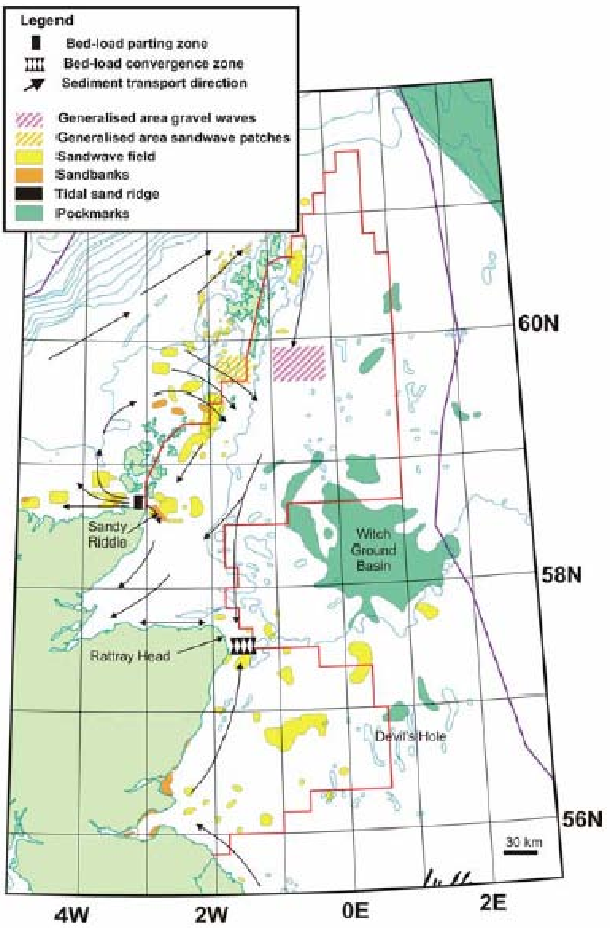
Significantly, comparing the results of the DTI survey with the previous BGS data indicates that the boundaries of the major sediment classes appear to have been more or less stable over the last 24 years or more.

5.2.6 Sediment transport

Offshore

The orientation of bedforms together with estimates of prevailing bottom current velocities have been used to identify sediment transport paths (Kenyon & Stride 1970). In the northern North Sea the main sediment transport path lies between Orkney and Shetland, with an overall sediment movement to the southeast (Figure 5.8). Northeast of Shetland, the transport direction is to the south and southeast, whereas to the southeast of Shetland it is to the north and northeast. Longitudinal sand patches east and northeast of Shetland show a general north-south trend (Kenyon & Stride 1970). The directions of the sediment paths to the east of Shetland imply the existence of a bed-load convergence zone (Johnson *et al.* 1993).

Figure 5.8 – Distribution of mobile sediment bedforms and pockmarks



Source: Holmes et al. 2004

Over much of the offshore central North Sea, sand transport rates are relatively low due to a decrease in tidal current strength and increase in water depth. Much of the seabed of this area is covered by extensive sheets of generally featureless sand indicating that hydraulic conditions are not favourable to the movement of sediment (Gatliff *et al.* 1994). Available evidence suggests that transport paths are aligned approximately north-south (Stride 1973, cited by Gatliff *et al.* 1994).

Nearshore

Sediment enters the Moray Firth from the north and disperses along routes parallel to the tidal streams, passing along the Caithness coast and into the inner firth, while sediment appears to migrate out of the firth in the southeast (Reid & McManus 1987). Stride (1973, cited by Gatliff *et al*. 1994) reported the occurrence of a bed-load parting zone off southeast Scotland, characterised by a net movement of sediment away from this zone both to the north and south. The northerly transport path extends up the east coast before terminating in a bed-load convergence zone off the northeast coast (Figure 5.8). Off the Aberdeenshire coast, large sand waves show convergent asymmetry towards the bed-load convergence zone (Gatliff *et al.* 1994).

This relatively simple pattern of sediment transport varies depending on the dynamic interplay of winds, waves and tidal currents, with topographical features such as the firths and estuaries adding further complexity.

Within the Moray Firth, several sites of major sediment accumulation occur, principally within the inner firths of Dornoch, Cromarty and Beauly. Much of the outer coastline of the inner Moray Firth is of soft sediment (Smith & Mather 1973, cited by Stapleton & Pethick 1996), the response of these deposits to longshore drift, wind and wave energy being long term migration of material into the inner firths. The development of spits and bars along the southern shores of the Moray Firth show both westward and shoreward migration commensurate with the general trend of longshore drift (Stapleton & Pethick 1996). The input of sediment from fluvial sources is largely restricted to the southern and south western shores of the Moray Firth and is estimated to be in the region of 460,000 tonnes per year (Reid & McManus 1987), of which approximately 24% is discharged into the inner firths where it is believed to become entrapped. The estuaries of the outer Moray Firth are characterised by a dominance of wave-driven shingle and sand on the outer coast. Most of the estuaries are enclosed to the seaward by large structures of shingle, the health and position of which determines the sedimentary regime within the estuary (Hansom & Black 1996).

Wave induced longshore transport is dominant in the Tay Estuary, although tidal currents are important on the northern coastline, particularly around Barry Buddon where sediment is moved offshore under ebb flows. Tidal currents are responsible for the circulation of sediment within the estuary and the complex interaction of sediment between the sand bars with the main accretionary area on the southern side of the estuary in the region of Abertay Sands (HR Wallingford Ltd 1997). Mussel *(Mytilus edulis)* shell fragments have been used as a natural tracer of sediment transport within the estuary (Al-Dabbas & McManus 1987), results indicating migration of sediment into the estuary from the sea with transport on to the tidal flats of the upper estuary prior to deposition.

Stride (1973, cited by Gatliff *et al.* 1994) indicated that some sand was diverted from the northerly east coast transport system into the Firth of Forth. A generally low, but locally moderate wave induced east to west littoral drift is present along the southern coast of the firth (HR Wallingford Ltd 1997). In the bay between Gosford and Port Seton, the drift forms an anti-clockwise gyre which is also present at Musselburgh and Prestonpans. There is little littoral interaction between the north and south coasts of the Firth and a westerly drift occurs along much of the southeast facing frontage due to wave conditions generated in the North Sea. In Largo Bay, the drift appears to move in the opposite direction due to locally generated wave conditions within the firth from the southwest (HR Wallingford Ltd 1997).

Summary details of littoral processes and nearshore sediment transport mechanisms in the SEA 5 area are presented in Table 5.3 and Figure 5.9 (HR Wallingford Ltd 1997).

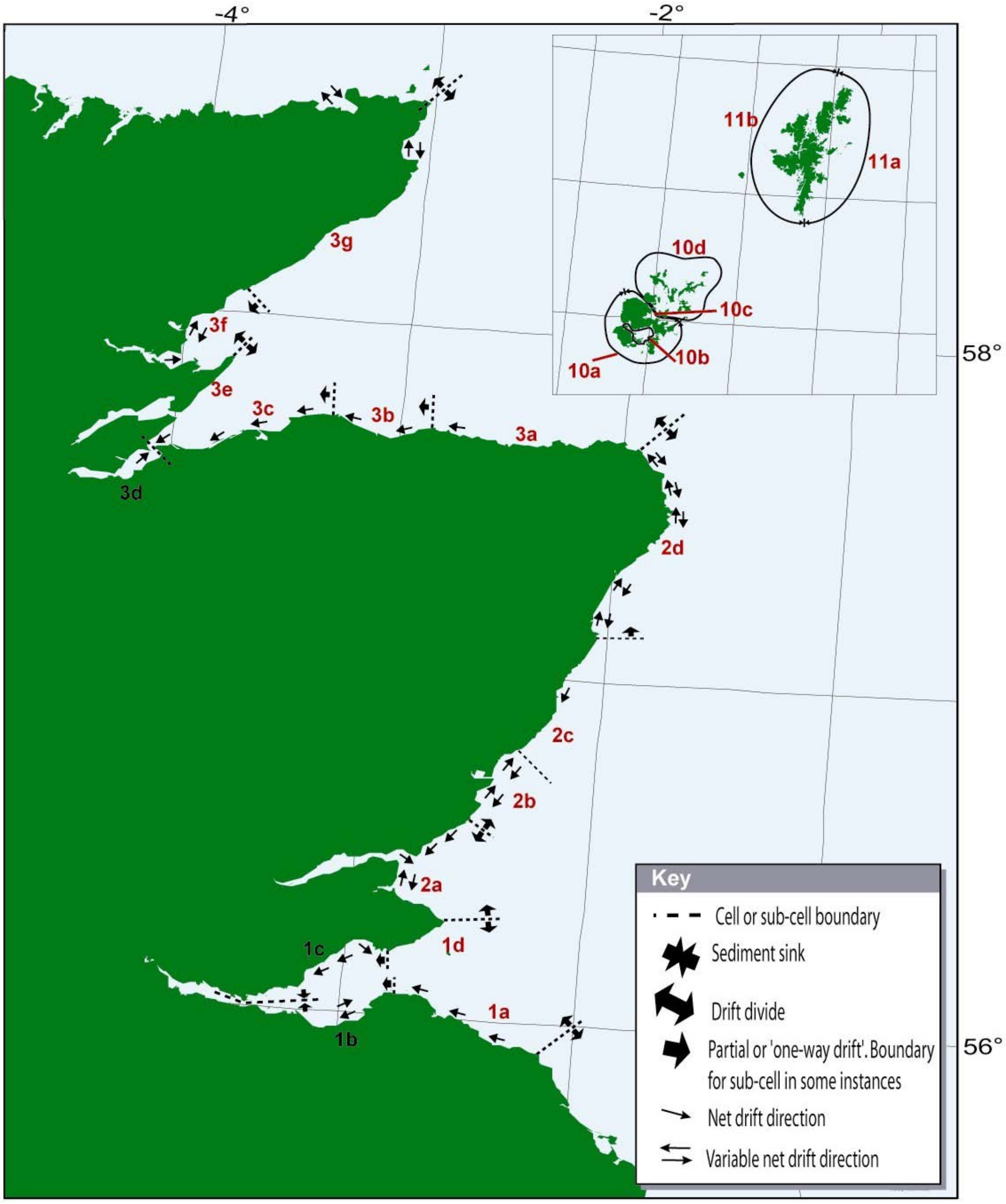
Table 5.3 – Littoral processes and transport in the SEA 5 area

Subcell*	Erosion/accretion	Littoral processes
1a	Local erosion and accretion.	Low rate of wave induced east to west littoral drift along coastline.
1b	Local erosion and accretion.	Generally low, but locally moderate wave induced east to west littoral drift.
1c	Local erosion and accretion.	Wave induced transport. Westerly wave induced drift occurs along much of the southeast facing frontage.
1d	Local erosion and little significant accretion.	Erosion and low levels of wave dominated longshore transport.
2a	Local erosion and accretion.	Wave induced longshore transport although tidal currents important for circulation of sediment within the estuary.
2b	Localised erosion and low rates of accretion.	Wave induced drift presently to the north although historically it has been virtually zero.
2c	Very low rate of erosion. No significant accretion.	No significant littoral drift due to lack of beaches and beach material.
2d	Local erosion and slight accretion.	Wave and tidal current effects. Net drift to the north is low. Complex sediment transport pattern around Don and Ythan estuaries due to the interaction of river, tidal and wave effects.
3a	Low rate of erosion and accretion.	Little evidence of significant longshore drift.
3b	Wave induced erosion. Localised accretion	Wave induced westerly drift occurs along entire frontage. Sediment transport complex around mouth of River Spey due to occasional high river flows.
3c	Localised wave induced erosion. Accretion to the east of Findhorn.	Strong westerly wave induced drift of sand and shingle. Tidal currents assist movement of sand and shingle particularly at mouth of Findhorn Bay.
3d	Low rates of erosion and accretion.	Locally generated wave action within the inner Moray Firth responsible for coastal erosion and littoral drift. Drift rates are low with direction dependent on wind direction.
3e	Low rates of cliff erosion. Local areas of accretion.	Wave action at the seaward toe of cliffs provides limited supply of beach material. Drift direction dependent on wave direction.
3f	Local areas of erosion and accretion.	Within Dornoch Firth sediment transport paths extremely complex with both wave and tidal current influences.
3g	Little erosion and local accretion.	Littoral processes wave dominated. Longshore drift low and varies with wave climate.
10a	Long-term erosion. Local sand accretion.	Wave processes dominate littoral transport. Strong tidal currents present in the straits separating the islands.
10b	Little erosion or accretion	Relatively low energy wave conditions. Current speeds high in straits between islands and off rocky headlands.
10c	Little erosion and local areas of accretion.	Wave action dominant factor in the movement of beach material. Littoral drift, where it occurs, is low.
10d	Little erosion or accretion	Wave dominated, dependent on orientation of beach and degree of exposure. Very strong tidal currents.

Table 5.3 – Littoral processes and transport in the SEA 5 area		
Subcell*	**Erosion/accretion**	**Littoral processes**
11a	Erosion of much of the 'soft' beach frontage. No accretion.	Littoral processes dominated by wave action. Beach material and sediment from eroding cliffs moved offshore under destructive wave conditions. As offshore seabed is steep, material is lost as a source of future natural beach replenishment.
11b	See Subcell 11a above. Little accretion.	See Subcell 11a above.

*Note: * Coastal cells are sections of the coast within which the littoral drift of sand and gravel 'bed load' is largely independent of other cells. Large cells are often divided up into smaller subcells.*
Source: Adapted from HR Wallingford Ltd 1997.

Figure 5.9 – Nearshore sediment processes and transport in the SEA 5 area



Source: Adapted from HR Wallingford Ltd (1997).

Potential effects of sea level change

It is predicted that sea level rise will vary regionally around the UK as a result of natural land movements and regional variations in the rate of climate induced sea level rise. Modelling results based on emission scenarios produced by the Intergovernmental Panel on Climate Change indicate that sea levels could rise by as much as 60cm over much of the SEA 5 area by 2080 (DEFRA 2002).

Sea level rise may increase the magnitude of erosive processes and lead to the accelerated erosion of intertidal and coastal habitats. An important factor which will determine the survival of sand and shingle beaches and dune systems in the face of rising sea levels is the supply of sediment. Sites which are presently accreting due to an abundant supply of sediment are more likely to survive relatively unchanged than sites where there is a limited supply of new material. Where areas of soft sediments are backed by hard coastal 'barriers', coastal squeeze and sediment erosion is likely. On 'unprotected' coasts, the eroded sediment is likely to be redeposited further inland (Stapleton & Pethick 1996).

Changes to extreme sea levels (storm surges) are also predicted although these may be more severe in the southern North Sea (DEFRA 2002). There is also the possibility of increased wind speeds during winter months, which could affect wave induced sediment transport mechanisms, although at present the accuracy of the wind modelling is uncertain (DEFRA 2002).

5.2.7 Coastal geomorphology

Overview

The modern SEA 5 coast reflects the interaction between land uplift, sea level change, resistance of coastline rocks and unconsolidated sediments to erosion and the sediment supply to the coast since the end of the last glaciation (Smith 1997, cited by Holmes *et al*. 2004).

The complex coastline of Shetland is formed from a variety of metamorphic, igneous and sedimentary rock types. Extensive stretches of exposed cliffs and rocky shorelines characterise the outer coast with long, narrow inlets, known locally as voes, extending for several kilometres inland (Stoker *et al.* 1993). Soft shorelines (sand spits, tombolos and bars) are rare and largely restricted to sheltered areas. In some of these, small lagoons have been impounded behind shingle or gravel sand bars providing special habitats including saltmarsh.

The Orkney Islands are generally low lying, with gentle slopes and rounded topography; some islands in the north, e.g. Sanday, Stronsay, North Ronaldsay are rarely more than 50m above sea level and are almost entirely covered in wind blown sand. Spectacular cliff and rock formations characterise much of the exposed western coastline, with eastern coasts displaying predominantly rocky shorelines interspersed with sandy and shingle beaches and sand dunes. The northern group of islands have complex coastlines of small bays and headlands; many bays are shallow with very low energy environments. The beaches are relatively static with the sediment being supplied from adjacent glacial deposits, but in a few locations, shingle ayres (as in Shetland) enclose shallow lagoons (SEA 4 Conservation Report website - www.offshoresea.org.uk/sea/dev/html_file/udsea4_document.php?documentID=30

As on Orkney, Old Red Sandstone cliffs of Devonian age predominate along the Caithness and outer Moray Firth coast. These cliffs are exposed to the full force of winter storms, allowing few opportunities for accretionary habitats such as sand dunes to develop, except in sheltered bays. Inner regions of the Moray Firth are less exposed, although tidal and storm effects have created extensive sand and shingle formations on either side of the Firth. The sheltered inlets of the firths (Dornoch, Cromarty and the Inner Moray Firth and Beauly Firth) represent a much lower energy environment in which intertidal mudflats and saltmarshes have developed (Doody 1996).

At Peterhead the sandy beach is replaced by a rocky platform and red granite cliffs. The cliffs continue to the Sands of Forvie, a large area of sand dunes at the mouth of the Ythan Estuary. Dune backed sandy beaches characterise the coast to Aberdeen and thereafter, rugged cliffs give way to the sandy shores and dunes of the outer Firth of Tay and the low lying rock platforms of Fife (Scott Wilson Resource Consultants 1997).

The Firths of Tay and Forth are major features, formed during the inundation of the land by the sea at the end of the last glaciation. Much of the shoreline is composed of exposed rock platforms with deposits of glacial drift. There are large areas of sand dunes on the outer coast, including the Fife promontory, with sheltered inlets holding extensive mud and sand flats. South of the Firth of Forth, cliffs reappear rising to 152m at St. Abb’s Head (Scott Wilson Resource Consultants 1997).

Shoreline sensitivity

The sensitivity of the SEA 5 shoreline to potential activities and accidents resulting from SEA 5 licensing is dependent on a number of factors. For example, the vulnerability of different shore types to oil pollution is largely dependent on substrate type and wave exposure (Table 5.4).

Table 5.4 – Vulnerability of SEA 5 shorelines to oil pollution

Shoreline type	General location in SEA 5	Vulnerability to oil
Exposed rocky cliffs and headlands	Exposed areas of Shetland and Orkney, outer Moray Firth and much of the east coast	Low vulnerability. Wave reflection keeps most of the oil offshore
Fine and coarse grained beaches	Sheltered areas of Shetland and Orkney, inner Moray Firth, areas of NE coast and within Tay and Forth estuaries.	Low to moderate vulnerability. Where oil penetrates into the sediment, may persist over several months.
Mixed sand and gravel beaches; shingle beaches	Sheltered areas of Shetland and Orkney, inner Moray Firth	Moderate to high vulnerability. Oil may penetrate rapidly and be buried resulting in persistence over years. Solid asphalt pavement may form under heavy oiling conditions
Sheltered rocky coasts	Sheltered areas of Shetland and Orkney, inner Moray Firth, areas within Tay and Forth estuaries	Moderate to high vulnerability. Oil may persist for years
Sheltered tidal flats	Inner areas of the Moray Firth, Tay and Forth estuaries	High vulnerability. Low wave energy; high productivity and biomass. Oil may persist for years
Saltmarshes	Sheltered areas of Shetland and Orkney, south coast of Moray Firth, local areas on NE coast and within Tay and Forth estuaries.	High vulnerability. Highly productive. Oil may persist for years.

Source: Adapted from Gundlach & Hayes (1978).

Seascape

As described, the SEA 5 coast is complex and contains a range of physical forms from high, rugged cliffs to flat, estuarine expanses. These different forms interact to produce a variety of different seascapes[1]. The visual interaction of these different forms with adjacent coastal areas, the sea and the perceived sensitivity to change of the seascape forms the basis of seascape assessment, an important tool in the appropriate placement of turbines and other structures in coastal and offshore areas.

Landform and geology influence the shape of the coast, the visual prominence of the land and the coastal characteristics. The shape and aspect of the coast influences how the sea is experienced from the land, i.e. exposed or sheltered, with coastal elevation determining the furthest point on the sea surface that is seen. On a clear day viewed from a beach, the horizon will be in the order of 3 nautical miles (approx. 6km) distant. Viewed from a height of 60m the horizon will be in the order of 16 nautical miles (approx. 32km). In addition, gently concave slopes allow maximum inter-visibility between sea and land whilst a level plateau or very steep land will limit views of the sea. The more complex a coastline the less likely clear views are possible to a particular point at sea (Hill *et al*. 2001). Coastal topography is therefore fundamentally important in determining the seascape characteristics of a particular area and the ability of that area to incorporate change.

5.3 Climate and meteorology

5.3.1 Overview

In general, the North Sea climate is characterised by large variations in wind direction and speed, a high level of cloud cover, and relatively high precipitation (OSPAR 2000). The North Sea climate is strongly influenced by the inflow of oceanic water from the Atlantic Ocean and by the large scale westerly air circulation which frequently contains low pressure systems (OSPAR 2000). This influence is variable and long-term changes in the strength and persistence of westerly winds are influenced by the winter North Atlantic Oscillation (NAO[2] – a pressure gradient between Iceland and the Azores). Atmospheric circulation has intensified over the last decades (OSPAR 2000), with the most extreme decadal change since the 1860s taking place from about 1960 (very weak westerly winds) to the early 1990s (very strong westerly winds). However, long-term wind data suggests a comparable period in the early 20th Century, and proxy data over several thousand years (from winter tree growth) indicate several occasions when similar increases have occurred.

The persistence/strength of the westerly winds has a significant effect on water transport and distribution, vertical mixing and surface heat flux. This atmospheric circulation is also closely related to cloud cover and therefore the light conditions in the water. This combination of factors has been shown to strongly affect productivity and recruitment, growth and distribution of fish stocks (Svendsen *et al*. 1995, cited by OSPAR 2000).

[1] Seascape has been defined as the views from land to sea; views from sea to land; views along the coastline, and the effect on landscape of the conjunction of sea and land (Hill *et al.* 2001).

[2] The NAO index is defined as the difference between the normalised pressure anomalies in winter at Punta Delgada (Azores) and Akureyri (Iceland). A high index (>1) is associated with strong westerly winds, and a low index (<1) represents weak westerlies. A "normal" index covers the mid range between -1 to +1 and stands for a zonal circulation of average strength (Koslowski & Löwe 1993, cited by Becker & Pauly 1996).

Metocean (weather and sea) conditions in the North Sea have been intensively monitored, especially since commencement of offshore oil and gas production in the 1970s. Reliable data is therefore available for engineering design and operational planning purposes, and in general the North Sea is no longer considered to be an "extreme" province in terms of metocean conditions.

5.3.2 Wind

Offshore areas

Meteorological Office wind data for the north, central and southern areas of the North Sea from the period 1854-1994 show the occurrence of winds from all directions, although dominated by winds from south-southwest and south. Predominant wind speeds throughout the year represent moderate to strong breezes (6-13m/s), with the highest frequency of gales (>17.5m/s) during winter months (November–March). The major contrast between the northern North Sea and central and southern parts is the relative frequency of strong winds and gales, particularly from the south. Percentage frequency of winds of Beaufort force 7 and above in January is >30% north of 57ºN, but <20% south of 55ºN (North Sea Pilot 1997).

Wind measurements from the Norwegian west coast since 1950 indicate that in addition to large seasonal variability, very large variations have occurred in the wind field, with an increasing trend in wind speed. This is in qualitative agreement with the NAO index, and has been noted from the early 1960s until today (but broken by a calm period in the late 1970s). Large variations in mean wind direction over the North Sea have also been observed (Furnes 1992, cited by OSPAR 2000).

Coastal areas

Predominant wind speeds and directions measured at coastal locations within the SEA 5 area are highlighted in Table 5.5.

Table 5.5 – Predominant wind speed and direction at coastal locations in SEA 5

	Wind speed (m/s)		Wind direction	
Location	**Summer**	**Winter**	**Summer**	**Winter**
Lerwick	6.3	8.2	SW	SW
Fair Isle	6.2	9.8	SW	SW
Kirkwall	6.2	8.2	SW	SW
Wick	5.2	6.7	SE	S
Rattray Head	4.6	5.2	S	S
Inverness (Dalcross)	4.6	5.2	SW	SW
Aberdeen (Dyce)	4.6	5.2	S	S
Fife-Ness	5.7	7.7	SW	SW

Note: Summer (June, July & August), winter (December, January & February).
Source: North Sea Pilot (1997)

Strong winds characterise the Shetland and Orkney climate. On Shetland, the mean wind speed during the year is 6.5-7.5m/s and gales occur on an average of 58 days per year. Winds from the south and west predominate. The prevailing winds on Orkney are from between west and southeast for 60% of the year. Wind speeds greater than 8m/s occur for over 30% of the year and gales occur on an average of 29 days per year (Jones 1975, cited by BGS & Scott Wilson Resource Consultants 1997).

The wind field experienced along the inner south coast of the Moray Firth is dominated by south-westerlies. Prevailing winds from the Atlantic are channelled through the Great Glen, with the effects felt as far east as RAF Kinloss on the east side of Findhorn Bay; 43% of observed wind directions at RAF Kinloss (between 1990-1991) occurred from the west-southwest sector, with a further 25% within the south to west quadrant. Wind records for the Beatrice Alpha oil platform also display a very strong trend from the west-southwest sector with a sharp decline in frequencies from other directions (Comber 1993, cited by Hansom & Black 1996). On the eastern extremities of the south coast, direct exposure to Atlantic winds is prevented by the shelter afforded by the topography of the northeast land mass (Hansom & Black 1996).

Contours of hourly mean windspeed exceeded for 75% of the time within the Moray Firth indicate a gradient of 2.5-3m/s for inner areas increasing to 3.5-4m/s for outer areas (Caton 1976, cited by BGS 1996). The maximum hourly wind speed at an elevation of 10m above Still Water Level with an average recurrence of 50 years varies between 36m/s at Fraserburgh to 38m/s at Duncansby Head. At Beatrice Alpha, wind speeds recorded during the winter months of 1990-1991 peaked at 29m/s, with 22% of winds between 15-20m/s (Hansom & Black 1996).

Further south, the Firth of Forth provides a natural corridor for airflow, with wind directions tending to follow the northeast/southwest axis of the firth. During the winter months, westerly airflows dominate, with occasional northeasterly flows. In contrast, during summer months westerly flows make up 50% of the air movements with northeasterly and easterly flows more important (35%). The easterly and north-easterly flows are a result of sea breezes which develop during periods of favourable synoptic conditions. The breezes become stronger during the day and progressively extend westwards from the outer Firth into the inner estuary (Harrison 1987, cited by Firth *et al.* 1997). Mean hourly windspeed exceeded for 75% of the time is 3-3.5m/s (Caton 1976, cited by BGS *et al.* 1997), with wind speeds greater over the open water of the Firth.

5.3.3 Rain

Mean annual rainfall, estimated from Nimbus-7 satellite passive microwave imagery, is relatively low over much of the northern North Sea (in comparison to the Atlantic seaboard and to Norwegian coastal waters to the east), in the range 200-400mm. The central North Sea experiences higher rainfall (400-600mm) (OSPAR 2000). Fog in the offshore North Sea is not especially common, with maximum frequencies (3–4%) in the extreme south during winter. In contrast, coastal fog ("haar") is common during spring and summer along the east coast of Scotland, with up to 14 days per month recorded in exceptional years (North Sea Pilot 1997).

5.4 Oceanography and hydrography

5.4.1 Data sources

The basic sources of oceanographic data are Current Temperature Salinity (CTD) profiles, and current measurements. A large number of individual CTD profiles and current meter deployments have been conducted in the North Sea to support scientific studies and since the 1960s, to support oil and gas exploration and production activities. Of particular relevance to the understanding of overall North Sea circulation were the series of JONSDAP '71 pilot exercises, JONSDAP '73 in the southern North Sea, and finally the INOUT experiment of JONSDAP '76, which involved the deployment of more than 200 current meters between Norway and Shetland (e.g. Riepma 1980, Turrell *et al.* 1992). JONSDAP

'76 took place when the northern North Sea was vertically homogenous and the Autumn Circulation Experiment was conducted in 1987-1988 to monitor circulation preceding and during autumnal breakdown of vertical stratification (Turrell *et al.* 1992). Data from many of these deployments is held by the British Oceanographic Data Centre (BODC).

5.4.2 Major circulation patterns

Several water masses in the North Sea can be identified on the basis of temperature and salinity distribution, residual current patterns and stratification. The major water masses of relevance to the SEA 5 area may be classified (after Turrell *et al*. 1992, see Figure 5.10) as Atlantic water, Scottish coastal water, north North Sea water and central North Sea water.

The temperature and salinity characteristics of these water masses (Table 5.6) are strongly influenced by heat exchange with the atmosphere and local freshwater supply. The deeper waters of the North Sea consist of relatively pure water of Atlantic origin, but they too are partly influenced by surface heat exchange (especially winter cooling) and, in certain areas, slightly modified through mixing with less saline surface water (OSPAR 2000).

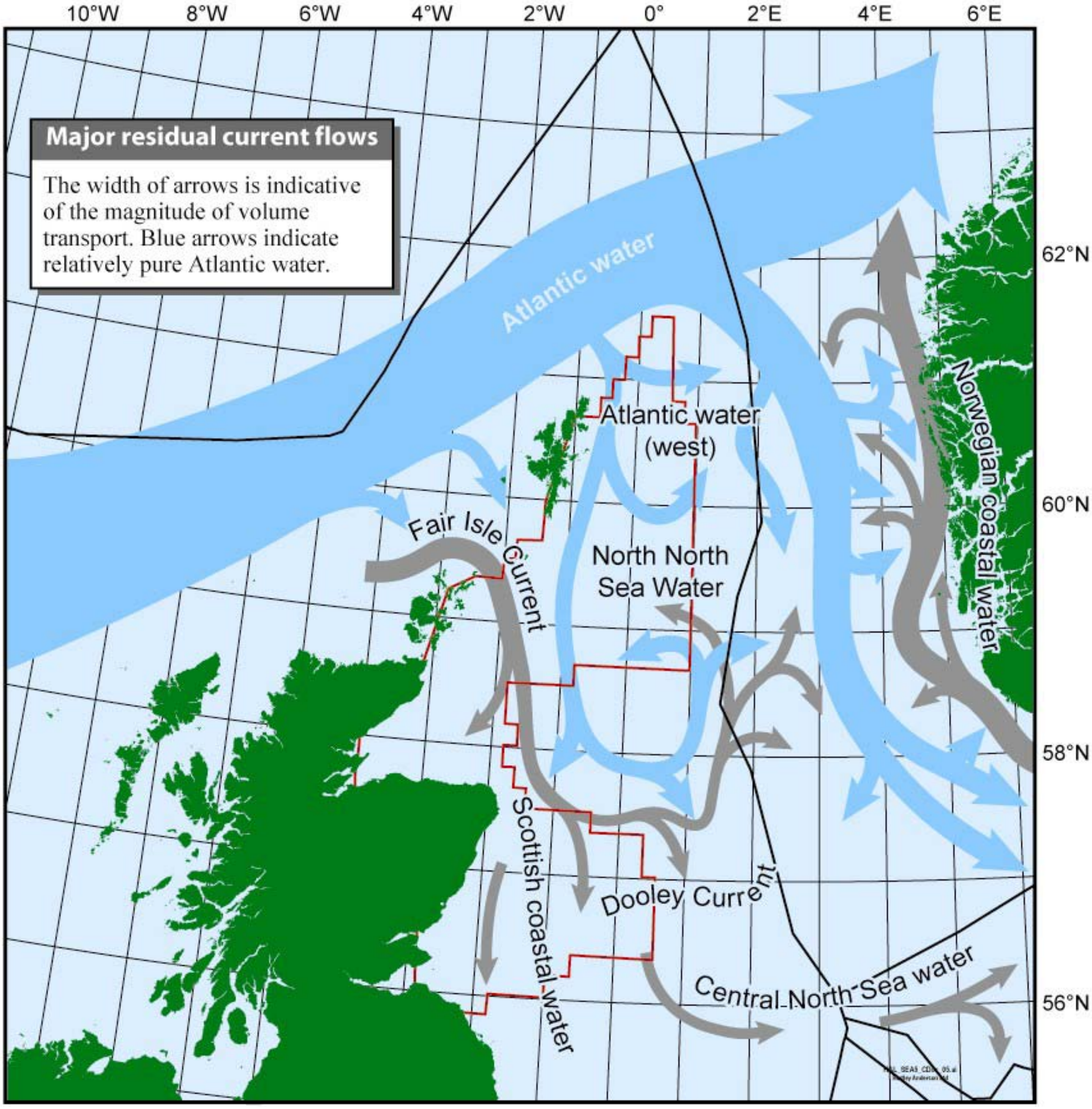
Table 5.6 – Typical temperature and salinity values of the main water masses in SEA 5

Water mass	Temperature (ºC)	Salinity (‰)
Atlantic water	7-15	>35
Atlantic water (deep)	5.5-7.5	>35
Scottish coastal water	5-15	33-34.5
North North Sea water	6-16	34.9-35.3
Central North Sea water	5-10	34.75-35

Source: OSPAR 2000.

The main inflow to the North Sea occurs along the western slopes of the Norwegian Trench, with more minor inflows east of Shetland, between Orkney and Shetland and through the Channel. These inflows are balanced by outflow mainly along the Norwegian coast, with most of the water probably passing through the Skagerrak. Figure 5.10 shows cyclonic circulation of mixed water from the Fair Isle inflow via the Dooley Current, and Atlantic water derived from southward flow to the east of Shetland. The resultant coherent gyre (Svendsen *et al.* 1991) is topographically generated, and is characterised by low velocity residual currents; typically 0.2m/s towards the south.

Figure 5.10 – Residual circulation of the central and northern North Sea



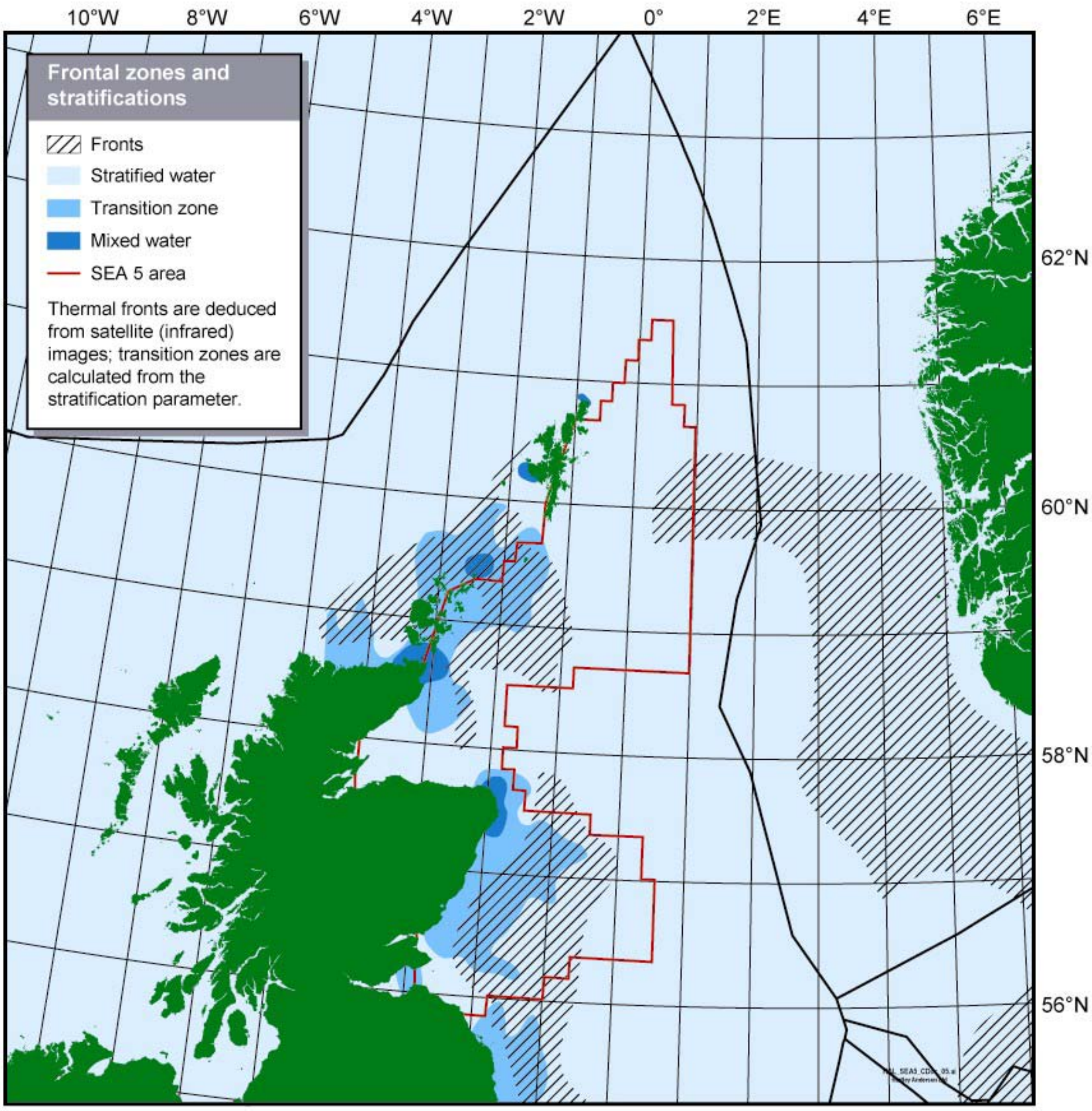
Source: After Turrell et al. 1992

This generalised pattern of water movement in the North Sea may be strongly influenced by short-medium term weather conditions, resulting in considerable seasonal and inter-annual variability. Drastic differences in Atlantic water inflow from year to year, caused by atmospheric forcing, explain some of the observed large scale differences in salinity between years (OSPAR 2000). The Atlantic inflow from the north has profound implications for the circulation of nutrients and contaminants, and for the supply of oceanic planktonic species (e.g. the dominant copepod *Calanus finmarchicus*) and fish larvae (Turrell *et al.* 1992). Using JONSDAP and ACE data, Turrell *et al.* (1992) considered circulation patterns in the northern North Sea under stratified and homogenous conditions, concluding that Atlantic inflow from the North was considerably greater under stratified conditions, with the Fair Isle current proportionately less important.

Density stratification is well developed in the summer months of most years in the central and northern North Sea, with the relative strength of the thermocline determined by solar heat input and turbulence generated by wind and tides. Temperature sections across the North Sea at 57º17'N demonstrate thermocline development at a depth of around 50m, with mean summer surface temperature around 11ºC and nearbed temperature around 6.5ºC. The shallow parts of the southern North Sea and the Channel remain well mixed throughout the year due to tidal action (OSPAR 2000) although the Kattegat, Skagerrak and Norwegian Trench region of the North Sea have stable salinity stratification all year. Deep water in these areas is circulated mainly by subduction of high salinity water.

Fronts or frontal zones mark boundaries between water masses, including tidally mixed and stratified areas, and are numerous in the central and northern North Sea (Figure 5.11). Fronts may restrict horizontal dispersion and may be associated with increased biological productivity. Density stratification in the central and northern North Sea breaks down after September due to increasing frequency and severity of storms and seasonal cooling at the surface.

Figure 5.11 – Frontal zones and stratification of the central and northern North Sea



Source: OSPAR 2000 (after Becker 1990)

Offshore waves and currents

The North Sea is considered to be frequently "rough" from October to March (North Sea Pilot 1997), with 20-30% exceedance of a significant wave height of 4m north of 57ºN, but <15% south of 55ºN. Satellite altimeter measurements from 1993-1997 indicate mean significant wave heights for the northern North Sea during spring (2-3m), summer (1-2m), autumn (2-3m) and winter (3-4.5m) months. Values for the central North Sea varied between 1-2.5m, with the largest waves in autumn and winter months (Woolf *et al.* 2002). Extensive measurements have been made to characterise the wave climate of the North Sea, with a range of estimated 50 year maximum wave heights from 32m in the north to 12m in the Channel. Following over thirty years of exploration and production activity, engineering design criteria for installations and infrastructure in the North Sea are well known and environmental conditions in this mature province are no longer considered a significant source of risk (as they once were).

Maximum surface tidal streams which vary from 0.25 to 0.5m/s over much of the northern North Sea are in excess of 1.0m/s on the Orkney-Shetland Platform (Pantin 1991). Over the central North Sea, tidal currents are strongest in shallow coastal areas, where the tidal stream is aligned parallel to the coast. Maximum surface current speeds are mainly in excess of 0.5m/s out to about 50km offshore, decreasing eastwards to less than 0.25m/s. (Gatliff *et al.* 1994).

5.4.3 Coastal hydrography

Temperature and salinity

Table 5.7 provides details of average temperature and salinity values found in nearshore areas of SEA 5 in summer and winter.

Table 5.7 – Average sea surface temperature and salinity of nearshore waters

	Summer		Winter	
	Temperature (ºC)	**Salinity (‰)**	**Temperature (ºC)**	**Salinity (‰)**
Shetland	12-13	35.2	7-7.5	35.3
Orkney	12-12.5	34.75-35	6.5-7	34.75-35
Moray Firth	11.5-12.5	34.75	5.5-6	34-34.5
Outer Firths of Forth and Tay	13	34.5	5.5-6	34-34.25

Source: Adams & Martin 1986, BGS 1996, BGS & Scott Wilson Resource Consultants 1997a, b, BGS et al. 1997.

Sea surface temperatures and salinity values around Shetland and Orkney are to a large extent influenced by the flow of oceanic Atlantic waters into the North Sea through the Fair Isle Channel (Turrell 1992). Oceanic inflow combines with less saline coastal waters to make up a southern flow down the Scottish east coast. This remains well mixed throughout most of the year, although surface heating and settled weather in late summer and autumn can often cause temporary thermoclines to develop (Heath *et al.* 1999). Temperature and salinity patterns are more complex within the semi-enclosed firths and estuaries.

Land run-off within the inner Moray Firth and along its southern coast is important in determining temperature and salinity profiles. In winter, low salinity surface waters from land run-off form a distinctive colder stream close to the southern shore which can be over 1ºC colder than bottom waters (Craig 1959, cited by Adams & Martin 1986). Similar temperature differences between surface and bottom are widespread during the summer months with the water resulting from land run-off being warmer than the water to the north (Adams & Martin

1986). In early spring, low salinity surface waters in the inner Firth and off the southern coast result in stratification, in contrast to the rest of the Firth which is still well mixed. Subsequently, late spring warming of the surface results in thermal stratification, which generally persists until late autumn (Adams & Martin 1986).

The River Tay, together with the River Earn form the major systems draining into the Tay Estuary and between them contribute the greatest volume of freshwater of any river basin in the UK (Pontin & Reid 1975). West (1972) calculated the mean longitudinal salinity distribution for the Tay Estuary and found under low river flow conditions, salinity at the estuary mouth was approximately 32-33‰ with the salinity intrusion extending 20-25km down the estuary. Under high river flows, salinity values at the mouth of the estuary were about 25‰ (West 1972). The estuary is generally turbulent and well mixed, although there is evidence of a saline 'wedge' penetrating as far as the narrows at Tayport, where the vertical salinity difference is about 7‰. This wedge is probably formed by saline water coming over the Abertay sands from St. Andrews Bay and plunging under the main flow coming up the main channel (Charlton *et al*. 1975).

Within the Forth Estuary (upstream of the bridges), the dominant water movement is tidal with the influence of freshwater from rivers being relatively low (Dyke 1987, cited by Firth *et al.* 1997). Further to seaward, there is more dilution from rivers on the south shore of the Firth than the north, leading to an outgoing stream of diluted water (32-34‰) along the southern side which is generally distinguished as far seaward as St. Abb's Head.

Coastal waves and currents

The east coast of Shetland and Orkney is more sheltered and less frequently exposed to large, powerful waves than the west. However, North Sea storms and swells can result in relatively large waves reaching these coasts (Table 5.8). Similarly, the outer Moray Firth is relatively exposed and can experience significant wave heights. However, only swell waves from the northeast are able to penetrate to the inner Firths due to the protection afforded by the coastal topography (Stapleton & Pethick 1996). Incident waves from this direction occur for only 29% of the year, the remainder of the wave record being dominated by wind waves generated within the Firth (BMT 1986, cited by Hansom & Black 1996). Waves reaching the northeast coast of Scotland are predominantly from the east and southeast, whilst the outer Firths of Forth and Tay are predominantly exposed to waves generated by winds from the north and east, the inner firths being more sheltered.

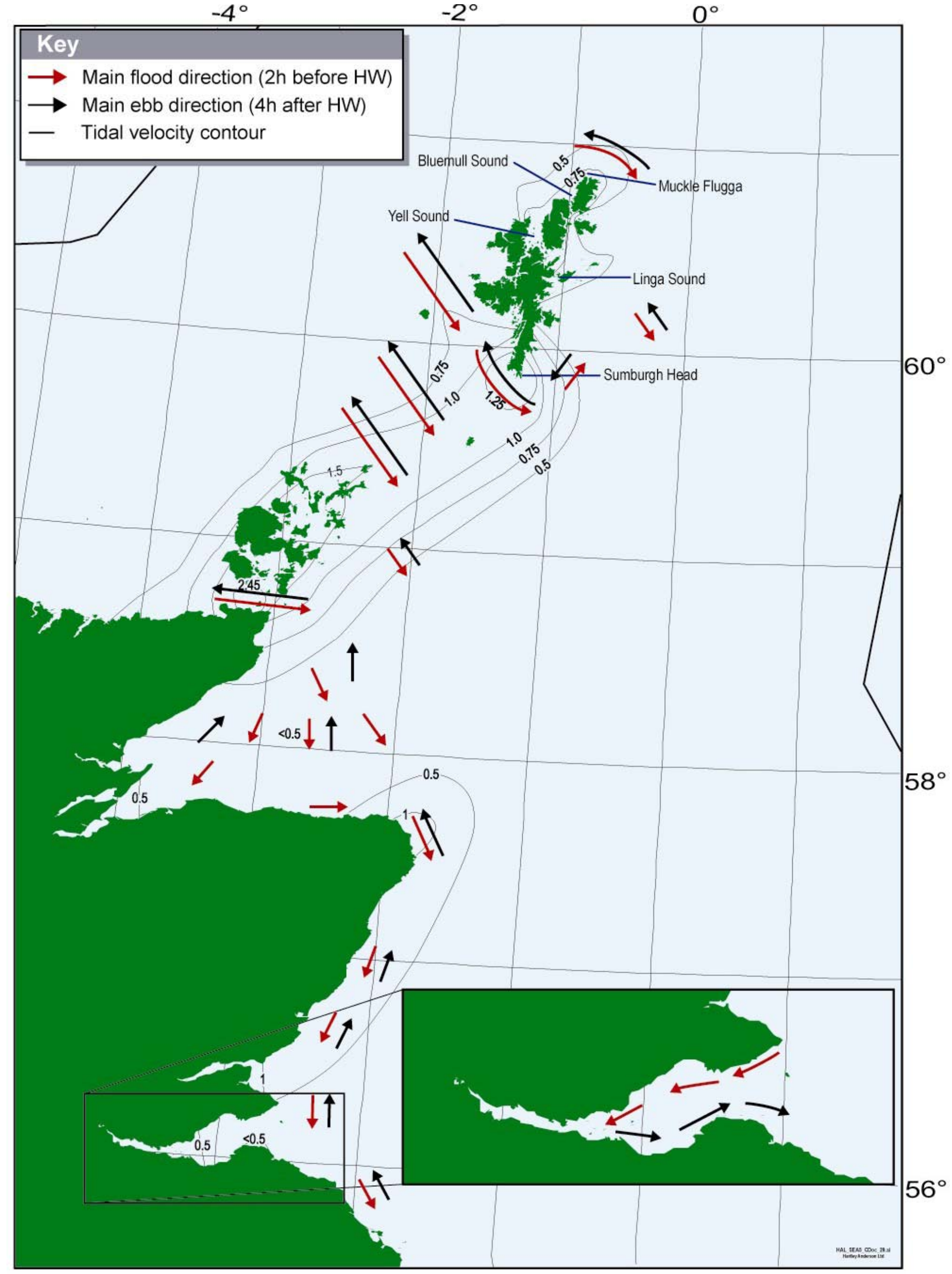
Table 5.8 – Significant wave heights expected to be exceeded for 10% and 75% of the year

	10%	**75%**
Shetland (East)	2.5m	0.5-1m
Orkney (East)	1.5-2m	0.5m
Outer Moray Firth	2-2.5m	0.5m
NE coast	2m	0.5m
Outer Firths of Forth and Tay	1-1.5m	0.5m
SE coast	2m	0.5m

Source: BGS 1996, BGS & Scott Wilson Resource Consultants 1997a, b, BGS et al. 1997.

Along the Scottish east coast there is a general southern flood and northern ebb tidal flow, the pattern being complicated by coastal topography, fluvial flow and wind-induced currents (Figure 5.12).

Figure 5.12 – Nearshore tidal flows and velocities



Source: Adams & Martin 1986, UKHO 1986

Tidal flows around the Shetland Islands move southwards on the flood tide, and northwards on the ebb, at speeds ranging from 0.5 to 1.25m/s. In certain places, notably near Muckle Flugga, in Yell Sound, Linga Sound, Bluemull Sound and near Sumburgh Head, tidal streams reach considerably higher velocities (3.5-4m/s). The speed of most tidal streams around Orkney ranges between 1.0-2.0m/s with some areas, such as Hoy Sound and the Pentland Firth, subject to considerably higher velocities (up to 4.5m/s) (BGS & Scott Wilson Resource Consultants 1997a, b).

The tidal streams present in the Moray Firth are complex and variable in direction (Adams & Martin 1986). Due to the passage of the tidal wave across the outer Firth, tidal currents are stronger in this area than inshore, where topographically induced localised gyral patterns occur (Adams & Martin 1986). Whereas currents can reach up to 1m/s offshore (Dooley 1973), within the inner Moray Firth most of the area is subject to currents of less than 0.5m/s (Stapleton & Pethick 1996). In general, the tides in the outer Firth flood in a south to south-easterly direction, reversing to ebb northwards. However, in the inner Firths of the Dornoch, Cromarty and Beauly/Inverness, the tides trend in a more easterly direction. Along the southern shore of the Firth, a notable feature of the tidal current pattern is a flood lasting approximately nine hours of the tidal cycle, with an insignificant ebb flow for the remaining three hours. This phenomenon occurs up to 8km offshore and is a result of the southern Moray coastline sheltering the area from the north flowing ebb current (Dooley 1973). The resultant residual current is an eastward flow along the southern shore of the outer Firth (Adams & Martin 1986).

The tidal flow across the mouth of the Tay Estuary runs in a southerly direction during the flood and northerly during the ebb. The south-going flood tide forms a large clockwise eddy in St. Andrews Bay spilling over Abertay sands into the main Tay channel (Charlton *et al*. 1975). Within the estuary, current velocities can be high with peak spring flood velocities of 1.15m/s to the southwest of Buddon Ness. Sand waves to the west of the Newcombe Shoal are evidence of considerable flow velocity (Charlton *et al.* 1975). River flow variations can have a significant effect on the tidal regime causing complex patterns of water movement (Ramsay & Brampton 2000).

Typical peak tidal flow velocities at Rosyth in the Firth of Forth are 0.7-1.1m/s on the ebb and 0.4-0.7m/s on the flood, with generally weaker flows to seaward of this location. In general, the flood currents are stronger on the north side of the Firth and the ebb stronger on the southern shore. Tidal currents produce a drift westwards along the northern and central Firth, compensated by an eastward flow of water along the southern shore. However, during certain times of year, usually late winter and spring, a seaward flow may also develop along the northern shoreline if the water near the coast becomes stratified. Brown *et al.* (2001) have proposed the existence of a strong and persistent seasonal coastal southward transport from the Firth of Forth to Flamborough Head, driven by bottom density fronts that fringe the dense pool of cold winter water formed in the central North Sea following stratification.

5.5 Contamination of water and sediments

5.5.1 Introduction

Anthropogenic contamination of the environment can be defined (e.g. DTI 2003) as the introduction, by humans, of materials in locations or concentrations in which they do not occur naturally. If present in sufficient concentrations, contaminants may have the potential to disturb biological processes through a variety of mechanisms, including increased availability of food and nutrients, toxicity, mutagenicity and interference with reproductive physiology.

Large scale contamination of the marine environment has been principally associated with industrial development since the 19^{th} century, with major sources comprising terrestrial emissions and discharges (transported to the marine environment via rivers and atmospheric transport); shipping; military activities; and offshore industries, including oil and gas production. In general, riverine and atmospheric transport account for the largest inputs of contaminants to the northeast Atlantic and North Sea (OSPAR 2000).

To support SEA 2 and SEA 3, CEFAS in collaboration with FRS were commissioned to review the extent of existing chemical contamination of relevant areas of the North Sea, in the context of "background" levels and trends (CEFAS 2001, 2002). The reviews were based on previous collations and publications, including CEFAS Aquatic Environmental Monitoring Reports (AEMRs), reports from UKOOA, including a review of seabed monitoring studies (UKOOA 2001) and OSPAR reports, including the Quality Status Report (QSR) 2000 (OSPAR 2000) which presents an assessment of marine environmental conditions and temporal changes observed in the Greater North Sea since 1993. The commissioned studies also reviewed monitoring data acquired through the National Monitoring Programme's first phase (NMP, see below) and second phase (NMMP2).

This assessment of contamination of the SEA 5 area is based largely on the SEA 2 and SEA 3 work, together with a range of published data relating to environmental monitoring of the east Scottish coastal margin. Preliminary interpretation of contaminant data collected from the SEA 5 area in 2003, on behalf of DTI, are also presented.

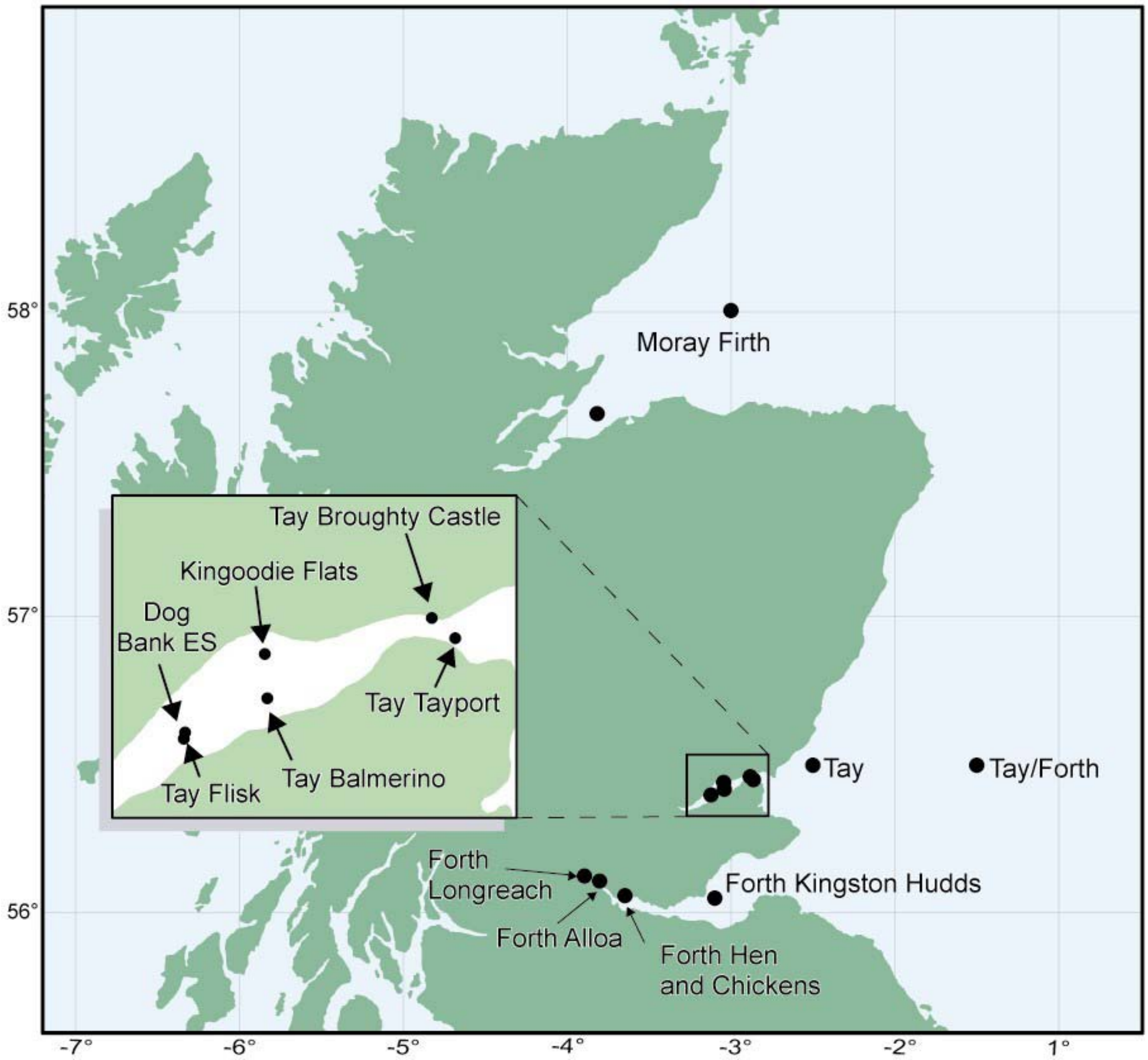
5.5.2 Data sources

In general, contaminant monitoring has concentrated on industrialised estuaries and to a lesser extent coastal waters, and there is therefore a strong bias in data availability towards these areas. Important environmental monitoring programmes and data compilations relevant to SEA 5 include:

- OSPAR publish a variety of compilations of data provided by contracting parties under JAMP and other agreed programmes, including periodic Quality Status Reviews (OSPAR 2000); annual reports (OSPAR 2003a); Assessment and Monitoring Series reports (e.g. concerning eutrophication, OSPAR 2003b); Best Available Technique (BAT) and Best Environmental Practice (BEP) Series reports (e.g. concerning reinjection of cuttings and produced water, OSPAR 2001a, 2002); and OSPAR Priority Substances Series reports (e.g. concerning PAHs, OSPAR 2001b). In 2003, the second Ministerial Meeting of the OSPAR Commission produced a strategy which will give the basis for a further comprehensive Quality Status Report in 2010.
- The National Marine Monitoring Programme, now in its second phase (NMMP2) followed a review of monitoring carried out in UK estuaries and coastal waters in 1987/88 (MPMMG 1998). NMMP2 seeks to integrate national and international monitoring programmes across UK agencies, and to ensure consistent standards, comparability of measurements and data exchange. In addition to monitoring of known impacted estuaries and offshore sites (the focus of NMP), some monitoring effort in NMMP2 is directed at less impacted estuaries and considering temporal trends and spatial variability. NMMP2 contributes to UK commitments under the OSPAR Joint Assessment and Monitoring Programme (JAMP); and compliance with EC Directives (water quality monitoring for metals and organic compounds to meet requirements of the EC Dangerous Substances Directive 76/464/EEC; and shellfish monitoring to meet requirements of the Shellfish Waters Directive 79/923/EEC, Shellfish Hygiene Directive 91/492/EEC and Fisheries Products Directive 91/493/EEC). The first holistic NMP report was published in November 1998, together with Regional Reports including one covering Scotland (NMP 1998). NMMP2 publishes an annual review of the programme (Green Book, NMMP 2003) and it is expected that temporal trends will be reported formally every three years from 2002 onwards. NMMP2 sites in the SEA 5 area include two in the Moray Firth and one offshore of the Forth/Tay (sampled by FRS); and two in the Cromarty Firth, two in the Tay and five in the Forth (sampled by SEPA) (Figure 5.13).

- A variety of monitoring activity undertaken by offshore industries (primarily oil, aggregate extraction and renewable energy sectors) and by statutory agencies in relation to offshore industrial activities.

Figure 5.13 – Locations sampled by the National Marine Monitoring Programme



In addition to activities carried out under NMMP2, SEPA conducts a range of monitoring of Scottish coastal environments; for example of bacterial quality of Bathing Waters designated under Directive 76/160/EEC. A total of 40 Bathing Waters are monitored within the SEA 5 area. Water quality and sediment monitoring are also undertaken in relation to coastal sewage and industrial discharges (including those associated with aquaculture). In future, the EC Water Framework Directive (2000/60/EC) will require, *inter alia*, the establishment of river basin management plans describing pressures and impacts of pollutants on fresh water and coastal waters and the measures needed to achieve good ecological status.

During the mid-1980s, the contaminant status of the Moray Firth and Firths of Tay and Forth were reviewed in a series of academic seminars organised by the Royal Society of Edinburgh (e.g. Davies 1987, Griffiths 1987, Leatherland 1987, Elliott & Griffiths 1987). In general these reviews describe the worst contamination conditions recorded in these industrialised areas, with subsequent conditions improving due to improved regulation and control of discharges.

The Effects of Oil Exploration and Production in the Fladen Ground: Temporal Trends in Hydrocarbon Composition and Concentration Between 1989 and 2001.

An intensive study of temporal trends in sediment hydrocarbon contamination of the Fladen Ground (south of the SEA 5 area) has been carried out by FRS, with 123 samples at 3km intervals along five transects spaced 5km apart. Sites were classified according to distances from oil installations – near field sites being <5km and far field sites >5km from an installation. All samples collected in 1989 were screened for the presence of polycyclic aromatic hydrocarbons (PAHs) by ultraviolet fluorescence (UVF). Twenty-five samples were further analysed for *n*-alkanes and PAHs. The same sites were revisited in 2001 with 123 samples screened by UVF. Of these, 119 were analysed for PAHs and *n*-alkanes.

Forties oil equivalent concentrations were significantly lower in 2001 compared to 1989 ($p>0.05$, paired t-test) with median values for the 2001 near field sites (21.1µg/g dry weight) being lower than the 1989 far field sites (51.4µg/g), indicating that the level of contamination had decreased. There was no significant difference in the mean of the Forties oil equivalents for the near and far field sites in 2001.

Total PAH concentrations ranged from 29.1 to 641.2ng/g dry weight in 2001. All 1989 sediments were screened by UVF in 1989 however only twenty-five of these sites were also analysed for PAHs. Total PAH concentrations in 2001, at the 25 common sites, were found to be significantly lower than the total PAH concentrations from the 1989 sediment collected from the same site. In addition, the 2001 near field sites had a lower median total PAH concentration (193.9ng/g dry weight) than the 1989 far field sites (584.4ng/g dry weight), emphasising the decrease in concentration from 1989 to 2001..

No significant difference was found between the total PAH concentrations in near and far field site sediments collected in 2001 when all 119 sites were included. Total PAH concentrations ranged from 30.6-455.1ng/g dry weight in near field sites and from 29.1-641.2ng/g dry weight in far field sites.

The PAH profiles of the 1989 and 2001 sediments were investigated further using principal component analysis (PCA). The statistical analysis assessed parent and branched PAH distributions to determine if there were any temporal trends. Differences were found between the 1989 and 2001 sediments with the 1989 sediments containing a higher proportion of 2- and 3-ring PAHs suggesting there was a greater petrogenic input in the 1989 sediments compared to the 2001 sediments.

Reference:
Russell M, Webster L, Walsham P, Packer G, Dalgarno EJ, McIntosh AD & Moffat CF
http://www.marlab.ac.uk/FRS.Web/Uploads/Documents/poster.pdf

5.5.3 Effects and fates of contaminants

SEAs 2, 3 and 4 provide brief synopses of the mechanisms by which substances (whether anthropogenic or of natural origin) may be harmful to the environment. Some, for example organic mercury compounds and some phytoplankton exudates, may be acutely toxic to aquatic species; whereas others are of concern due to their persistence in the marine environment, potential for bioaccumulation and chronic toxicity. Substances which have endocrine disrupting properties or otherwise interfere with reproductive development (e.g. tributyl tin TBT) are of particular concern. Excessive inputs of organic material (as dissolved organic matter in water, or as particulate settlement to sediments) can result in organic enrichment and deoxygenation. Finally, excessive input of nutrients (phosphorus and nitrogen-containing compounds) can result in hyper-nutrification and eutrophication; either of local extent in enclosed waters (e.g. estuaries) or over-extensive areas.

Contaminants are re-distributed within, and removed from, the environment through a number of processes, which largely depend on the physical and chemical characteristics of the contaminants. These include:

- Physical transport of soluble contaminants, suspended particulates and sediments.
- Phase partitioning between soluble, chelated, adsorbed and insoluble compartments.
- Biodegradation by microbial activity and (following uptake) by metabolic processes in invertebrates and vertebrates.
- Bioaccumulation in organisms.
- Biomagnification as a result of transfer between trophic levels in food chains.

There are two main sources of potential biological effect upon marine organisms that are associated with oil and gas production activities: those caused by production discharges, e.g. produced water (mainly soluble contaminants); and those associated with drilling activities (mainly particulates). Both categories of discharge are expected to be much lower in future developments than has historically been the case in the North Sea. Emissions to atmosphere may also give rise to deposition of contaminants (in particular the lower molecular weight combustion products such as naphthalenes and pyrenes) on the sea surface.

Much of the work carried out on contaminant effects (including acute toxicity) relates to Polycyclic Aromatic Hydrocarbons (PAH) associated with oil-based drill cuttings. Although this work is of great relevance to the management of “legacy” contaminants in cuttings piles, current and future drilling activities will not result in discharges of oil-based cuttings to the marine environment. Activities considered within the scope of SEA 5, therefore, will not result in environmental effects from this source. Metals and organic compounds (including low concentrations of aliphatic oils and monoaromatics) discharged in water-based muds do not appear to result in significant toxicity, although associated contaminants (principally metal salts contained in cuttings and barite) may be detectable in the proximity of drilling locations.

Contaminants in produced water plumes could potentially have direct effects on populations of both pelagic invertebrate and vertebrate species in the vicinity of the discharge and also indirect effects via bioaccumulation and biomagnification of contaminants through the food chain. However, composition and toxicity of produced water varies greatly (reviewed by CEFAS 2001, 2002) and although laboratory and enclosure studies have demonstrated the toxicity of produced water from various sources (e.g. Gamble *et al.* 1987, Davies and Kingston 1992, Stromgren *et al.* 1995), high dispersion means that significant toxicity in actual receiving waters has rarely been demonstrated (Stagg *et al.* 1996, Burns *et al*. 1999, Gray 2002). There will be a regulatory presumption against discharges of produced water from any new developments in the SEA 5 area.

5.5.4 Hydrocarbons

Many biogenic hydrocarbons occur naturally in seawater and marine sediments, derived mainly from phytoplanton and other marine biota. Petrogenic hydrocarbons also occur naturally, associated with seeps. However, hydrocarbon contamination through anthropogenic inputs are widespread in the marine environment, with inputs from the offshore E&P industry, shipping, atmospheric transport and coastal sources. Hydrocarbons discharged to the water column are subject to a range of physical processes and biodegradation, and elevated concentrations of most petrogenic hydrocarbons in the North Sea are limited to the vicinity of point source discharges, in areas with intense shipping (especially the Dover Straits and German Bight) and in major estuary systems (notably the Elbe) (OSPAR 2000).

Offshore discharges of oil and organic phase fluids into the North Sea are monitored and reported by OSPAR. The total quantity of dispersed oil discharged into the maritime area of OSPAR (mainly to the North Sea) was 9317 tonnes in 2001 (OSPAR 2003a) excluding organic drilling fluids, mainly from produced and displacement water, spills and flaring operations. Produced water is the major contributor (98.3% in 2001), spillage minor and flaring even less.

In general, the offshore SEA 5 area has been subject to lower historical and current inputs of hydrocarbons than the mature oilfield areas considered in SEA 2, and heavily industrialised coastal areas of SEA 3. Within the SEA 5 area, significant point sources of hydrocarbon discharges include:

- Mature oilfields, notably Beatrice; and previous drilling locations.
- Terminals and petrochemical facilities, notably at Grangemouth and Nigg.
- Previous oil spills, notably *Braer* and *Captain.*

Each of these has been the subject of monitoring studies (e.g. Beatrice: OPRU 1982, 1984, 1985; AUMS 1987, 1992; Grangemouth: Elliott & Griffiths 1987; *Braer*: Kingston *et al*. 1995; DTI survey 2003) and hydrocarbon contamination has been shown to be of limited spatial extent, with peak sediment concentrations up to 6100µg/g (total n-alkanes, Beatrice, 1985 survey). Hydrocarbon concentrations in other parts of the SEA 5 area are generally close to background. Data for total aliphatic hydrocarbons and total PAHs in surface sediment samples taken by the DTI 2003 survey, are summarised in Table 5.9 below:

Table 5.9 – Total aliphatic hydrocarbons and total PAHs in surface sediment samples taken by the DTI 2003 survey

	Total aliphatic hydrocarbons		PAHs	
	Number of samples	**Concentration range (µg/g)**	**Number of samples**	**Concentration range (ng/g)**
Fair Isle	9	0.07-0.28	4	38.75-604.93
Outer Moray Firth	33	0.06-1.55	14	20.41-559.38
Smith Bank	2	0.12-0.17	-	-
Sandy Riddle	8	0.04-1.09	4	39.24-399.62
Southern Trench	22	0.13-2.18	9	36.65-2948.23

There was no clear spatial trend in hydrocarbon concentration, or correlation with water depth; although highest concentrations were generally recorded in samples from the Southern Trench.

During the SEA 5 survey, sites affected by oil from the *Braer* spill in 1993 (Kingston *et al.* 1995) were revisited to investigate the persistence of effects. Although only preliminary results are available, it is clear that hydrocarbon concentrations in sediments have substantially decreased over a 10 year period and now are at, or around, background levels.

5.5.5 Metals

“Heavy” metals, including barium, cadmium, copper, iron, lead, mercury, nickel and zinc, are naturally present in seawater and marine sediments, in a range of forms and concentrations. In excessive concentrations, metals can exhibit toxicity and result in significant environmental effects; with cadmium, lead and mercury generally regarded as the elements of greatest concern (OSPAR 2000). Concentrations of metals in seawater and sediments are greatly influenced by adsorption on to clay particulates, and suspended solids loading and sediment particle size distribution, therefore, have a significant effect on measured concentrations. Similarly, analytical methods usually involve an acid extraction procedure, and “total” metal concentration may have little relation to the proportion which is soluble or otherwise bioavailable. Variability in extraction efficiency and, therefore, the reliability and interpretation of analytical data, is a particular issue in the case of barium, which is a major constituent of drilling fluids and is therefore used as a “tracer” for oilfield contamination (Hartley 1996).

There are few measurements of offshore water column metals in the SEA 5 area, or adjacent offshore areas (OSPAR 2000), although concentration ranges for the northern North Sea from the 1985-1987 ICES Baseline Study of Trace Metals in Coastal and Shelf Sea Waters (ICES 1991) and German ZISCH Project (Circulation and Contaminant Transfer in the North Sea) are reported by OSPAR (1993). These data indicate dissolved trace metal concentrations similar to open ocean water (cadmium 0.004-0.024µg/l, copper 0.11-0.42µg/l, lead 0.036-0.051µg/l, mercury 0.003-0.008µg/l, nickel 0.16-0.30µg/l).

The NMP specified that for aqueous determinands (including trace metals) three sampling locations were required in each of the three major Scottish estuaries (Clyde, Tay and Forth), with some samples from intermediate and offshore locations in the Moray Firth and east of the Tay/Forth. Summary data from NMP (1998) are presented below to allow comparison of the SEA 5 locations in a national context:

- Other than the sites in the Tay estuary, median concentrations of **cadmium** were all less than 0.05mg/l. In the Tay the detection limit of the method resulted in all values being quoted as <0.07mg/l. Cadmium concentrations at intermediate and offshore sites were <0.02mg/l.
- The median **lead** concentration at all sites was <0.5mg/l and at most sites <0.2mg/l. Only in the Forth estuary was the analytical method sensitive enough to quantify dissolved lead concentrations; here they ranged from 0.024 to 0.046mg/l.
- The NMP data for dissolved **chromium** represent the results of the first reliable survey for this element in Scottish estuarine and coastal waters. Chromium concentrations at intermediate and offshore sites were generally less than 0.5 mg/l. Concentrations in estuaries were higher but below 2mg/l in the SEA 5 area.

- **Copper** concentrations at intermediate and offshore sites were generally less than 0.5mg/l. Within estuaries median concentrations were lowest in the Tay (0.8-1.7mg/l) and slightly higher in the Forth (1.2–2.4mg/l).
- Dissolved **nickel** concentrations were low in the Tay (0.4-0.5mg/l), but slightly higher in the Forth (0.7-1.3mg/l). At intermediate and offshore sites concentrations were generally <0.5mg/l.
- **Zinc** concentrations at intermediate and offshore sites were typically 1-2mg/l; in estuaries however they were higher; (2.2–4.3mg/l) in the Forth and (2.9–5.3mg/l) in the Tay. The relatively high concentrations of dissolved Zn reported for the Tay estuary are not consistent with previously published data (Balls *et al.* 1997a) and may be indicative of a contamination problem for this element.

At each of the 18 Scottish NMP sites, nine sediment samples were obtained. A general conclusion from these samples was that trace metal concentrations in sediments from the Forth estuary were consistently higher than those from offshore locations (NMP 1998). The contrast in concentrations between estuarine and offshore sites is greatest for mercury and arsenic, least for cadmium and copper. Trace metal concentrations in sediments from the Tay estuary were generally much lower than those in the Forth with the exception of one site located close to Dundee.

It is well established that trace metal contaminants are preferentially associated with the fine fractions of sediments. Aluminosilicate minerals are dominant within these fractions and the concentration of aluminium is often used as a measure of their abundance. Relative to trace metals aluminium is abundant in sediments and consequently its concentration is not greatly affected by geochemical processes. To assess to what extent the variations in trace metal concentrations between sites were a consequence of those in grain size, a normalisation procedure to aluminium was adopted by the NMP.

Relative to aluminium, enrichment of metals was evident in the outer part of the Tay estuary and in all samples from the Forth. Enrichments for individual metals showed a similar pattern between the sites, i.e. high in the Forth, low at offshore sites. There were, however, some notable differences in the degree of enrichment for individual metals. Enrichment values for chromium, nickel, copper, zinc and cadmium were generally <5, those for lead and arsenic were greater and those for mercury were highest of all (>10 in the Forth estuary). The Forth estuary has a history of mercury contamination. Industrial inputs have now been eliminated, but the turbid nature of the estuary has resulted in considerable retention of mercury within the system (Elliott & Griffiths 1986).

As noted above, barium is a major component of drilling fluids, and is generally regarded as an indicator of oilfield contamination (Hartley 1996, OSPAR 2000). For example, recent accumulation of barium in depositional areas of the Skagerrak (Longva & Thorsnes 1997) are considered likely to be associated with drilling discharges in the North Sea. Elevated barium concentrations in the SEA 5 area have been detected only in close proximity to drilling locations.

5.5.6 Persistent contaminants

A range of organic contaminants are characterised as persistent, i.e. are biodegraded or degraded by physical processes (e.g. photo-oxidation) very slowly. Such contaminants may be transported over global scales, and in some cases are highly toxic or contribute to global environmental effects. Persistent organic contaminants include chlorinated hydrocarbons such as polychlorinated biphenyls (PCBs), chloro-fluorocarbons (CFCs), polychlorinated dioxins and dibenzofurans (PCDD/Fs) and organochlorine pesticides; brominated flame retardants; octylphenol and nonylphenol ethoxylates (OPE and NPE) and organo-metallic compounds such as tributyl tin (TBT).

The discharge of persistent organic contaminants from UKCS installations is now strongly presumed against (effectively prohibited) by the chemical permit system (*Offshore Chemicals (Pollution Prevention and Control) Regulations 2002)* which include a requirement for substance- and site-specific risk assessment. The regulations implement OSPAR Decision 2000/2 on a Harmonised Mandatory Control System for the Use and Reduction of the Discharge of Offshore Chemicals. As well as comprehensive testing, pre-screening, ranking, hazard assessment and risk management of chemicals, the OSPAR decision requires the substitution of certain chemicals by less hazardous alternatives. All highly persistent substances, or preparations containing substances, will be prime candidates for substitution. The UK approach to substitution is set out in Guidance Notes to the above regulations (http://www.og.dti.gov.uk/regulation/legislation/environment/chemregs2002.doc).

Some PCBs and ethoxylates have been used historically (in transformers, paints and drilling fluids) and detectable concentrations may be present in "legacy" cuttings piles, although Beatrice is the only such location within the SEA 5 area (significant quantities of PCBs were also released following the Piper Alpha disaster, again outside the SEA 5 area).

Localised "hotspots" of PCB contamination in SEA 5 coastal waters are associated with previous industrial activities (e.g. the Cromarty Firth). At each of the 18 Scottish NMP sites, analysis of sediment samples included the determination of a range of PCB congeners, DDT (ppTDE, ppDDE, ppDDT), hexachlorbenzene (HCB), dieldrin, aldrin and endrin (NMP 1998). Many trace organic compounds are preferentially adsorbed onto the organic fraction of sediment. The NMP data have therefore been normalised to the organic carbon content to assess to what extent the variations in contaminant concentrations between sites are a consequence of the variations in organic carbon. This reduces, but does not fully explain, PCB concentrations in the Forth which are attributed to historic inputs (Harper *et al*. 1992).

- Relatively high concentrations of **PCB** were found in the Forth estuary. When the data are normalised to organic carbon the contrast in concentrations between sites is much reduced, i.e. a dominant factor controlling PCB content is the organic carbon content of the sediment.
- The highest concentrations of **HCB** were found in the Forth and this is still the case when the data are normalised to organic carbon. Concentrations in the Forth are two orders of magnitude greater than elsewhere in Scotland.
- High concentrations of **DDT** were found at estuarine sites in the Forth. Normalising the data to organic carbon decreases the difference in concentrations between sites. The sediments in the Forth estuary are still shown to contain relatively high concentrations of DDT, although concentrations are below the sediment action levels.
- Absolute concentrations of **dieldrin** are generally low, and again the highest concentrations are found in the Forth estuary.

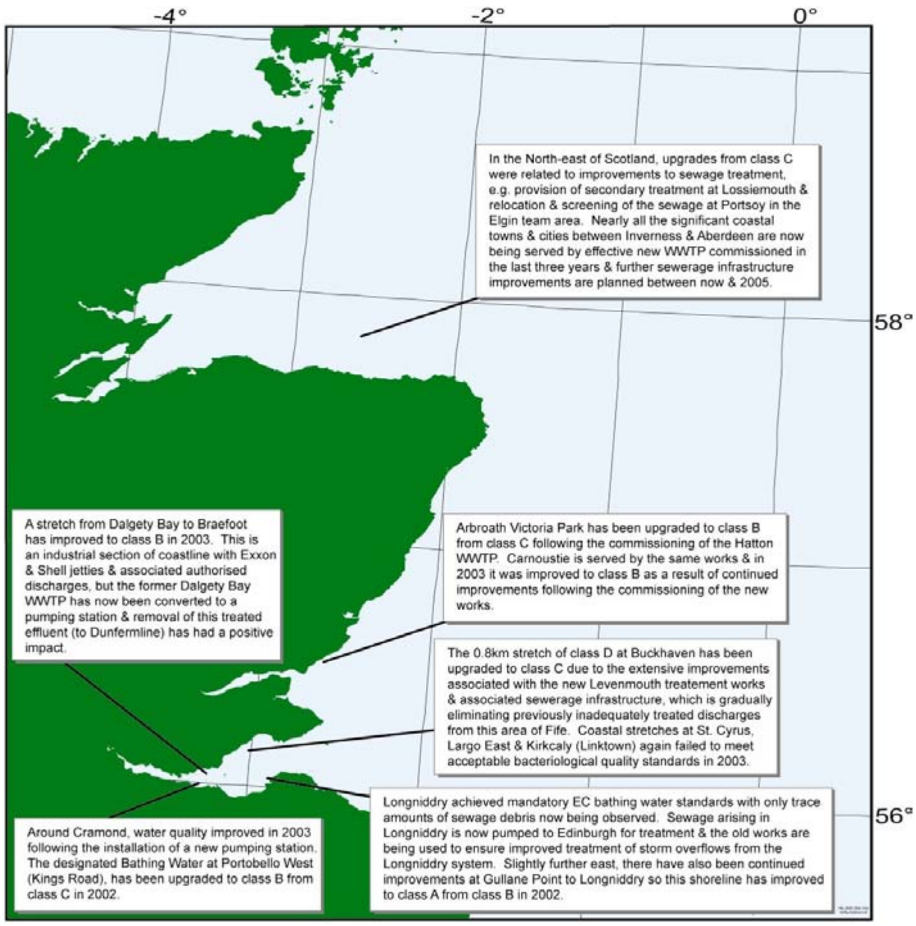
5.5.7 Sewage and faecal coliforms

Sewage discharges are associated with coastal communities along the SEA 5 coastal margin, with a range in size associated with population equivalents from <100 to >100,000. Following implementation of the Urban Waste Water Treatment Directive (91/271/EEC), which sets treatment levels on the basis of sizes of sewage discharges and the sensitivity of waters receiving the discharges, the UK has stopped all disposal of the sewage sludge left over from treatment processes to sea or to other surface waters. None of the east Scottish, Orkney and Shetland coasts are classified as Sensitive Areas on account of eutrophication (although the adjacent Ythan estuary and lower River Don are designated as such); various Bathing Waters and Shellfish Production Waters have been designated on the SEA 5 coast. Estuarine and coastal waters formerly identified as *Less Sensitive Areas* (*High Natural Dispersion Areas* under the transposing regulations) have now all been revoked.

The Bathing Waters Directive (76/160/EEC) requires monitoring of microbial indicators of faecal contamination (faecal coliform, total coliform and faecal streptococci). Forty of Scotland's 60 identified Bathing Waters are located in the SEA 5 area: in 2003, monitoring by SEPA classified all 40 as "excellent" (i.e. met the Directive's guideline quality standards) or "good" (i.e. met the Directive's mandatory quality standards).

Coastal classification
Following its establishment in 1996, SEPA introduced a new quality classification scheme, which results in a single classification class outcome incorporating biological, chemical and aesthetic elements for rivers and coastal waters. SEPA has reported annually on the progress made on improving water quality classification. In general, data from 2003 demonstrate continuing substantial quality improvements in rivers and coastal waters, due mainly to improvements in sewage discharges; with some expected short-term downgrading of estuarine waters due to particular weather conditions (SEPA 2003, Figure 5.14).

Figure 5.14 – Changes in Scottish Environmental Protection Agency National Water Quality Classification 2003



5.5.8 Data gaps

In general, there is a reasonable basis of data with which to assess contaminant status of the SEA 5 area, and it is unlikely that significant areas of contamination have not been identified, although spatial coverage of offshore areas is limited. Until the SEA 5 programme, there had been no systematic attempt to identify potential contaminant sinks in offshore areas, and results from the 2003 survey programme suggest that temporal monitoring in the Southern Trench (where hydrocarbon concentrations were generally highest, probably associated with fine sediments) should be instigated. Long-term temporal monitoring (5-10 years) of the Fladen ground area (south of SEA 5) and known “hotspots” (e.g. Beatrice area) could usefully be integrated with ongoing NMP monitoring.

Contamination monitoring is also dependant on analytical methodologies, especially where low concentrations close to detection limits are involved. Analytical methods continue to develop, and it can be difficult to relate recent data to historical results. Archiving of samples, for future analysis, may be useful in this context.