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NORTH SEA GEOLOGY

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SUMMARY

This review presents a summary of published data and their interpretation from areas in the mature oil and gas areas of the UK North Sea occurring to the east and north of the British Isles. The basis for this review is the premise that the modern environment is a synthesis of past environmental conditions. The purpose is to review (1) the evolution of the deeply-buried sediments with reference to the petroleum geology and production-related seabed subsidence (2) the evolution of the shallow seabed sediments with reference to present sediment distributions and seabed features (3) the evidence for possible hydrogeological exchange across selected onshore/offshore areas (4) the history of earthquakes and the hazard that they may pose. It is intended that the review will provide a basis for a better understanding of the impacts of possible future changes in the natural environment.

The overall modern topography of the North Sea sea bed has originated from the influences of deep geological structure on the patterns of basin subsidence, uplift and climate on sediment input. The smaller-scale seabed geometry of the continental shelf is a relict 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 the North Sea continental shelf is now dominated by very low sediment input and the reworking of the seabed by near-bottom currents.

A precursor to the submarine evolution of the North Sea occurred more than 375 million years ago with the deposition of marine limestones. Subsequently, subsidence and burial under thick accumulations of basin sediments has generated gas from coal source rocks, possibly commencing prior to approximately 140 million years ago. Oil and gas has been generated from deeply-buried mudstone source rocks from approximately 65 million years ago to the present day. Commercial petroleum reservoirs occur in almost every sedimentary succession ranging in age from approximately 410-36 million years. Exceptionally, the extraction of oil and gas has lead to production-related seabed subsidence, the effects of which are locally felt. This process appears to be restricted to a few types of reservoir and to date does not appear to have had major environmental impact.

Extreme changes from arctic to temperate climates have been the dominant control on sediment type and the overall very high rate of sediment input into the North Sea from approximately 800,000 years ago to the present day. The overall effect of the repeated glaciations during the cold periods has been to keep the North Sea basin filled with sediments during a time when there was very rapid basin subsidence.

The bulk of the modern seabed sediments comprises substrates that are more than 10,000 years old and have been reworked from strata by currents that have been generated by tides and sea waves. The reworked sediments typically form large areas of seabed sand and gravel. Such sediments also form the large-scale sandbanks and ridges and smaller sand waves. These characterise much of the seabed topography in the southern North Sea and are of strategic environmental interest. The largest ridges and banks have formed sub-parallel to the dominant tidal currents and occur as open-shelf ridges, estuary-mouth ridges or headland-associated banks. Many of these nearshore sand banks are mobile, others show little evidence for long-term mobility except at seabed where sandwaves appear to indicate that there is modern clock-wise circulation of sand around the bank.

Hard substrates which are resistant to reworking are of interest to environmentalists and developers alike as they form areas of stable seabed for biota and may present problems for seabed site developments. The main types of hard substrate occurring at or near seabed comprise the unconsolidated gravel spreads, boulders, hard cohesive sediments which were formed during the glaciations and rock outcrops. All these commonly occur together in the nearshore western margins of the North Sea. The distribution patterns of rock, gravel spreads and the hard cohesive gravelly Quaternary sediments that have been deposited under or adjacent to the last ice sheet are quite well known and have been mapped by regional surveys. Other, usually older, seabed or superficial hard cohesive substrates are patchily developed mid-shelf and are therefore relatively unpredictable.

Soft muds typically cover wide flat areas in the deeper waters of the continental shelf. In the central and northern North Sea the spreads of soft muds are locally characterised by small depressions or ‘pockmarks’, most of which appear to have been formed at times of fluid escape at seabed. The areas of seabed pockmarks have therefore originated by unusual processes resulting in seabed excavation and soft-sediment mobility.

Few data are available with which to assess the possible effects of development operations on onshore and offshore aquifers. What data there are indicate that saline water ingresses inland locally from restricted zones offshore from East Anglia whilst the predominant movement elsewhere is that of freshwater movement offshore. There is a local risk of groundwater contamination if developments are superimposed on areas at seabed outcrop. There is a negligible risk of contamination of onshore supplies of freshwater from the mature areas of the oil and gas development provinces in the central and northern North Sea. Overall, the risk of onshore aquifer contamination decreases with increasing distance from the offshore to developments.

The regional distribution patterns of earthquakes occurring under the North Sea are related to the deep geological structure. Expectations of earthquakes with magnitude of 4 or higher may require special structural design and are therefore also of environmental concern. In the North Sea as a whole, the expectations for a magnitude 4 natural seismic event is approximately every 2 years and a magnitude 5 natural seismic event every 14 years.

1. GEOLOGICAL HISTORY AND PETROLEUM GEOLOGY INCLUDING SPECIFIC SEA2 AREAS

1.1 Northern and Central North Sea

1.1.1 Geological history

1.1.1.1 Palaeozoic (about 590 - 250 million years ago)

The configuration of Lower Palaeozoic crystalline and metamorphic basement rocks that underlie the North Sea sedimentary basins (Figure 1) was assembled during the Caledonian Orogeny (about 420 - 390 million years ago) to form the Caledonian basement. This was achieved through the closure of the Iapetus Ocean and the Tornquist Sea, at the Iapetus Suture and 'Trans-European Fault Zone', respectively (e.g. Andrews *et al*. 1990; Johnson *et al*. 1993; Gatliff *et al*. 1994; Glennie and Underhill 1998). Many of the major faults within the Caledonian basement formed lines of weakness that experienced significant reactivation during subsequent phases of earth movements.

During the Devonian (about 410 -360 million years ago), there was widespread red-bed molasse and lacustrine sedimentation as the newly-formed Caledonian mountain ranges were eroded. Mid-Devonian (about 375 million years ago) marine limestones in the south of the Central North Sea were probably formed during an early rift phase. This was a precursor to the main phases of Permo-Triassic (about 290 - 210 million years ago) and Late Jurassic rifting (about 160 - 140 million years ago) and associated strike-slip movements.

During the early Carboniferous (about 360 - 325 million years ago), fluviodeltaic and shallow-marine sediments and local volcanics accumulated in parts of the Central North Sea at times of regional crustal extension, though the Northern North Sea area was mainly source of clastic sediments. As in England, these Carboniferous rocks were gently folded, faulted, uplifted and eroded during the Late Carboniferous Variscan Orogeny approximately 300-290 million years ago.

During the Late Permian (about 270 - 250 million years ago) redbeds and local volcanics (Rotliegend Group) accumulated within the widespread Northern Permian Basin. Following marine transgression, cyclical evaporitic successions (Zechstein Group) were deposited and locally reach over 1000 m in thickness. The evaporites have been deformed by halokinesis intermittently since mid-Triassic times (about 230 million years ago), leading to the widespread growth of salt pillows and salt diapirs, especially in the Central North Sea (Figures 2 and 3, cross-section B-B').

1.1.1.2 Mesozoic

For the ages of the geological systems and events in this section the reader is referred to Figure 2. In the Triassic there was a return to arid, continental climate conditions and both sandstone- and mudstone-dominated redbed successions were laid down. During the Early Jurassic there was a spread of marine deposits over much of the North Sea during a phase of thermal subsidence following Permo-Triassic rifting.

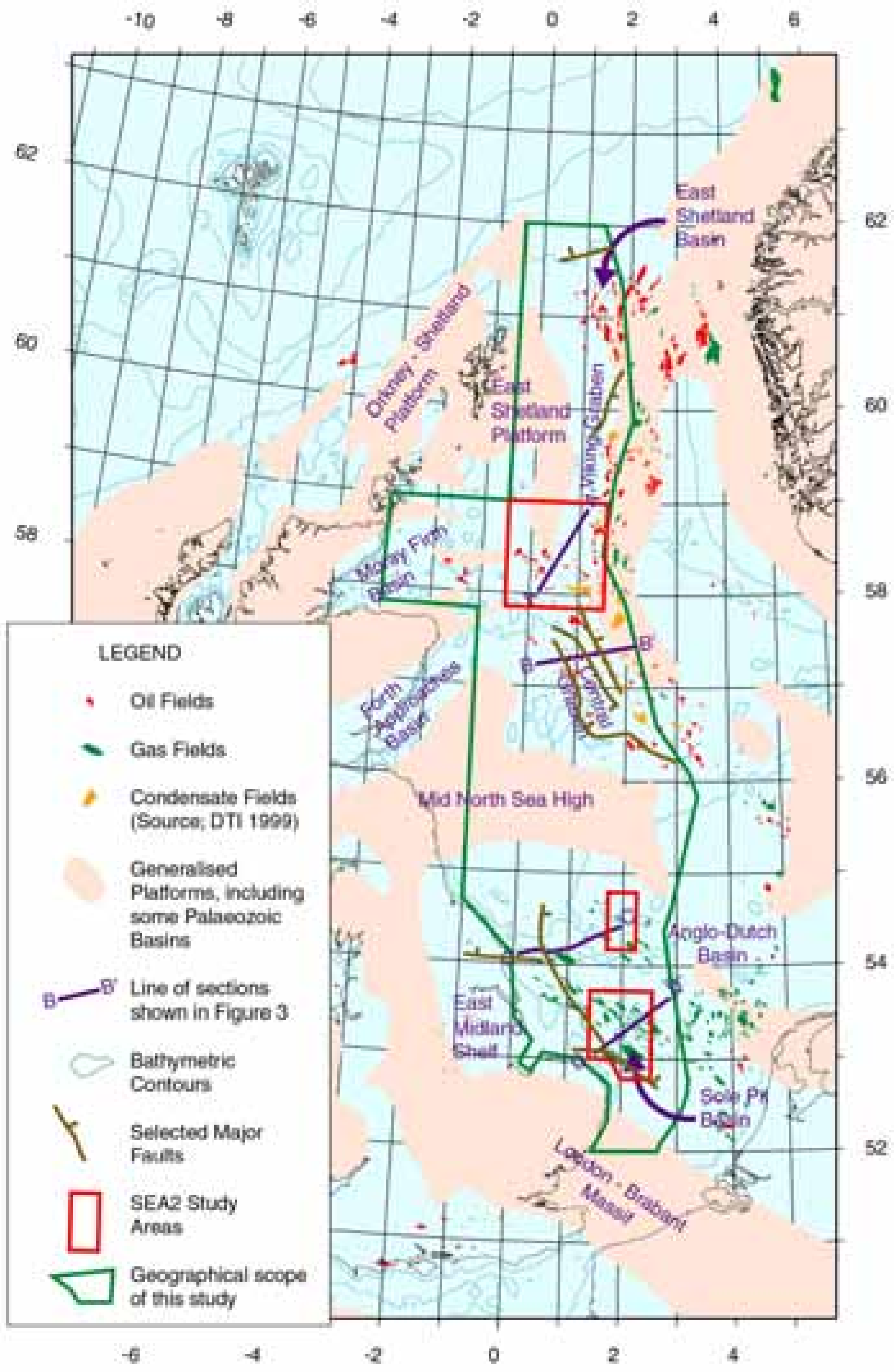

Figure 1. ***Generalised structural framework of the North Sea region. Compiled from Andrews et al. (1990), Cameron et al. (1992); DTI (1999), Gatliff et al. (1994), Johnson et al. (1993). Cross sections A-A' to D-D' are illustrated in Figure 3.***

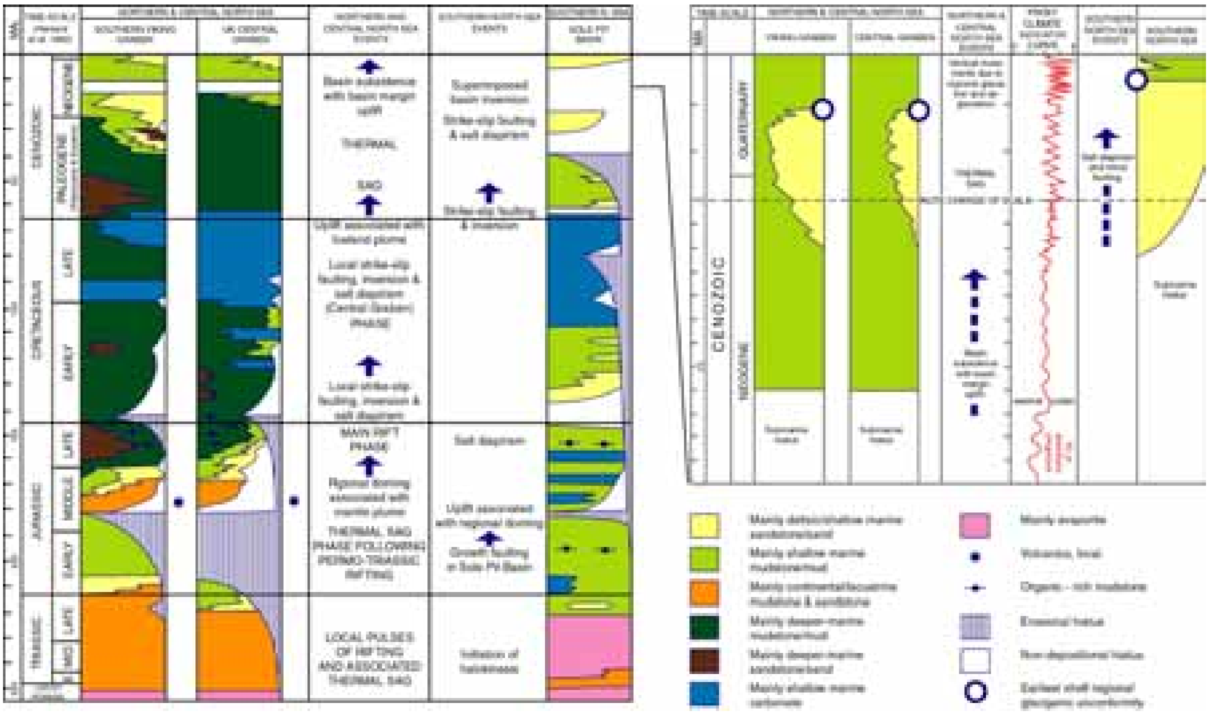

Figure 2. Generalised tectono-stratigraphical development of the UK North Sea. 250-15 million years adapted after Zeigler (1990), 15-0 million years adapted after Cameron et al. (1992), Johnson et al. (1993), Gatliff et al. (1994) and Holmes (1997). The proxy climate indicator curve was adapted from Abreu and Anderson (1998).

During the Middle Jurassic, regressive, paralic sediments accumulated when a major subaerial thermal dome formed within the Central North Sea (Figure 2), probably due to the development of a warm, diffuse and transient mantle-plume head (Underhill and Partington 1993). The Late Jurassic was a time of major extensional faulting. The rifting was initially most intense at the extremities of the present graben system and as time elapsed it propagated back towards the centre of the dome (Rattey and Hayward 1993; Fraser 1993). The onset of major rifting probably occurring in the middle Oxfordian to early Kimmeridgian (approximately 157 - 155 million years ago) (Underhill 1991; Glennie and Underhill 1998). Seismic data reveal that the Upper Jurassic sedimentary successions commonly thicken dramatically towards syndepositional faults (Figure 3, cross-sections A-A' and B-B'). This pattern of sediment thickness variation is in contrast with that formed during the 'thermal sag' phase of basin development (e.g. McKenzie 1978) in Early-mid Jurassic times, when the basin was more 'saucer-shaped' and the thickest deposits accumulated at its centre.

Rift styles vary substantially between the northern and the central North Sea and there were two principal controlling factors. Firstly, differences in the basement composition and tectonic grain between the two regions strongly influenced structural development. In the central North Sea, the rifts are more complex and were segmented along NE 'Caledonide' and NW 'Trans-European Fault Zone' trends (e.g. Errat *et al*. 1999; Jones *et al*. 1999). Secondly, in the northern North Sea, Upper Permian salt is largely absent, and there is no major detachment between basement and cover rocks. In contrast, the Zechstein evaporites in the central North Sea provide a major detachment level that essentially separates the basement rocks from the cover sequence of rocks or 'carapace' (e.g. Hodgson *et al*. 1992; Smith *et al.* 1993; Helgeson 1999). This structural contrast is reflected in the smaller size of the oil and gas fields discovered within the pre- and syn-rift successions of the central North Sea.

Local inversion of central North Sea depocentres during the Early Cretaceous is considered to be a response to strike-slip faulting (Pegrum and Ljones 1984). Transpressional pulses are believed to have triggered the halokinesis of Zechstein salts within the Central Graben, which exerted an additional control on the patterns of subsidence and sedimentation (Oakman and Partington 1998; Gatliff *et al*. 1994).

1.1.1.3 Cenozoic

Thermal subsidence in response to Late Jurassic rifting, dominated much of the Cenozoic, with some relatively minor pulses of earth movements (e.g. Pegrum and Ljones 1984).

Regional patterns of sedimentation changed dramatically in early Paleogene times, with the influx into the basinal areas of huge volumes of coarse clastic detritus including debris flows and turbidites. This detritus was shed from the uplands of northern Scotland and the Orkney-Shetland Platform, which were undergoing thermal uplift in response to the development of the Iceland Plume (White 1988; White and Lovell 1997).

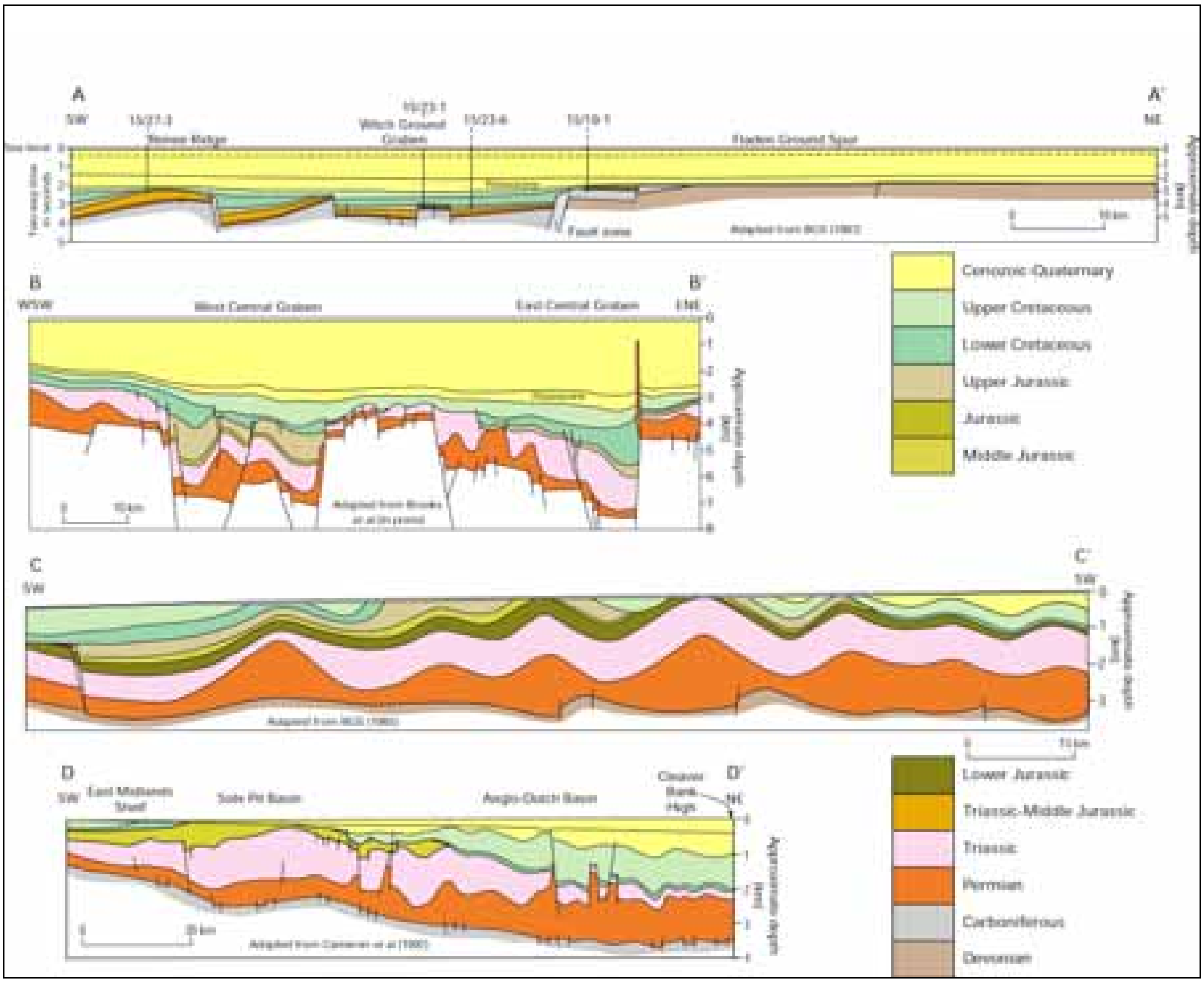

Figure 3. Generalised geological cross-sections across the UK North Sea. Adapted after BGS (1985), BGS (1987), Cameron et al. (1992) and Brooks et al. (in press).

1.1.2 Petroleum geology

Upper Jurassic syn-rift, organic-rich marine mudstones (the Kimmeridge Clay Formation) provide the source material for most of the region's hydrocarbons (Brooks *et al*. in press). Cretaceous and Cenozoic post-rift thermal subsidence and burial (Figure 3) has enabled the source rocks to become mature for hydrocarbon generation along the rift axes from Paleogene times onward (Johnson and Fisher 1998). Hydrocarbon migration has been mainly vertical, but with significant lateral migration restricted to the Upper Jurassic and Paleogene successions. Hydrocarbons extraction is from almost every clastic and carbonate sedimentary succession, ranging in age from, and including, Devonian and Eocene strata.

Pre-rift producing fields comprise Palaeozoic, Triassic to Lower Jurassic and Middle Jurassic categories (Brooks *et al*. in press). The Middle Jurassic tilted fault-block play is best developed in the East Shetland Basin and is one of the most productive in the North Sea.

Syn-rift reservoirs within producing fields comprise Upper Jurassic to Lower Cretaceous sandstones according to Brooks *et al*. (in press), though many authors prefer to interpret the Lower Cretaceous succession as post-rift deposits formed during a phase of local strike-slip tectonism (e.g. Rattey and Hayward 1993; Oakman and Partington 1998). The producing Upper Jurassic reservoirs include both shallow and deep marine sandstones, though Lower Cretaceous reservoirs were almost exclusively formed within deep marine settings.

The syn-rift hydrocarbons producing fields display a wide variety of trapping mechanisms, including tilted fault blocks, domes, and stratigraphic closures. Thick, post-rift Lower Cretaceous mudstones also provide a regional seal for many traps.

Post-rift thermal subsidence has continued from Cretaceous times to the present day. Within the UK sector, the Upper Cretaceous Chalk is relatively insignificant as a producing reservoir.

Mass-flow sandstone reservoirs of Paleogene age are estimated to contain about 20% of the oil province's proven hydrocarbon reserves (Pegrum and Spencer 1990). Virtually all of the UK sector Paleogene sand systems become progressively distal to the east or SE. There was an evolution from the emplacement of laterally extensive sheet sands on the basin floor during the early Palaeocene, to restriction of sand bodies into narrow, elongate channels intercalated within mud-dominated slope facies during the mid-Eocene.

1.1.3 Petroleum geology of SEA2 Area 3

SEA2 Area 3 lies within the Central North Sea and includes many important producing hydrocarbon fields. These fields mainly produce from syn-rift Upper Jurassic and/or post-rift Lower Cretaceous or Paleogene reservoir sandstones. Halokinesis has generally not exerted a major influence on the structural development of SEA Area 3.

Many of the Upper Jurassic and some of the Lower Cretaceous hydrocarbons traps are located within either the footwall or hangingwall blocks of major faults (e.g. the Piper and Brae fields). Other, younger Lower Cretaceous hydrocarbons traps include a larger component of stratigraphic trapping (e.g. the Britannia Field). All the Mesozoic traps are deeply buried by the thick Cenozoic successions which occur within or overlie the rift-basins. In contrast, many of the Paleogene traps are buried at relatively shallow depths. For example, the Balmoral Oilfield lies at about 2150 m depth (Tonkin and Fraser 1991).

1.2 Southern North Sea

1.2.1 Geological history

1.2.1.1 Palaeozoic

The Southern North Sea Basin has developed as a result of a long and complex history of basinal subsidence. This has been punctuated by discrete episodes of uplift and widespread erosion during end Silurian ('Caledonian Unconformity'), about 420-410 million years ago, Late Carboniferous ('Variscan Unconformity') about 300-290 million years ago, Late Jurassic ('Cimmerian Unconformity') about 160-140 million years ago, Late Cretaceous about 97-66 million years ago and at several times during the mid-Cenozoic (Cameron et al. 1992). Lower Palaeozoic sediments are likely to be many kilometres thick beneath most or all of the southern North Sea. They were mildly deformed and intruded by granite plutons during the Caledonian Orogeny of Late Silurian to Early Devonian about 420 - 390 million years ago.

The dominantly WNW and NW trends of the faults within the Late Palaeozoic, Mesozoic and Cenozoic successions (Figure 1) may be inherited from the structure of the underlying Lower Palaeozoic basement.

Following Caledonian uplift, most of the Southern North Sea remained an upland area of net erosion during the Devonian about 410-360 million years ago. Crustal extension was initiated early in the Carboniferous after approximately 360 million years ago, following which up to 4000 m of deep-water or deltaic sediments were deposited within the graben areas. Some or all of the granite batholiths inferred from their geophysical signatures may lie beneath early Carboniferous horsts (Cameron et al. 1992), though significantly different interpretations exist for the locations of the syn-rift blocks and basins (e.g. Collinson et al. 1993; Besley 1998). By approximately 325 million years ago rifting had effectively ceased and a phase of thermal subsidence had commenced.

From approximately 360 million years ago Variscan crustal movements increasingly affected the southern North Sea Basin. During the Variscan Orogeny, about 300-290 million years ago, the Carboniferous rocks were gently folded and faulted. During about 310 - 270 million years ago differential Late Carboniferous to Early Permian regional uplift accompanied by peneplanation led to the erosion of more than 1500 m of Carboniferous strata from parts of the Southern North Sea Basin. The Mid North Sea High was formed by the regional inversion occurring during this time.

Following the Variscan Orogeny, the southern North Sea Basin began to subside again in the Permian times, and more than 2700 m of Permo-Triassic strata, covering an age range of about 290-210 million years) were deposited, including red beds and a thick, cyclical, evaporite succession.

1.2.1.2 Mesozoic

For the ages of the geological systems and events the reader is referred to Figure 2.

Enhanced Late Triassic and Early Jurassic subsidence in the Sole Pit Basin was related to reactivation of its Variscan basement faults (Glennie and Boegner 1981). These tectonic movements triggered the earliest mid-Triassic halokinesis of the Upper Permian salts (Figure 3, cross-sections C-C' and D-D').

Fully marine conditions were then re-established in the southern North Sea at the end of the Triassic. Subsequently, during early–mid Jurassic times, differential subsidence of the Sole Pit Basin was accentuated by the development of growth faults along its western margin. It is these faults that account for the major thickness and facies changes of the Lower and Middle Jurassic sediments between the Sole Pit Basin and the East Midlands Shelf.

In the Middle Jurassic, widespread domal uplift centred in the central North Sea and resulted in an erosional unconformity. More than 1000 m of Jurassic and Triassic strata were eroded from the Cleaver Bank High at this time (Glennie 1986). During the Late Jurassic there was a widespread pulse of diapirism (Glennie and Underhill 1998).

Lower Cretaceous sediments are typically less than 200 m thick, but reach up to 1000 m in local zones of growth faulting, associated with sinistral fault movement (Kirby and Swallow 1987). During the Late Cretaceous, the Cleaver Bank High became established as the main depocentre and accumulated more than 1000 m of Upper Cretaceous chalk.

1.2.1.3 Cenozoic

A major phase of basin inversion during, or at the end of, the Late Cretaceous affected many basins in NW Europe, including the Sole Pit Basin and the Cleveland Basin (Figures 1 and 2), and has been attributed to both strike-slip reactivation of basement faults (Glennie and Boegner 1981).

Cenozoic subsidence in the North Sea has been dominated by broad synclinal downwarping towards a depositional axis that extends from the Viking Graben, through the Central Graben towards the Netherlands. During Oligocene to Miocene times, many of the basement faults in the Southern North Sea were reactivated by dextral strike-slip (Glennie and Boegner 1981), which triggered further major halokinesis. Most of the salt pillows north of 54º North were initiated in mid-Cenozoic times, and Glennie (1986) related contemporaneous inversion of the Sole Pit Basin to Alpine earth movements. There are very few Miocene sediments, and only local outliers of Pliocene deposits. Rapid subsidence became more widespread early in the Quaternary resulting in the preservation of more than 600 m of Pleistocene progradational delta deposits and glacigenic deposits.

1.2.2 Petroleum geology

Around 85% of all gas production has been from pre-Zechstein Permian (Rotliegend Group) aeolian dune sandstones, and 13% from Triassic fluvial sandstones. Much of the remaining production has been from Carboniferous fluvial sandstones.

The Permian Leman Sandstone play is restricted to the southern part of the gas province, because the reservoir facies passes northwards into contemporary playa lake mudstones and evaporites.

The principal source rocks comprise up to 800m of Westphalian A-C coal measures, which unconformably underlie the Permian reservoir rocks (Figure 3, cross-sections C-C' and D-D'), though Namurian marine source-rocks are also significant (Brooks *et al*. in press). The

Westphalian source rocks beneath the Sole Pit Basin may have generated their gas as early as the Jurassic.

The preservation of large volumes of gas contained within the Permian sandstones throughout a long history of tectonic reactivation testifies to the efficiency of the seal provided by the Permian evaporite-rich succession (Zechstein Group).

1.2.3 Petroleum geology of SEA2 Area 1

SEA Area 1 straddles the Sole Pit Basin and Cleaver Bank High and includes many gas fields, the majority of which have Permian Leman Sandstone (Rotliegend Group) reservoir rocks, sealed by Permian evaporites (Zechstein Group). An exception is the Hewett Gasfield, on the SW margin of the Gas Province, which has substantial reserves of gas in Triassic reservoir rocks, the Hewett Sandstone unit of the Bunter Shale Formation (Johnson *et al*. 1994). At the Hewett Gasfield and along the northern flank of the London-Brabant Massif, the Permian halites are relatively thin, and many faults extend through the Permian succession to offer migration routes for the accumulations of gas in the Triassic reservoirs.

1.2.4 Petroleum geology of SEA2 Area 2

SEA Area 2 lies within the Anglo-Dutch Basin and includes the Gordon Gasfield, which has now ceased production. This gasfield has a Triassic, Bunter Sandstone Formation reservoir, like the Forbes and Esmond fields, with which it was developed jointly (Cameron *et al*. 1992). The mudstones and evaporites of the Haisborough Group provide a regional seal for the gas trapped in the Bunter Sandstone Formation. Despite excellent reservoir properties and the identification of many large closures, almost all tests of Triassic sandstones have been abandoned as dry. Only at very few places have the underlying Upper Permian evaporites been breached by Carboniferous-sourced gas. The Esmond, Forbes and Gordon are located above the crests of large Zechstein salt swells, and contain/contained substantial reserves of gas only because they are adjacent to zones of extreme thinning and failure of the Permian evaporite seal.

1.3 Late Cenozoic climate-driven sedimentary processes

Changing patterns of polar and continental ice accumulation and associated relatively low eustatic sea levels, which are followed by polar and continental ice melt and higher eustatic sea levels are related to cyclical changes in global climate (Shackleton, 1987). These have influenced the global-scale patterns of sedimentation and erosion for at least the last 25 million years (Abreu and Anderson, 1998) and by implication, those of the North Sea.

The imposition of cyclical global temperature changes on a climate that is generally becoming colder is illustrated for the last 15 million years (Figure 2). This cooling has been accentuated for the British Isles and the North Sea, by their northward drift on the Eurasian lithospheric plate of approximately 10° latitude over the last 60 million years (Smith et al, 1981).

From between approximately 40 and 5 million years ago, the palaeo environment of the southern North Sea is characterised by a depositional hiatus and the central and northern North Sea by rapid deposition associated with basin subsidence induced by thermal sag (Figure 2). Possibly as a result of Atlantic plate re-organisation approximately 10-5million years ago, the central North Sea basin subsidence was contemporaneous with the likely uplift of the adjacent British Isles and Fennoscandia (Cloetingh et al, 1990). Later these uplifted areas became centres of ice accumulation and facilitated the expansion of the major ice sheets into the North Sea.

The significance of the transition over the last few million years to possible uplift-induced glaciation and an alternating warm-to-cold climate during a period of overall global cooling, is that it marks the onset of an underpinning climate-driven influence on North Sea sedimentation. This influence has lasted to the present day. Climate change has influenced the sediment types, their preservation potential, their depositional rate and their sediment transport pathways. The impact of extreme climate change on the distribution of sediment types within the North Sea also varied with latitude. For example, sand-dominated shallow marine and deltaic deposition may have ceased in the northern North Sea at a time when an ice sheet first crossed the northern North Sea approximately 1.1 million years ago (Holmes, 1997). Thereafter sediments deposited in the northern North Sea were mainly mud-dominated (Figure 2). Several climate cycles later, the cessation of large-scale deltaic sedimentation originating from northwest Europe is correlated with a period approximately 440, 000 years ago when the southern North Sea was bridged by an ice sheet, also possibly for the first time (Gibbard, 1988).

From approximately 800,000 years ago until the present day, the marine oxygen isotope curve indicates that there have been possibly 7 periods of intense cold compared to the present-day temperate conditions (Figure 2). The longest and most intensively cold periods averaged approximately 100,000 years in duration (Figure 1 in Funnell, 1995). Of these, perhaps 4 have left indirect evidence for ice sheets having invaded the furthest offshore areas of the UK North Sea (Holmes, 1997). During the coldest periods, the North Sea and its margins experienced extremely high and variable rates of erosion and deposition, originating from sub-glacial, sub-aerial and submarine glacigenic processes. The boundaries between the features formed by these processes varied in space and over short period of time, with the positions of the ice sheets and with the extent of sub-aerial exposure of the North Sea floor (for an example, see Section 5, Figure 8). The crustal response to the changing loading imposed by ice, sea water and sediment has added local and regional complexity to patterns of relative sea level change (Lambeck, 1995, Lambeck et al, 1998) and has also influenced the distribution and thickness of the seabed and shallow sediment types.

One of the diagnostic features of the invasion the North Sea by shelf-wide ice sheets is a regional glacigenic unconformity, under which erosion in the form of incisions and channels may have extended locally to between approximately 50-400m depth below bed. Thus, the best near-seabed records of a range of glacigenic sediment types and geomorphologies has been preserved only since the last major ice-sheet retreated from the North Sea, approximately 22,000 to 14,000 years ago. Such records include moraines, over-deepened and enclosed basins, ice-pushed sediments, fluvial channels with sandy outwash, large flat areas with soft often gravelly muds and overconsolidated formations typified by gravelly sandy muds. These last may have been overconsolidated under grounded ice, or by desiccation following sub-aerial exposure of the seabed. Although the bulk of the glacigene sediment volume consists of rapidly deposited muddy and gravelly sediments, there is often insufficient evidence to indicate whether they originated in subglacial, submarine or in mixed environments. The glacigenic and post-glacial features that are more than 10,000 years old typically underpin the variety of sedimentary environments presently found in the North Sea (sections 3 and 4).

As relative sea level rose and the ice sheets retreated landwards during deglaciation, rapid sediment input to the outer and middle shelf decreased and for the most part became restricted to fluvial sediment discharge into the inner shelf. During the following temperate climatic period, dating from approximately 10,000 years ago to the present day, shelf-wide sediment erosion and transport has been driven by the strength and direction of tidal and sea-wave-driven near-bottom currents. The effectiveness of these currents at reworking the seabed is today influenced by the lithology and consolidation of the seabed and its topography, all of which, as indicated above, were mostly inherited. Over the last 800,000 years the periods of temperate climate had durations typically in the order of 10-30,000 years, the preceding interglacial to the present interglacial having had a duration of approximately only 20,000 years (Jones and Keen, 1993). This geological perspective indicates the transient nature of the modern environment.

2. PRODUCTION-RELATED SEABED SUBSIDENCE

Significant subsidence of the sea floor over the Ekofisk Oilfield chalk reservoir was first recognised by the Operator (Phillips Petroleum Company Norway) in 1984. Though initial measurements at Ekofisk indicated a sea floor settlement of 4.4 m for the end of 1986, actual bathymetric measurements and satellite elevation data show that this was actually 3.8m at this time (Jones 1990). The maximum rate of settlement was estimated to be approximately 0.5 m per year and by late 1989 it had diminished to 0.3 m per year.

In 1984, the production-driven subsidence that has been observed over the deeper oil fields like Ekofisk was so uncommon as to have been regarded as impossible (Potts *et al*. 1988; Jones *et al*. 1987). However, hydrocarbon production from chalk reservoirs in the North Sea has led to various problems of a geotechnical nature, including compaction of the reservoir rock, subsidence of the ground surface, damage to well casings and production of reservoir solids. All of these are related to changes in the reservoir fluid pressure due to fluid extraction (Jones 1990). Occasionally, the hydrocarbons reservoirs in other sediments exhibit similar problems, but the mechanical properties of the reservoir chalks, together with the present geological setting of these chalk reservoirs and their extreme fluid overpressures serve to compound these difficulties (Jones 1990).

Complex diagenetic and hydrocarbon migration processes have affected the chalk hydrocarbon reservoirs, which are sealed above by a thick mudstone succession and laterally and below by low permeability chalk. Although these reservoirs are highly overpressured, they receive no pressure support from external renewable sources of overpressured fluids (Jones 1990).

Subsidence of the sea floor over the Greater Ekofisk Area oil fields occurs because the reservoir itself undergoes a reduction in volume. This volume reduction is the direct result of a reduction in the pore fluid pressure due to hydrocarbon extraction that leads to an increase in the vertical and horizontal effective stresses acting on the reservoir. As the reservoirs are laterally extensive, and confined by rocks of equivalent, or greater stiffness, deformations in response to effective stress changes are dominantly expressed as a reduction in the vertical dimensions of the reservoir (Jones *et al*. 1990).

If the reservoir rock comprised strong sandstone, the increase in the vertical and horizontal effective stresses acting on the reservoir would not present a major problem because the pressure change would be accompanied by a small vertical compaction due to elastic shortening. In the North Sea reservoir chalk this is not the case. In fact, increase in effective stress acting on the chalk reservoir progressively mobilises large elasto-plastic strains in chalks of decreasing pre-production porosity. Elastic bonding in the chalk that contributed a resistance to the gravitational loading from the overburden is destroyed at yield. As more of the overburden load is transferred to the pore fluids the reduction in deformation resistance leads to pore pressure generation. However, these pore pressures are dissipated through hydrocarbon production, and with no external fluid support because of the all round seal, the reservoirs respond by compacting (Jones 1990).

Within a significant proportion of the Greater Ekofisk Area, chalk porosity exceeds 35% and this material is of a weakly bonded nature. Whilst compaction will occur in all high porosity chalk reservoirs produced through pressure depletion, only when certain requirements are satisfied will these displacements be transferred to the sea floor to produce a settlement of serious magnitude (Jones *et al*. 1990).

Reservoirs of large surface area, that are not excessively elongate, with a broad distribution of high porosity chalks, such as Ekofisk, will be prone to serious subsidence problems. Smaller reservoirs (such as the West Ekofisk Oilfield) and structures of more elongate geometry (e.g. the Eldfisk and Valhall oilfields) will be protected from subsidence by the arching stresses generated as they compact.

No other chalk hydrocarbon reservoirs of Ekofisk proportions have been discovered in the North Sea, so new subsidence problems in chalk fields are considered unlikely. However, some of the larger sandstone reservoirs have geometries that are probably appropriate for subsidence. Thus, if their reservoir rocks are highly compressible and pore pressure dissipation is anticipated, they are possible candidates for subsidence (Jones *et al*. 1990).

Phillips Petroleum Company Norway has addressed the problem of surface subsidence at the Ekofisk Oilfield by elevating the platforms of the Ekofisk Complex by 6 m. Sea floor subsidence over the Ekofisk Oilfield is significantly reduced if the reservoir pore pressure is maintained through re-injection of natural gas. It should be noted, however, that solutions to subsidence problems that involve re-injection of valuable reservoir fluids or major modifications to production complexes are expensive (Jones 1990).

3. HARD SUBSTRATES

The main types of hard substrate that crop at seabed or under the seabed and shallow sediments (<5m thick) are (1) Holocene unconsolidated gravel spreads shown in Figure 4; (2) Geological formations occurring with hard strata and gravel. The hard strata with strengths greater than approximately 288 kPa occur in formations with overall >40 kPa strengths, the distribution patterns of which are shown in Figure 5; (3) pre-Quaternary rock, with strengths usually greater than 1.25 MPa, also shown in Figure 5. The figures showing the distribution patterns of these substrates have been adapted from the published BGS reports and 1:1 million scale Quaternary maps (Pantin, 1991, Holmes et al, 1993, 1994).

The internal complexity of multi-phase incision and channel fill deposits means that, other than to indicate their potential for containing hard substrates, no further analysis of their distribution is warranted. Similarly, the areas of shelf unconsolidated deposits <25m thick are shown with undivided lithologies because their complexity could not be resolved with the existing regional seismic reflection and sample datasets (Figure 5).

3.1 Holocene unconsolidated gravel spreads

The Holocene is an epoch which is identified with times in the Quaternary from about 10,000 years ago to the present day.

Gravel ranges in size classes from granular gravel, between approximately 2 and 3.4mm diameter, pebbles up to 16mm diameter, cobbles up 64mm diameter and to boulders more than 64 mm diameter. Boulders may theoretically reach any size greater than approximately 64mm diameter, for example they may be 'house sized', but boulders do not usually exceed 2m diameter at the modern seabed. In reality, the larger boulders, whether occurring as isolated features or in boulder fields, are rarely referred to as gravel.

Although the gravel spreads, shown in Figure 4 are predominantly terrigenous, they almost always contain some proportion of calcium carbonate in the granular gravel to pebble size class. This carbonate consists almost entirely of biogenic shells, and shell fragments, the distributions and sizes of which vary with the source, fragmentation history of the source-shell biota and winnowing by near-bottom currents. Gravel-size shell fragments typically originate from bivalves and are transported more easily than the terrigenous grains of equivalent size.

Gravel spreads mostly occur in the nearshore areas (Figure 4) with very strong tidal and sea-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). The immediate source of the large pebble, cobble and boulder size classes of seabed gravel must therefore be local and probably originate from older gravelly formations that have been submerged during rising sea level. These formations will include drowned beaches, fluvial and glacigenic sediments from which most of the finer sediments have been washed out.

The significance of gravel spreads, particularly those occurring as an interlocking pebble-gravel armour and with cobble and boulder size gravel clasts is that they provide a relatively stable substrate. The distribution patterns of sandy muddy gravels or sandy gravels often indicate where very thin or patchy seabed sediments rest on older substrates.

3.2 Quaternary geological formations with hard strata and gravel

Normal consolidation occurs below ground level as a result of dewatering when sediments are buried and compressed under their own weight. Hard cohesive (clay- or mud-rich) sediments (>288 kPa, brittle or very tough) may originate at ground level when the sediments are compressed by weight of ice during or after the times when the sediments were deposited. Muddy sediments may also transform to hard sediments after they have been sub-aerially exposed and, for example, desiccated at times of low glacio-eustatic sealevel. One impact of the dynamic nature of the positions of the ice-sheets and the relative sea level changes is that sediment types and sediment strengths can vary vertically and laterally within one geological formation. Further, it appears that some of the older, Quaternary sediments have been uplifted at the basin margins as a result of the crustal response to long-term unloading of rock. The processes associated with glacigene erosion thus feed back so that the hard formerly deeply buried Quaternary formations may be exposed at seabed.

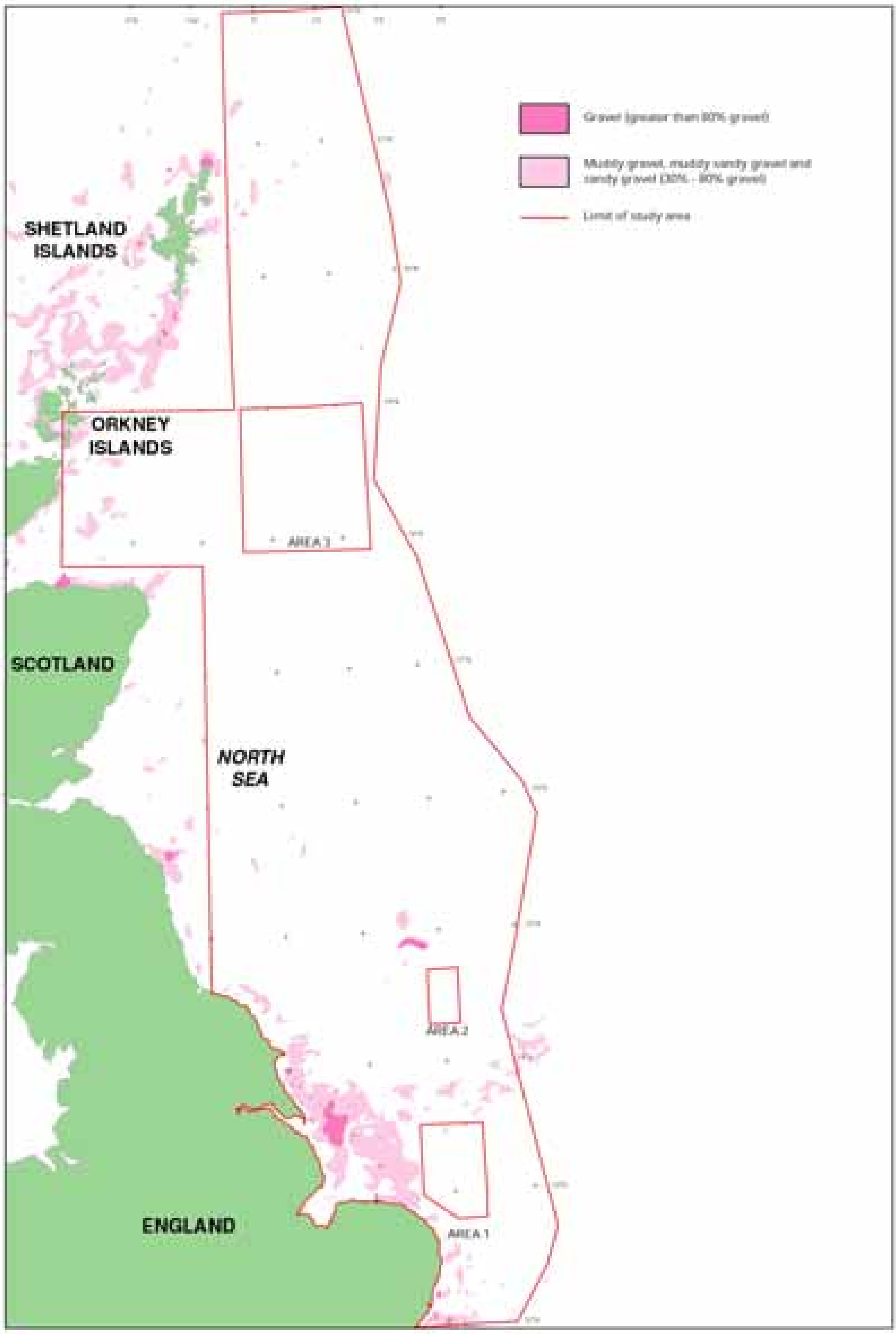

Figure 4. Distribution of gravel spreads. Adapted after Pantin (1991)

Diamicton is term for a distinctive sediment, the bulk of which is unsorted gravel, sand and mud in various proportions. Uncertainties still abound as to its precise origin in some areas. However, its crop at seabed on the western margins of the North Sea has been interpreted as marking the approximate extent of the last ice sheet (Figure 5). Thus, some proportion of the mapped diamictons certainly originated as till. The environmental significance of diamicton is that it underpins a diverse modern seabed geomorphology and is often the source of the hard gravel substrates on submarine banks and ridges.

The remaining semi-consolidated formations which have the potential to form hard substrates are shown as mud and interbedded mud and sand (Figure 5) with various proportions of gravel. The formations have different ages and are grouped into one descriptive sediment strength category that also includes firm sediments (>40kPa, moderate finger pressure required to mould), stiff sediments (>72kPa moulded only by strong finger pressure) and very stiff (>144kPa, cannot be moulded by fingers). As summarised above, this variability of sediment type and strength is the most important aspect of the sedimentary formations illustrated. The complex diversity of sediment strengths and sediment types within the geological formations can not be resolved at the scale of (data) presented here. Thus, in effect, the distribution patterns of the diamicton, mud and interbedded mud with sand are illustrative of the general areas, or geographical ‘provinces’, which have the potential for containing geological formations with hard substrates at or near seabed (Figure 5).

The provinces illustrated with hard cohesive sediments range in age from approximately 2.4 million years, to less than 25,000 years before present.

3.3 Pre-Quaternary rock formations

Submarine rock substrates are patchily distributed around the margins of the North Sea (Figure 5) and range in age from Pre-Cambrian basement (more than approximately 590 million years year old) to Upper Cretaceous (approximately 95 to 65 million years old) (Chesher, 1991 a and b). Their hardness ranges from extremely strong, more than 200MPa (sparks may fly when hit by a hammer) in the older crystalline rocks to very weak, or weak, (<5MPa crumbles in hand or thin slabs may break easily in hand) in other usually younger sedimentary rocks. Relatively weak sediment sedimentary units may be included in the very hard and old formations if they have weathered at seabed. Offshore from East Anglia the Upper Cretaceous formations include cemented carbonate platforms of chalk crop at seabed. Chalk is an important aquifer in the onshore and offshore margins of the southern North Sea where it covers large areas (section 8).

3.4 Cemented carbonate hardgrounds in soft sediments

Exceptionally, carbonate cements may form hardgrounds that are observed in areas of soft muds or uncohesive sediments. Such hardgrounds have been reported from pockmarks (section 4). In the UK block 15/25 they occur in a pockmark with methane gas which is actively venting at seabed (Hovland et al, 1987; Hovland and Judd, 1988). These hardgrounds are formed during the biogenic oxidation of methane, they are attractive to biota and are possible sites of special interest for future preservation. Other hardgrounds occurring in soft muds have been reported adjacent to Shetland but at this site (Figure 5) there is an insecure connection with gas seepage (Hovland and Judd, 1988). For detailed reports on pockmarks and the related cemented carbonate hardgrounds in soft sediments the reader is referred to Technical Reports 001 and 002.

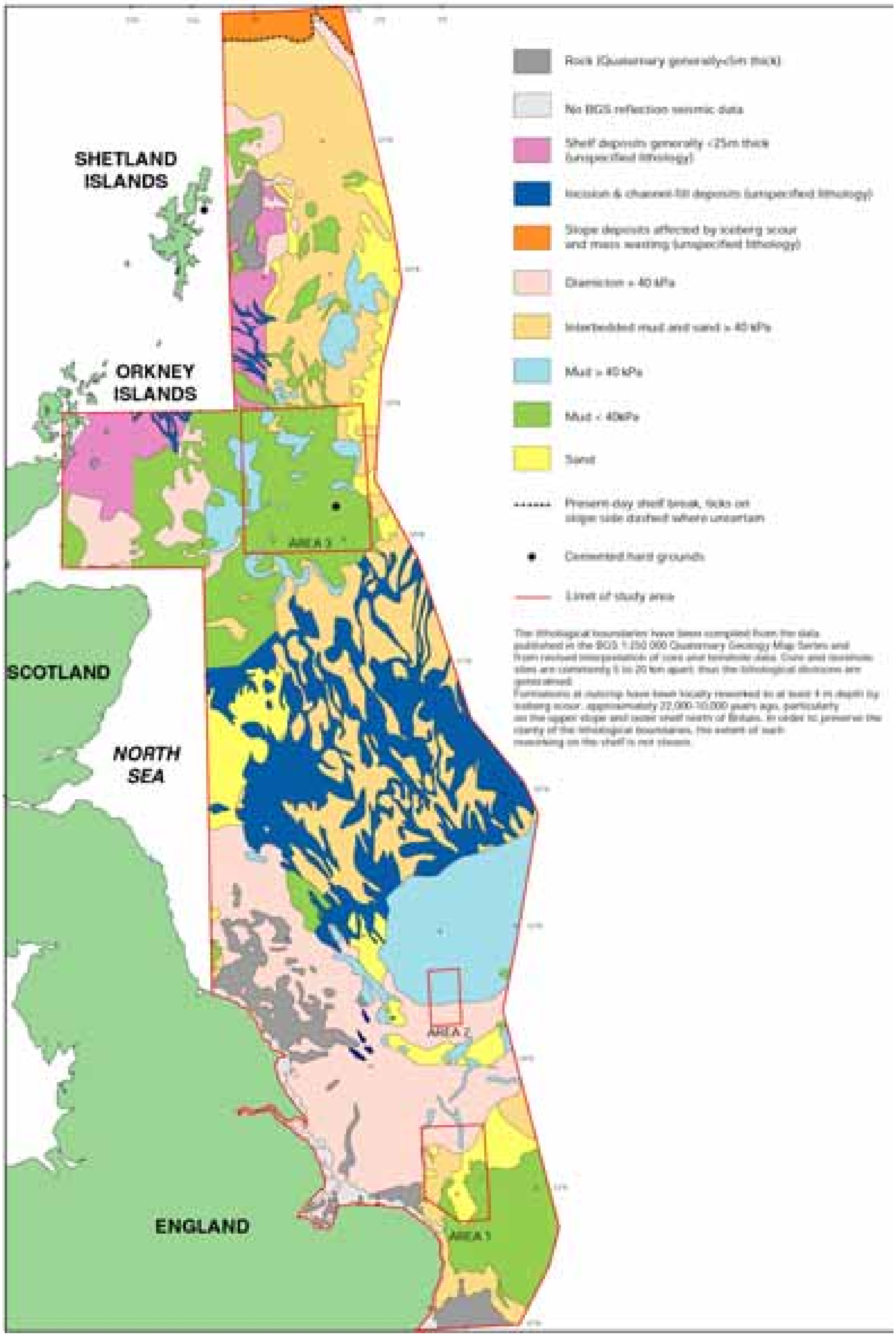

***Figure 5.** Distribution of provinces with potential for cohesive hard Quaternary formations (>40kPa) and rock substrates. Adapted after Holmes et al. (1993,1994), occurrences of cemented hardgrounds after Hovland et al. (1987), Hovland and Judd (1988).*

4. SEDIMENT MOBILITY AND RELEVANCE TO SEABED DEVELOPMENTS

The section of interest to so-called ‘seabed’ foundation developments commonly extends to 30m to 100m or more below seabed, and even in the case of the relatively shallow cable or pipeline-installation surveys, site investigations from 1m to 20m or more below seabed are not uncommon. Here, the emphasis is more on selected Holocene seabed sediments, particularly the mobile sediments, and the interface between them and older and usually less mobile sediments. The boundaries of this interface typically vary from millimetres to perhaps several metres in depth below seabed and from centimetres to several tens of kilometres in plan. It is important to study the conditions at and on either side of this interface as whilst they flag important changes to a range of key substrates that are important to benthonic biota, the sedimentary environments above the interface are rarely stable.

4.1 Normally consolidated muds

Normally consolidated or slightly underconsolidated soft to very soft muds with strengths <40kPa are widely distributed at or near seabed where they may crop under extensive areas of mobile seabed sediments (Figure 6). The bulk of the thicker mud formations originated from outwash emitted after the last ice sheet had retreated from the North Sea, when glacigene sediments were reworked during the subsequent marine transgression and when Holocene mainland river discharge was captured in sheltered submarine or estuarine basins. The extensive areas of modern soft seabed muds typically form an overall flat seabed, where, except in areas with pockmarks, there is little physical evidence for significant seabed sediment mobility.

Soft muds are associated with pockmarks in the deeper-water areas of the central and northern North Sea. Pockmarks are closed seabed depressions that are typically 2-5m deep, 50-200m wide and elongated parallel to the direction of the predominating near-bottom tidal currents. The largest modern pockmarks usually occur in the softer and finer-grained muds and they have formed following seabed excavation by processes involving fluid, gas or liquid, escape at seabed. For detailed reports on pockmarks the reader is referred to Technical Reports 001 and 002. The distribution and likely ages of buried pockmarks indicate that such processes have probably onset with the overall change to a warmer climate following the last glaciation (Long. 1992). Giant pockmarks some 50-200m deep and 0.5 to 4km diameter have formed since about 55 million years ago and are now deeply buried under parts of the modern pockmark fields in the central North Sea (Cole et al, 2000). Some seabed pockmarks are sites of modern gas discharge (section 3). Fields of moribund pockmarks with densities of up to approximately 20 per km^2 at the modern seabed provide spectacular examples of historically spasmodic fluid and sediment mobility. There is, however, uncertainty about the precise age and duration of the processes that formed the majority of the presumed inactive (relict) pockmarks that are now observed at seabed.

The pockmarks are regarded by commerce as a possible hazard to safe operations during pipeline and other seabed development operations and they are usually avoided whenever possible. The main seabed geohazards are perceived as foundation suspension on the relatively steep gradient changes associated with the pockmarks and the potential for loss of formation strength should sediment fluidisation occur.

4.2 Overconsolidated muds

Firm, stiff, very stiff or hard muds (strength from 40-288+ kPa) are widely distributed in the North Sea (Figure 5). Where they crop at seabed or just below sub-seabed the muds in this strength range, vary from being slightly overconsolidated to heavily overconsolidated. The muds ranging in strength from stiff to hard are effectively immobile in the natural state. The distributions and sometimes complex variability of the lithologies and strength changes associated with overconsolidated muds at or near seabed are summarised in section 3. The geohazards that they present to pipeline and other development operations are mitigated by detailed site investigation surveys.

4.3 Uncohesive sediments

Uncohesive sediments comprise loose sediments with little mud content and range in size from silt (0.0039mm - 0.053mm diameter), through sand (<0.84mm diameter) and gravel (>2mm diameter).

The distribution and significance of gravel with reference to hard substrates is discussed in section 3. The processes affecting sand mobility and the distribution patterns of the large bank and ridge bedforms associated with the mobile sands occurring in the central and southern North Sea are summarised in section 5.

The main geohazards to development operations in the areas with the large-scale mobile sand ridges and mobile banks are those associated with extreme near-bottom currents. The geohazards include the risks from abrasion by suspended sediments, swamping by mobile bedforms, foundation exposure and the potential for suspension of development plant. Other hazards in this environment arise from seabed scour originating from emplaced structures.

Sand banks and sand ridges of similar size to those occurring in the southern North Sea are absent north of approximately 56ºN (Gatliff et al, 1994, Johnson et al, 1993). The largest mobile bedforms in the northern North Sea are sand waves (Figure 6). Sand waves are mesocale features typically with a width of 0.6 to 500m (Pantin, 1991) and grade down in size to ‘megaripples’. Sandwaves occur with the larger-scale sand ridges and sandbanks (section 5) but commonly extend between and beyond them. Sandwave bedforms indicate an overall coast-parallel direction of net sand transport but net sand transport into the Wash in the southern North Sea (Figure 6). Although sandwaves are the largest mobile bedforms in the northern North Sea, for the most part they do not fall within the area of study defined for the SEA2. Where they do, adjacent to Orkney, they occur as trains and as individual features with crest heights of between 3.5m and 7.5m and their bedforms indicate an overall southwards net sand sediment transport direction. The geohazards posed by sand waves and to a lesser extent ‘megaripples’ are similar to those posed by the larger-scale mobile sand banks and sand ridges in the southern North Sea.

Large areas of rippled seabed and other uncohesive cover comprise superficial sand and silt with various amounts of gravel. Such cover is ubiquitous through out much of the North Sea and, as previously summarised, may obscure to varying degrees the underlying nature of shallow formations. This effect may not be of additional concern to developers if there is underlying rock, thick sands, a strong cohesive muddy formation or a thin gravel lag on a strong cohesive formation. It is of concern if the cover overlies very soft cohesive muddy formations. In this case, if the seabed is overloaded by the weight of development structures, ‘punch through’ may occur resulting in unexpected subsidence. Displacement of the cover can also lead to seabed scour and undermining of the deeper underlying soft sediments.

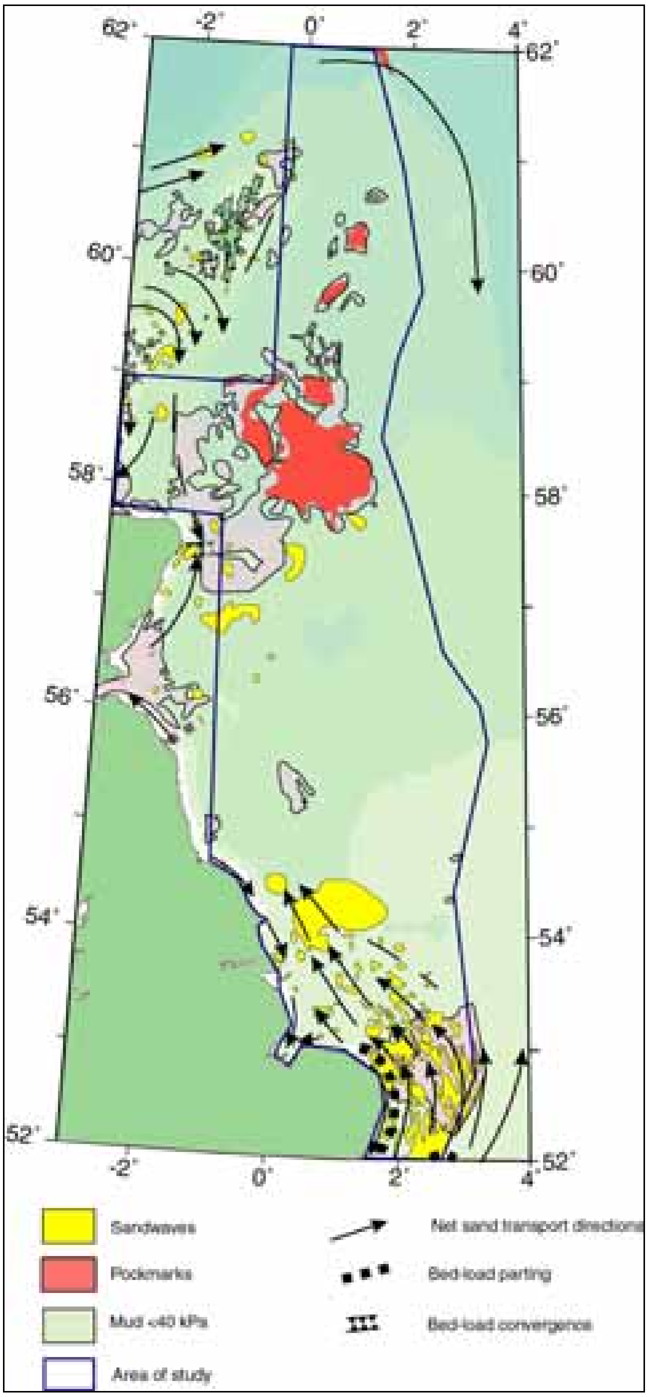

Figure 6. ***Distribution of shallow muds, pockmarks, sandwaves and selected other features relevant to sediment mobility. Where the areas of mud and sandwaves are shown with common boundaries, the muds extend under the sandwaves. Adapted after Andrews et al. (1990), Pantin (1991), Cameron et al (1992), Johnson et al. (1993), Gatliff et al. (1994), Holmes et al. (1993, 1994)***

5. SANDBANKS

5.1 Sandbank types and classification

Sandbanks are very large bedforms which are characteristic of tide-dominated continental shelves. The area includes some of the best known examples of continental shelf sandbanks which have been studied as classic examples of this bedform and as analogues for sedimentary deposits in the rock record. A map of the distribution of major sandbanks in the area is given in Figure 7. A summary of the characteristics of the sandbanks in this area can be found in Balson (1992).

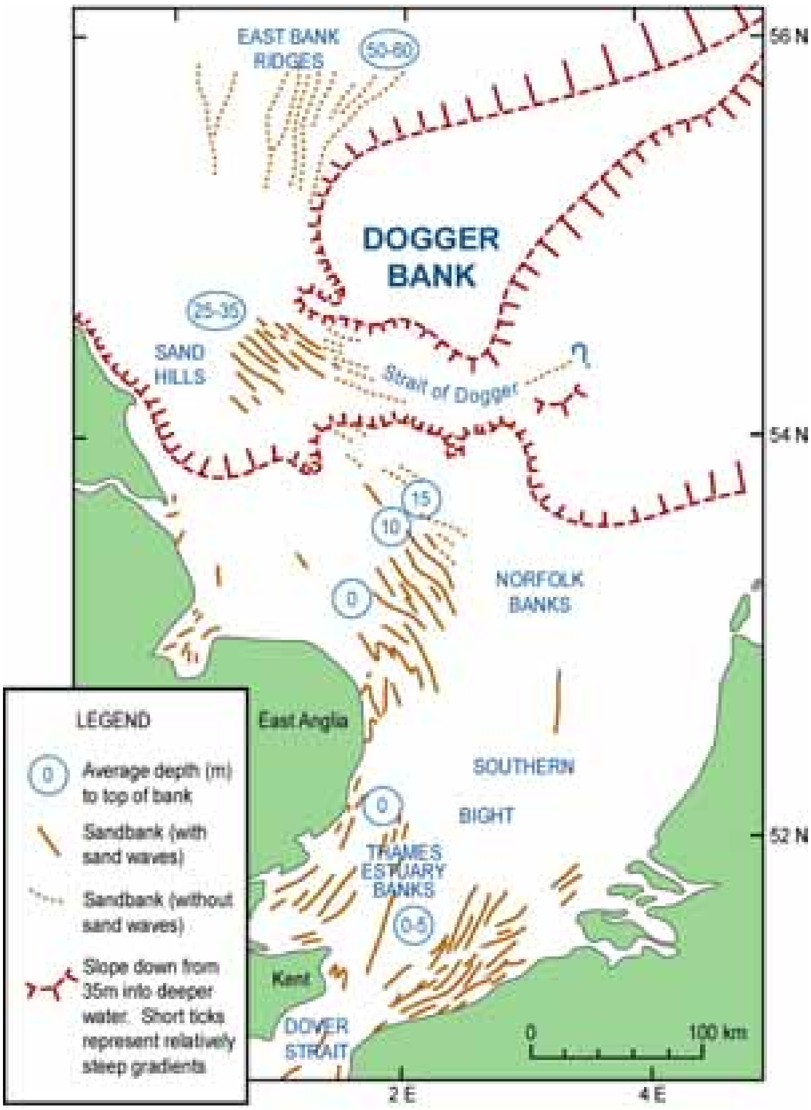

Figure 7. Distribution of major sandbanks in the southern North Sea. After Stride et al (1982)

In this area the majority of the sandbanks are found in four main groups:

The East Bank Ridges are a group of sub-parallel ridges in relatively deep water to the north west of the Dogger Bank. These banks were believed by Stride et al (1982) to be features which initially formed early in the Holocene transgression but which are now in water depths too great and with tidal currents too weak for their active maintenance. They were therefore considered to be 'moribund'. They are composed of very fine to fine sand (Davis and Balson, 1992) which contrasts with the fine to coarse sand composition of other sandbanks in shallower water further to the south. Their surfaces are smooth and lack the cover of mobile sandwaves seen on other sandbanks in the area.

The Sand Hills are a group of parallel ridges to the south west of the Dogger Bank. Some of these banks are seen to be covered by sandwaves so may in part be presently 'active'.

The Norfolk Banks are the best known group of sandbanks and lie off the coast of north east Norfolk. The banks are sub-parallel to the modern coastline and, at the southern end of the group, sandbanks may be shore-connected.

The Wash is a large coastal embayment on the east coast of England which has extensive intertidal flats around its margins and a number of large sandbanks within it. These banks are aligned parallel to the sides of the embayment and to the dominant tidal current directions in and out of the embayment. Most of these banks are partially exposed at low tide.

Although most of the sandbanks in this area fall within the four groups above there are also a number of isolated individual sandbanks. All of the sandbanks so far mentioned are elongate accumulations of sandy sediment formed primarily by the action of, and sub-parallel to, the dominant tidal currents. A number of other sea bed features in the area which have a more irregular plan shape and may be composed of gravels or other non-mobile lithologies are not considered here to be sandbanks. Many of these features are relict glacial features or erosional forms. The Dogger Bank is not a sandbank at all but is a large shallow plateau which is a relict erosional landform and will be briefly described below.

In the past there has been considerable debate over the origins, classification and interpretation of the sedimentary processes responsible for producing sandbanks. A summary of this debate and a useful recent classification of sandbanks can be found in Dyer and Huntley (1999) who classify sandbanks into a number of categories based on their morphology and hydrodynamic origin.

Type 1 are defined as open shelf ridges. The East Bank Ridges, Sand Hills and Norfolk Bank Groups all fall into this category.

Type 2 are defined as estuary mouth ridges. The Wash Group falls into this category.

Type 3 are defined as headland associated banks. This category was further divided into two sub-categories; Banner banks (3A) form in the lee of relatively resistant headlands. Smithic Shoal to the east of Bridlington appears to have formed in the lee of Flamborough Head and may be an example of this type of sandbank within the area. Alternating ridges (3B) form when a relatively soft headland recedes by the process of coastal erosion to form a group of parallel ridges. There is thus the possibility that sandbanks which formed in this way will subsequently become detached from the headland and become open shelf ridges (Type 1 above). The origins of this type of sandbank are thus intimately linked to the processes of sea level rise and coastal recession over time scales of thousands of years. The sediment needed to build the banks comes from the erosion of the adjacent coast so that, after a period of time, the coast recedes and the bank becomes ‘detached’ from its sediment supply. It is perhaps therefore significant that the Norfolk Banks lie in an area which was originally a periglacial plateau (Figure 8) and, due to the low gradient, was transgressed rapidly by the rising sea level between 8000 and 6000 years before present. Once this initial rapid phase of transgression was complete, coastal erosion would provide the necessary sediment supply as the coast continued to recede (Balson, 1999).

Several studies have attempted to reconstruct the rapidly changing coastal configuration of the southern North Sea as sea levels rose over the last 18,000 years. The early reconstructions of Jelgersma (1979) have now been improved taking greater account of post-glacial crustal movements as the melting of the glacial ice resulted in isostatic rebound of the North Sea region (Lambeck, 1995; Shennan et al, 2000).

The Dogger Bank is a very large shoal area in the central North Sea with water depths less than approximately 30 metres. It is shallowest in the south west where water depths are only 15 metres. The ‘bank’ is largely composed from a 42 metre thick formation of glacio-lacustrine clays which were deposited adjacent to lobes of glacial ice during the last glaciation (Figure 8). When the ice retreated 18,000 years ago the deposits were left behind as an upstanding plateau. As sea levels rose the Dogger Bank became an island and was probably not completely covered by water until approximately 7500 years ago. The presence of freshwater and saltmarsh peat beds and clays containing intertidal molluscs are evidence of former coastal environments around the margins of the Dogger Bank at that time. The East Bank Ridges and Sand Hills group of sandbanks may have formed in association with the flooding and erosional retreat of the western margin of this large landform (Figure 7).

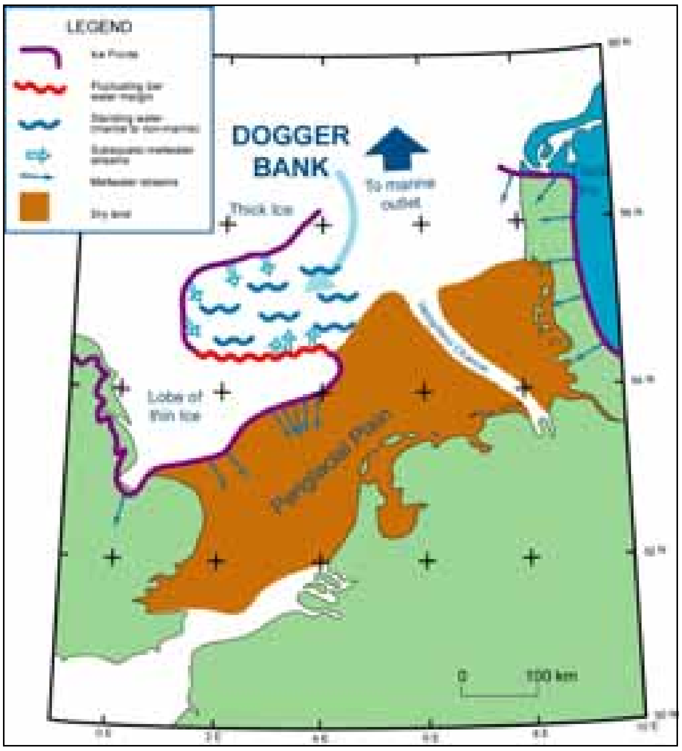

Figure 8. Ice limits during last major glaciation in the southern North Sea in relation to the location of the Dogger Bank . After Jeffery, 1992.

5.2 Sandbank mobility

Sandbanks in shallow near coastal settings are known to be extremely mobile and may require frequent survey in the vicinity of ports to ensure the safety of navigation. Considerable changes in shape and volume have been determined through analysis of historic bathymetric data (e.g. Posford Duvivier, 1997a). The sandbank Scroby Sand to the east of Great Yarmouth for example, has exhibited significant changes at both its northern and southern ends. These changes include trends of both accretion and erosion since 1865 but with no consistent direction of overall bank migration (Posford Duvivier, 1997a). From an analysis of historic bathymetric charts Caston (1972) found that some of the more offshore Norfolk Banks had elongated towards the north west, the direction of net regional sand transport. The evidence for bank migration perpendicular to their long axis is, however, more equivocal (see discussion in Balson, 1992, p124). These offshore banks are markedly asymmetrical in cross-section with their steeper flanks oriented towards the north east suggestive of migration in that direction. The internal structure within some of the banks (Houbolt, 1968; Balson, 1999) is evidence of north eastward migration but cannot conclusively prove that migration of these more offshore banks still occurs at the present time.

The surfaces of many of the Norfolk Banks are covered in active sandwaves which reflect the pattern of modern sand transport around these banks. The sandwaves have their crests aligned more or less at right angles to the bank crest with their steep faces in opposing directions on either side of the sandbank reflecting the dominance of a clockwise circulation of sand around the bank (Collins, et al, 1995)

5.3 Sandbank interactions with the coast

Sandbanks can interact with the coast in a variety of ways:-

- They provide a physical barrier to incoming wave energy which may directly reduce the energy of waves reaching the coast and therefore reduce the degree of beach or cliff erosion within the shelter of the bank. Recent studies on Scroby Sand have shown that the presence of this bank may reduce the wave height of waves with a 50-year return period by over 75%. This effect is greatest at low tide when water depths over the crest of the bank are reduced (Posford Duvivier 1997b).

- They may refract incoming waves to focus wave energy onto the shore enhancing beach or cliff erosion on short coastal sections. Subsequent changes in sandbank configuration may change the focus of wave attack.

- They may provide an offshore sink of sand which may be exchanged with the coast. Sandbanks on the north east Norfolk and Suffolk coasts are connected to the shore at the location of small headlands or ‘nesses’ which occur on sections of coast where longshore sediment transport paths converge. These points represent ‘corridors’ where sediment exchanges between the littoral system and the offshore bank system take place. Scroby Sand which is connected to the coast near Great Yarmouth has been observed to have steadily increased in volume since 1865 which has enhanced its protective value to the coast (Posford Duvivier 1997a)

6. POTENTIAL EFFECTS OF DECADAL CHANGES IN METOCEAN CONDITIONS ON PRESENT DAY SEDIMENT DISTRIBUTIONS

The impacts of potential changes on sediment distribution resulting from changes in oceanographic conditions are difficult to predict with accuracy. Although it may be possible to predict the effect of global warming, for instance, on sea level it is extremely difficult to determine the effect that this will have on sediment transport pathways and fluxes. The response of the coastline in this area to scenarios of climate change is currently being considered by a consortium led by Halcrow Maritime working on a DEFRA-funded project called 'Futurecoast'. The Futurecoast project is due to report in March 2002.

Three oceanographic factors which have the potential to change in the future may be considered as important in this area:-

- Sea level
- Wave height and direction
- Storminess

6.1 Sea level

Current estimates are that over the next century the southern North Sea will experience a rise in sea level of up to 0.7 metres. This figure is made up of two components; the rise in global sea levels caused by warming of the oceans and melting of polar ice caps, and by tectonic regional subsidence estimated to be up to 2mm/year in the southern part of this area.

The increase in sea level will allow larger waves to reach the coast with less of their energy lost to friction with the sea floor. This increase in wave energy may lead to an increase in coastal erosion on undefended parts of the coast and a consequent increase in sediment yields to the shelf. Coastal defences may be put under increased pressure with increased likelihood of overtopping of flood embankments. Sandbanks in shallow water will be less effective in sheltering sections of coast which may also lead to increased coastal erosion. Changes in wave refraction might also occur. However these predicted changes may be substantially mitigated as part of a natural feedback in that increased sediment supply may nourish the sandbanks allowing crest heights to build in line with the rate of sea level rise. Coastal tidal flats and beaches also provide an important natural defence which reduces the wave energy striking the coast. Sediment supply is critical to the maintenance of the elevation of tidal flats in a scenario of increasing sea levels to maintain the degree of wave attenuation. Where tidal flats are unable to keep pace with rising sea levels, rapid retreat of the coastline, loss of intertidal habitats and pressure on coastal defences can result. On a more regional scale the shallow plateau of the Dogger Bank also plays a part in reducing wave energy from northerly storms.

6.2 Wave height and direction

An increase in future wave height in the North Atlantic and adjacent shelf seas has been predicted. When considered together with potential sea level rise the situation regarding increased wave energy at the coast will be exacerbated. Although the majority of sediment fluxes on the shelf in this area appear to be driven by tidal currents it has been shown that transport can be considerably enhanced by superimposed wave-driven currents (e.g. Jago, 1981). In the nearshore area the sediment exchanges with the coast are dominated by wave processes which are sensitive to directional forcing. The potential for future changes in wave direction particularly in response to climate change are unknown but any change could produce significant geomorphological changes at the coast.

6.3 Storminess

The impact of storminess can be considered as the result of several interlinked factors; storm intensity, storm frequency, and storm track. Changes in any or all of these parameters may have significant implications for sediment transport within the area. It is widely perceived that storms are capable of moving large quantities of sediment at the coast and on the shallower parts of continental shelves. In some cases it is believed that sediment transport by storms may dominate the sediment flux and the morphological responses on the shelf and coast. Storms may therefore leave an environmental imprint which may not be removed on the decadal time scale. Any increase in storms therefore must potentially have a significant effect on sediment distribution.

7. SEDIMENT TRANSPORT PATHWAYS AND POTENTIAL FOR SINKS AND CONTAMINANT ACCUMULATION

The need for a greater understanding of sediment transport pathways in the Southern North Sea has long been recognised. The offshore area includes important offshore commercial interests such as hydrocarbons, aggregates and fisheries. It is adjacent to England's east coast where the relatively soft geology has given rise to rapidly eroding cliffs and accreting lowland areas with internationally important habitats. The east coast is also important for leisure activities and tourism with a number of important resort towns including Great Yarmouth, Skegness and Scarborough. The area also includes a major commercial estuary, the Humber Estuary, which is one of the UK's most important ports and is also a source of contaminants into the North Sea. To address this need a major study, the Southern North Sea Sediment Transport Study has recently been commissioned by DEFRA and a group of Coastal Authorities. The project is being investigated by a consortium led by Hydraulics Research Wallingford and is due to be completed in March 2002. An earlier study conducted by Associated British Ports Research and Consultancy and the University of Southampton reviewed the current state of knowledge of sediment transport pathways in the area (Associated British Ports, 1996).

The source, transport pathway and ultimate sink for sediment is to a large degree dependent on its grain size. Mud, sand and gravel sediments will therefore be considered separately.

7.1 Mud

The mud fraction of a sediment (<63µm) is regarded as the most important for the study of the transport of contaminants many of which can be adsorbed onto clay particles. The rivers draining eastern England transport a certain quantity of mud-sized sediment onto the adjacent shelf but the quantities of river borne sediment are dwarfed by the quantities derived from coastal erosion. The River Humber may input approximately 100,000t/year whereas erosion of the adjacent Holderness cliffs may account for an input of over 2,000,000t/year. Other sources of natural mud come from atmospheric dust, seafloor erosion and advection of water masses from the northern North Sea or from the English Channel (Eisma and Kalf, 1979). NERC's North Sea Community Research Project (1987-1992) measured concentrations of fine suspended particulate matter at over 100 locations in the North Sea and confirmed that, not only were river sources relatively unimportant, but that coastal erosion was also a relatively minor source compared to that of advected material from the northern North Sea and through the Dover Straits (McManus and Prandle, 1997).

The suspended mud from the Holderness coast and Humber estuary form a conspicuous plume which moves south eastwards away from the coast and out into the southern North Sea (Dyer and Moffat, 1998). The main sinks for mud in the area are within the estuaries of the Humber, Wash, and North Norfolk coast (McCave, 1987). Offshore there are no major sinks for sea bed mud accumulation. The Humber plume moves east and may deposit much of its sediment beyond the UK sector in the Oyster Grounds area or even further east within the German Bight. The Outer Silver Pit is partially infilled with muddy deposits which may be a further sink for mud within the southern North Sea. In these areas there is evidence of reworking so that older uncontaminated sediment particles may be resuspended and replaced by more recent contaminated particles. In this way pollutants may become part of these deposits without any net deposition (Eisma and Irion, 1988). Observations and numerical modelling suggest that this cycle of deposition and erosion may be strongly seasonal with the majority of supply of fine particles occurring in the winter and with deposition mainly during summer months (Odd and Murphy, 1992).

Fine particles can also be deposited in more sandy areas where they may be trapped within the interstitial pore spaces between the coarser grains (Eisma and Irion, 1988). The quantities involved are usually small but the process is significant as contaminants close to their source are trapped, as also are some of the geochemical signatures of the more widely dispersed contaminants observed in the North Sea (Stevenson, 2001).

Organic particles may be even more important than the fine-grained inorganic sediments such as clays in the transport of contaminants. Dissolved metals can be adsorbed onto organic matter and transported over large distances throughout the North Sea (Stevenson, 2001). The contaminant history, particularly within fine-grained sediments can also be used as a measure of sediment deposition rates (e.g. Irion *et al*, 1987). In particular, studies of radionuclides within coastal sediments has yielded evidence of deposition rates and contaminant fluxes in the North Sea (e.g. Andrews et al, 2000).

7.2 Sand

The major sources of sand in the area are the eroding cliffs of Holderness, north east Norfolk and eastern Suffolk. Cliff erosion north of Flamborough Head may provide smaller, more localised inputs. An unknown quantity may come from sea floor erosion but, because of the widespread gravel lag substrate, it is unlikely the amount is significant under non-storm conditions except from the immediate coastal foreshore. Sandy sediment derived from coastal erosion is carried alongshore in the beaches and may move offshore at a number of places. The sandy headlands or 'nesses' on the Norfolk and Suffolk coasts are believed to be points where sand may be lost from the coastline. The nesses are also points where offshore sandbanks may be attached and it is believed that this is the route for offshore transport of sand.

The main sinks for sand in the area consist of the coastal beaches and dune systems, the sand flats and sandbanks of the estuaries of the Humber and Wash, the offshore sandbanks and sandwaves, and the sandy infills of a number of offshore depressions such as Inner Silver Pit, Sole Pit and Well Hole (Balson, 1999). Despite the apparent abundance of sandy bedforms, particularly in the Southern North Sea, the offshore sandwaves and sandbanks here rest on a scoured lag surface which is often exposed in the swale areas between the banks and over large areas of the seafloor showing the area to be relatively sand-starved.

Sand transport in the southern North Sea is largely parallel to the tidal flow with net transport dominantly to the north east in the offshore area (Johnson *et al*, 1982). This is evidenced by the orientation of the steep faces of the sandwaves, the prolongation of the major sandbanks and is supported by the results of numerical modelling (Associated British Ports, 1996). Reversals to this regional trend may occur in the nearshore area.

7.3 Gravels

Even under the relatively high tidal currents in the area, gravel is probably not mobile except in the wave-dominated littoral zone along the coast or during storms. Most of the beach gravel in the area north of Norfolk is derived from glacial deposits either through the process of coastal cliff erosion or from the floor of the North Sea. On the Suffolk coast gravels have been derived from older, pre-glacial deposits through coastal erosion. Offshore the gravels are dominated by pebbles derived from glacigenic sediments with only a relatively small percentage coming from biogenic sources. Shell fragments generally form less than 10% of gravel-sized sediment. Some of this shell material is almost certainly derived from the erosion of early Holocene intertidal deposits which were reworked during the rapid marine transgression across the area (Balson, 1999).

8. HYDROGEOLOGICAL CONSIDERATIONS

8.1 Overview

Groundwater contamination moves in the groundwater flow so a critical issue is the groundwater flow direction and rate. These are determined by the hydraulic gradient and the physical properties of the aquifers. Local factors such as the extent of groundwater pumping will determine whether the natural or disturbed situation is the most important. The most common factor in determining groundwater potability in coastal environments is the salinity, usually expressed as chloride concentration. The Council of European Communities Directive 80/778 Maximum Admissible Concentration for chloride is 250 mg/l. The World Health Organisation Guideline Value for drinking water quality for chloride concentration is also 250 mg/l.

Under natural conditions, groundwater flows from onshore aquifers to the sea through the seabed under a hydraulic gradient. Pumping of groundwater on land can cause groundwater levels to fall below sea level leading to local hydraulic gradients becoming reversed and saline water being drawn into the coastal parts of aquifers. Chloride concentrations in uncontaminated groundwaters are generally low (less than 100 mg/l), reflecting concentrations in the recharge from rainfall, which are in turn a function of many factors including predominant wind direction and distance from the sea. High chloride concentrations in shallow aquifers can be an indication of contact with evaporites, the presence of connate water or saline intrusion. Connate water is original formation water which has not been flushed out of the aquifer by more recent recharge; its presence is indicative of limited throughflow in the aquifer.

8.2 Review of hydrogeological conditions

8.2.1 Onshore hydrogeology of East Anglia

There are local cases of saline water in the Chalk and Crag aquifers of East Anglia. These are generally caused by local lowering of the groundwater level, which is naturally above sea level, leading to the normal direction of groundwater flow out to sea, being reversed. These are discussed in more detail below.

8.2.1.1 Chalk

Water levels in the Chalk aquifer are below sea level at various locations (I-V) along the East Anglia Coast (Figs. 9A and 9B). This is derived from data from Institute of Geological Sciences (1976; 1981) and East Suffolk and Norfolk River Authority, (1971). Water levels are below sea level locally along the north coast (area I), as well as over a significant part of eastern East Anglia. The areas where it is below sea level extend more than 10 km upstream of the tidal parts of the rivers Bure (area II) and Yare (area III) rivers. Waters levels are also below sea level as far upstream as Ipswich on the River Orwell (area V) and Waldringfield on the River Deben (area IV) rivers (East Suffolk and Norfolk River Authority, 1971).

Over large parts of East Anglia, chloride concentrations in the Chalk are less than 100 mg/l, with an average of about 50 mg/l. The maximum chloride concentration in groundwater along the north coast is 320 mg/l (Institute of Geological Sciences, 1976). Figure 9C indicates the areas where chloride concentrations are likely to be more than 250 mg/l. There are three main areas where this is the case; beneath the Eocene along the eastern coastal strip, within the synclinal area of Suffolk and around Ipswich and Felixstowe (East Suffolk and Norfolk River Authority, 1971).

Along the east coast, high chloride waters occupy a coastal belt some 2 to 18 km wide (Figure 9C, area I). Because they are of little value for water supplies, only a limited number of boreholes have been drilled in the area and little information is available. The transition zone between the normal groundwater and the high chloride waters beneath the Eocene occurs over a short distance, with the chloride concentration increasing locally from less than 50 mg/l to over 500 mg/l within 1.5 km. In the transition zone, fresh water (due to its lower density) is present above the saline water. Any pumping could reduce the fresh water head and induce the inflow of saline water from the east (East Suffolk and Norfolk River Authority, 1971). However, high chloride concentrations generally preclude the aquifers from being used for potable groundwater and further exploitation. Hence saline intrusion is restricted here.

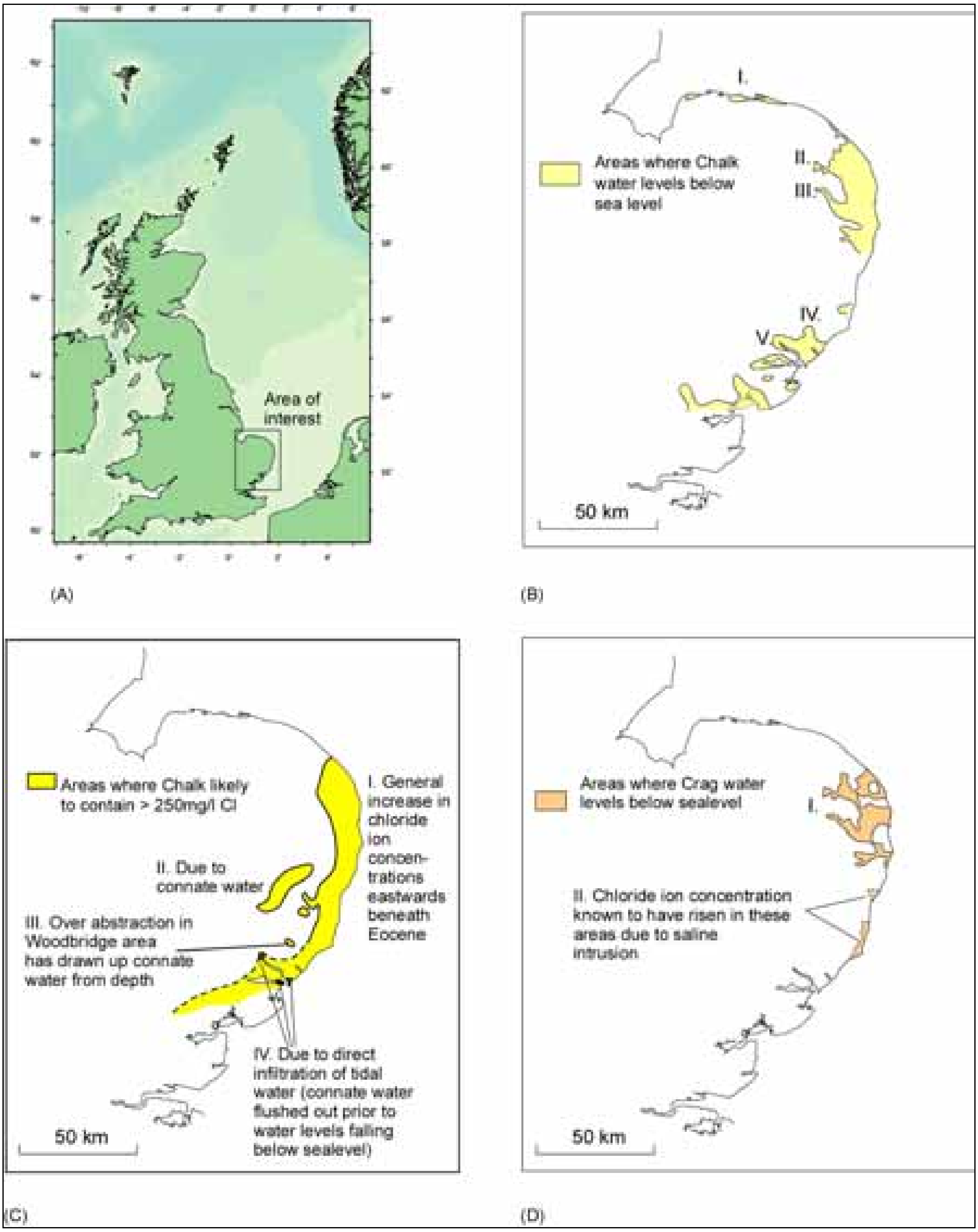

Figure 9. ***Maps indicating where enhanced chloride ion concentrations are found and water levels are below sea level in the Chalk and Crag aquifers of East Anglia. Map A: Area of interest, Map B: Areas where Chalk water levels are below OD, Map C: Areas where Chalk likely to contain >250mg/l chloride, Map D Areas where Crag water levels are below OD. Maps B,C,D adapted after Institute of Geological Sciences (1976, 1981) and east Suffolk and Norfolk River Authority (1971).***

Around Ipswich and Felixstowe restricted areas of the aquifer contain high chloride concentrations (Figure 9C area IV). These are caused by groundwater pumping drawing in saline water. Along the line of the Orwell estuary, the London Clay is locally absent and thus an outlet from the Chalk aquifer to the sea is present. The connate water is likely to have been flushed out while piezometric levels remained above sea level. Increased abstraction more recently has reversed the hydraulic gradient, allowing saline water from the estuary to flow into the aquifer. Another area of high chloride water exists around Woodbridge (Figure 9C, area III). However, here the saline water is thought to be connate water from depth, rather than induced infiltration of modern saline estuary water (East Suffolk and Norfolk River Authority, 1971).

Between Debenham and South Elmham (Figure 9C, area II), the high salinities are due to connate sea water present in the Chalk. A combination of low heads in the aquifer and limited fissure development in this synclinal area, means that there is no significant flow through the Chalk and the original formation water has not been flushed out. This is supported by the fact that boreholes are artesian, indicating significant heads in the Chalk aquifer with a hydraulic gradient towards the sea, rather than the other way round, as would be necessary to cause saline intrusion into the aquifer (East Suffolk and Norfolk River Authority, 1971).

The situations described in the preceding paragraphs indicate that in the Chalk aquifer, there are two sources of saline water; saline intrusion and connate water.

8.2.1.2 Crag

Along the coast the Crag aquifer is in direct contact with the sea and saline intrusion of the aquifer is known in a few areas. Figure 9D, based on data from the Institute of Geological Sciences (1976; 1981) and East Suffolk and Norfolk River Authority, (1971), indicates those areas where the water levels are below sea level. In the northern Broads, drainage of the marshes has reduced water levels to around sea level and led to the intrusion of saline water (area I). Further south, groundwater pumping has led to saline intrusion (area II) (East Suffolk and Norfolk River Authority, 1971).

8.2.2 Offshore hydrogeology of East Anglia

The mean porosity of 127 samples of Upper Chalk from East Anglia was 38.4% (Allen et al., 1997). This agrees with the geological section of this report that states that over a significant proportion of the Greater Ekofisk Area, Chalk porosity exceeds 35%. Despite these high porosities, the Chalk's permeability is predominantly secondary from fissures developed primarily in the zones of past and present water table fluctuation. No significant fissures have been noted at depths greater than 130 m below current sea level, corresponding to the minimum level to which sea level dropped in the Pleistocene. Hence, as the top of the Chalk is at an elevation of more than 150 m below sea level along the east coast, south of Winterton-on-Sea (TG 5020), there should be no fissures south of this point capable of transmitting groundwater. North and north-east towards the Hewett field, the surface of the Chalk is shallower, but even in this area, Chalk permeabilities are low and the likelihood of there being a hydraulic connection between the gas field and the onshore aquifer is minimal.

In the Southern North Sea Area, some of the highest chloride concentrations are reported in the formation waters of the southern gas fields within rocks of Permian and Triassic ages. Within the Leman Field, adjacent to the Hewett field, values are typically 100,000 to 300,000 mg/l (Warren and Smalley, 1994). The chemical properties of water in rocks such as the Chalk overlying these oil reservoirs and sub-cropping the ocean are not generally recorded. The lowest chloride concentrations in oilfield formation waters are found in the Brent Group reservoirs of Mid Jurassic age in the Central North Sea and are typically about 10,000 mg/l (Warren and Smalley, 1994).

Offshore outflows from the Chalk aquifer along the south coast of England, have been detected by thermal infrared surveys, which detected the differences in temperatures of groundwater and the sea in February when groundwater flows are highest (Davies, 1973; Brereton and Downing, 1975). BGS has no knowledge of surveys for groundwater outflows off East Anglia; however, there is anecdotal evidence that fishermen bailed for fresher water from the seabed (for making fish broth), just offshore around Lowestoft. Where outflows occur, they are an indication that groundwater flow is from the land towards the coast and offshore.

Between the coast and the Hewett Fault Zone, the Chalk forms a gently dipping syncline with dips typically of the order of less than 1º. Hydraulic gradients in the Chalk and Crag aquifers are expected to be very low, but overall in an offshore direction, over the approximately 25 kilometre distance to the Hewett Field. This is the nearest commercial gas field in the Study Area to the East Anglian coast.

The 1:250,000 maps of East Anglia indicate that the submarine distribution of the Crag extends from the north east corner of the East Anglian coast near Bacton north easterly to the Hewett Fault Zone. The Crag and Palaeogene tend to occur over similar areas, i.e. where the Palaeogene is absent, the Crag tends to be absent also. Off the north coast of East Anglia, Quaternary deposits tend to be absent and the sea bed sediments contain less than 10 percent mud (silt and clay). Therefore there are extensive areas where the Chalk is in hydraulic continuity with the sea.

8.2.3 Onshore hydrogeology of Moray Firth: Turriff Basin and Elgin

The Middle Old Red Sandstone and PermoTrias aquifers are adjacent to the coastline between Peterhead and Elgin. The Devonian Turriff Basin comprises hard conglomerates and extends some 30 km inland. The topography is variable and there are coastal cliffs in the north around Pennan Head. There are no boreholes in the northern part of this aquifer to indicate whether salinity levels are elevated, but due to the natural hydraulic gradients no saline intrusion is expected to have occurred. There is no evidence of saline intrusion further west in boreholes near the coast around Elgin.

The gas terminal at St Fergus and oil terminal at Cruden Bay are situated on non-aquifers.

The risk of significant groundwater contamination in the area is low

8.3 Risk of pollution to aquifers

8.3.1 Onshore Activities

The area of the existing gas terminal at Bacton is situated on the sands and gravels of the Corton Formation, and is underlain in turn by the Crag and the Chalk. The piezometric level in the Chalk and Crag, which are in hydraulic continuity in this area, as the Eocene is absent, is approximately at sea level. There is therefore some potential for pollution of all three of these permeable formations from leakages.

8.3.2 Offshore Activities

Constituents (fines) of drilling muds from oil and gas wells often include barium salts, which are used because of their high density. Barium mobility in aquifers is likely to be limited because of the insolubility of sulphate and carbonate salts. Therefore it is unlikely that these would be transported in significant concentrations even after the unlikely event of a reversal of the hydraulic gradient in permeable rock formations towards the land. The concentrations of sulphate and carbonate in the formation water will tend to control the solubility of barium in aquifers.

If the onshore Chalk were to be pumped close to areas where it outcrops on the seabed then it is more probable that seawater intrusion would be induced directly through shallow fissure systems than through the chalk matrix from deeper in the aquifer or further offshore.

Under the current coastal groundwater pumping regimes in East Anglia, the potential risk of contamination from infiltration of drilling fines onto seabed sediments and then into the Chalk or Crag aquifers, is low. Dispersal of contaminants by dispersion in the sea water and bed load currents parallel to the coast will also reduce the risk. The potential risk to these aquifers or to granular sediments in the Palaeogene, from the injection of formation brines, from the Triassic or Permian hydrocarbon reservoirs must also be very low. The reinjection of produced formation water into low circulation zones in the producing reservoirs themselves should present little risk. The large distances to fields other than Hewett will reduce the risk still further.

8.4 Sea level change

In the event of higher global sea levels, there would be a small increase in saline intrusion. The rate of sea water level rise is likely to be slow and it is likely that local pumping will be controlled so as to minimise the tendency for saline intrusion. This will also tend to control the extent of any pollution from contaminants in the aquifer.

8.5 Summary

The hydraulic gradients of the Chalk and Crag aquifers are generally in an offshore direction. In this situation, there is minimal risk of aquifer contamination from seabed or sub-seabed production fines or formation and other fluids.

The Hewett field, currently the nearest commercial gas field, is approximately 25 km offshore and fits into the minimal risk category summarised above.

There is a local risk of groundwater contamination if developments are superimposed on areas of aquifer at outcrop.

Local areas of high chlorides, caused by saline intrusion due to over abstraction (Chalk and Crag) have reversed hydraulic gradients. In these areas there is a very low risk of activities close to the shoreline polluting the onshore aquifers. However, due to the predominant current direction being parallel to the coast, rather than onshore, contaminants are likely to be quickly dispersed.

Overall, the risk of onshore aquifer contamination decreases with increasing distance offshore to developments.

In the event of higher global sea levels, there would be some equilibration with groundwater on land leading to some rise in onshore water levels. Therefore although this could result in overall larger areas with reversed hydraulic gradients, abstractions from the coastal fringe would reduce as chloride ion concentrations increased. The rate of water level rise is likely to be slow and the possibility of contaminant migration could be monitored in association with the water levels and chloride ion concentrations.

9. SEISMICITY

Understanding the seismicity of an offshore area is inherently harder than dealing with onshore areas because of the practical limitations on the availability of data. This is particularly the case in an area like the British Isles, where, for assessment of seismic hazard, there is a dependence on the existence of good historical records to counterbalance the relatively low rate of earthquake occurrence, and for providing adequate amounts of data for analysis.

9.1 Constraints on seismicity data

One can divide the earthquake record for convenience into four periods: early historical (up to 1800); late historical (1800-1900); early instrumental (1900-1970); and modern instrumental (1970 to the present).

In the early historical period the seismicity of the North Sea is very obscure. There are two possible cases for any offshore earthquake – it is reported from one side of the sea only, or it is reported from both sides. In the former case it is hard to assess how far offshore the epicentre should lie. In the latter case, only the largest events are likely to be observed on more than one coast. Because of the generally poor nature of historical records for Norway in this period, it is impossible to find clear cases of large earthquakes in the northern part of the North Sea. It is conjectured by Musson (1994) that the large earthquake of 19 September 1508 occurred in the northern North Sea. The large offshore earthquakes in this period that can be well located are significantly all in the extreme south of the North Sea, where many records are available from the Low Countries and France (earthquakes of 1382, 1449 and 1580). The damaging earthquake of 15 April 1185 which partly destroyed Lincoln cathedral is suggested by Davison (1931) to have had an offshore epicentre, a reasonable proposal. There are also a number of moderate earthquakes (magnitude probably between 4 and 5 ML) that were reported as felt in Eastern England only, which, from the distribution of felt effects, seem to have occurred offshore.

In the 19th century, historical records improve and more information is available on earthquakes felt in Norway (see Kolderup 1936, Muir Wood et al 1987). This would improve the location of large offshore events in this period, but in fact, few seem to have occurred during the 19th century. The principal event is the Northern North Sea earthquake of 4 January 1879 (4.8ML) felt in Norway and Shetland. Thanks to the detailed records surviving from the late 19th century, there are a number of observations of events in the Northern North Sea from lighthouse records (Musson 1998), although these events cannot be located from the single observations.

With the beginnings of instrumental seismology around 1900 (the first seismogram of a British earthquake was recorded in 1903), there exists the possibility of detecting an offshore earthquake without felt reports. However, early instruments were insensitive to small high-frequency events, and in many cases, the seismograms that do exist for British earthquakes in this period were only analysed because the time and day of the earthquake was known from felt observations. The recordings can be so weak as to be almost undetectable unless one knows exactly what part of the record to scrutinise. As a result, the capacity for detecting offshore earthquakes does not increase greatly in this period. However, the use of seismograms allows more accurate determination of the epicentral position of the larger events in this period: the earthquakes of 1927, 1931 and 1958 in particular.

Since 1970, instrumental monitoring of the region in general and the UK in particular has improved enormously, particularly with close co-operation between the seismological monitoring agencies in the UK (BGS) and Norway (University of Bergen). By the 1980s it became possible to locate earthquakes as small as around magnitude 3 ML in the Central North Sea.

9.2 Geographical distribution of earthquakes

The seismicity of the study area is shown in Figure 10. This represents a combination of historical and modern data, and shows all the data that can be plotted; the distribution is thus not homogeneous with reference to space and magnitude. Earthquakes known or suspected to be offshore from very limited historical data are not plotted; thus earthquakes like the 1185 event mentioned above are not plotted; any position assigned would have an uncertainty of more than 100 km and not be helpful. Some earthquakes occurring outside the area of study may impact on developments within the area of study. Thus seismicity has also been illustrated for the regions surrounding the UK North Sea.

One can divide the study area up into four areas of activity. From north to south these are: the South Møre Basin (north of the East Shetland Basin), the Viking Graben, the Central Graben, and the Sole Pit Basin (Section 1, Figure 1).

The South Møre Basin represents an area of high seismicity, perhaps the most active area in Europe north of the Alps, off the west coast of Norway. Its southern limit is around 61 N; Figure 10 only plots the seismicity up to the limit of the study area at 62 N, but activity continues further north of this. The largest earthquake here that fell within the study area was the 6 April 1977 event, with magnitude 5.6 ML. A further large earthquake occurred to the north on 8 August 1988, with a magnitude 5.4 ML. The seismicity appears to have some detailed structure; the Horda Platform, a structural high within the high seismicity area, stands out as a small area free of earthquakes.

The Viking Graben is a roughly N-S trending feature which is also associated with high seismicity, although not at the same rate as the South Møre Basin to the north. The graben itself is discussed in (Johnson et al 1993). Prominent events associated with it are the earthquakes of 4 January 1879 (4.8 ML), 24 January 1927 (5.7 ML), and the most recent one of note was 23 March 1971 (4.7 ML). The earthquake of 1927 was felt throughout Scotland and W Norway, and weakly down the E coast of England as far as Norfolk (Musson et al 1986) but without causing any structural damage.

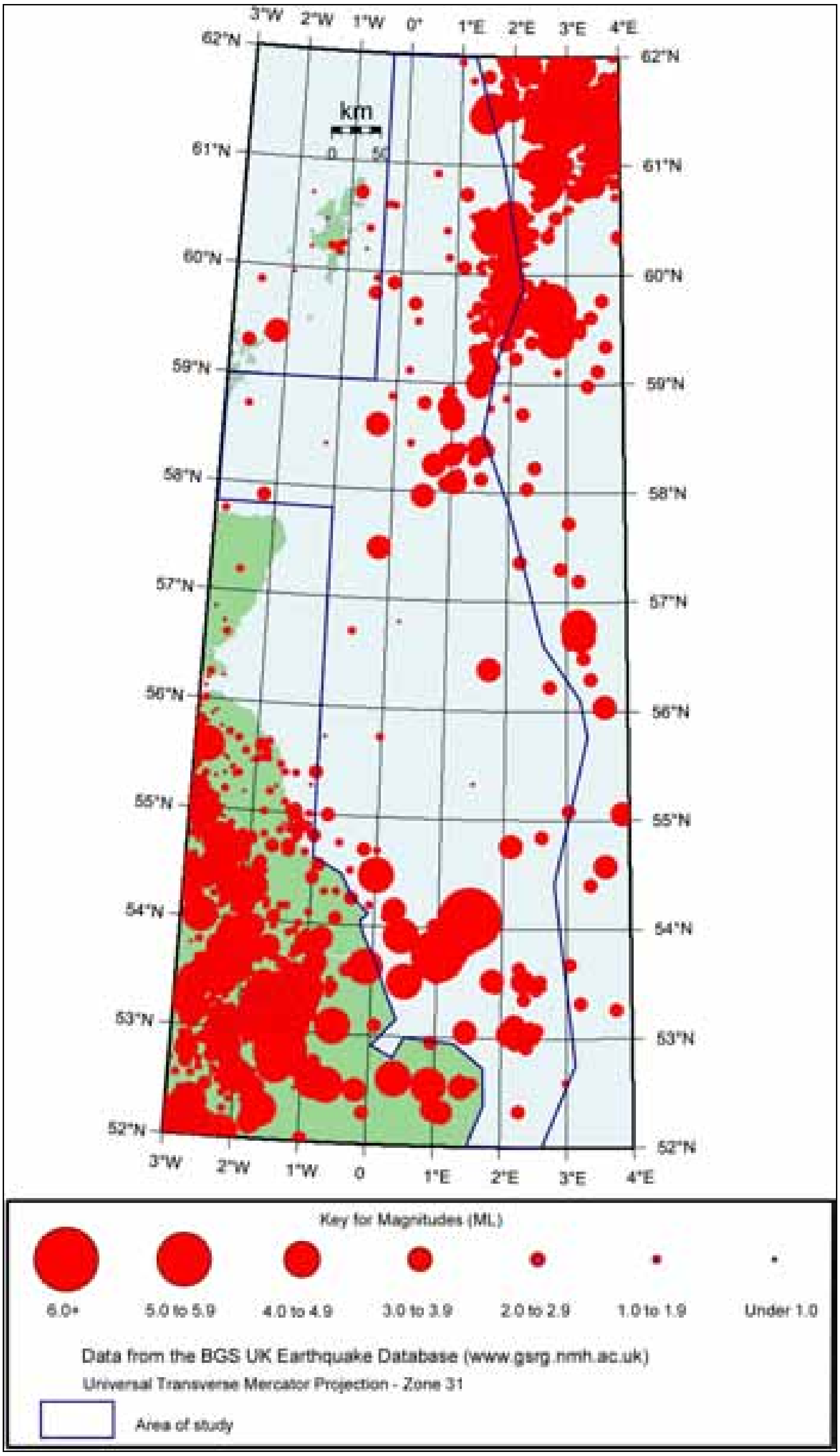

Figure 10. Seismicity of the North Sea

It was a matter of conjecture for some time whether the Central Graben system of the N Sea was seismically active, and it was only with the improvements in instrumental monitoring already discussed that events began to be located in this area after 1980. With the exploitation of hydrocarbons in this area, some earthquakes have also been felt on offshore structures such as the Ekofisk platform. No events larger than 3.7 ML (on 31 August 1992) have been detected in this area yet, and it does not appear to be as active as the Viking Graben.

The last active area is a NW-SE tending zone running roughly from Flamborough Head and N and NE of Norfolk (Figure 1). This zone appears to be associated with further graben structures in the Southern North Sea Basin. This area has been clearly active in historical times, and was responsible for the largest ever UK earthquake on 7 June 1931 (6.1 ML), which was felt over the whole of the UK and also around the coasts of other countries bordering on the North Sea (Neilson et al 1986).

9.3 Seismic hazard

There are two very significant contrasts that can be made between offshore seismicity in the North Sea and the onshore seismicity of Great Britain. In the case of British seismicity in general, it is notoriously difficult to associate the distinct spatial pattern with geological structure (Musson 1996). This is not the case offshore, where the pattern is linked clearly with graben systems and structure (Figures 1 and 10). The second contrast is that there is no evidence for any onshore earthquake in the British Isles having exceeded 5.4 ML in magnitude; with the possible exceptions of earthquakes in 1247 and 1275. For these two events the data are too obscure to determine magnitude values, but the earthquakes were certainly substantial. Offshore earthquakes clearly can be larger, as witness earthquakes of 5.6, 5.7 and 6.1 ML in the last 100 years. This may be symptomatic of the fact that onshore seismicity is a result of local reactivation of very old crustal weaknesses with little connection to current deformation. This situation contrasts to that of offshore seismicity where there is a clear link between seismicity, structure and a long history of rapid late Cenozoic deformation (section 1).

Seismic hazard in the North Sea has been studied by Musson et al (1997); despite the publication date, this study was actually undertaken in 1992 and is due for revision to reflect advances in seismic hazard methodology since then, and new data. If earthquakes of magnitude 4ML or above are expected then the stresses arising from these may require consideration for incorporation into the design specifications for the seabed developments. There is an inherent problem, though, with any study off offshore seismic hazard in that the attenuation of strong ground motion offshore is rather a matter of speculation, due to a lack of data.

Some general remarks on earthquake return periods can be made. For the whole of the study area, the expectation is for a magnitude 4 ML earthquake every two years, and a 5 ML every fourteen years. The return period for larger events is less certain; for a 6 ML the value is about every 130 years. Since the historical rate for magnitude 6 events is not more than three events in 900 years, then there are three possibilities: there are some missing large events in the extreme north of the study area (probable – but not necessarily as large as 6 ML); there has been a temporary downturn in the rate of large events (possible but not likely); or a 6 ML event is near the maximum for earthquakes in this area and the magnitude-frequency curve is tapering off towards the value at which it truncates (the most probable explanation). Dividing the study area in two parts, north and south, at 58ºN, one finds for the north part the return period for a magnitude 5 ML event is a little over 20 years;

for the southern part the corresponding value is over 100 years. The return period for a magnitude 6 ML event, computed from smaller events, is computed at around 900 years for the southern part, which is consistent with historical observation.

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11. GLOSSARY OF SELECTED TERMS

Accretion	The addition of island-arc or microcontinental material to a continent by convergent and transform motion, i.e. by collision and welding or suturing.
Aquifer	A body of rock that is sufficiently permeable to conduct ground water to yield economically significant quantities of water to wells and springs
Artesian	An adjective referring to ground water confined under hydrostatic pressure.
Basement	(a) The undifferentiated complex of rocks that underlies the rocks of interest in an area. (b) The crust of the Earth below sedimentary deposits, extending downwards to the Mohorovicic discontinuity.
Batholiths	A large, generally discordant plutonic mass that has more than 40 sq. mi (100 km^2) of surface exposure and no known floor. Its formation is believed by most investigators to involve magmatic processes.
Caledonian Orogeny	A name commonly used for the early Palaeozoic deformation in western Europe that created an orogenic belt, the Caledonides, extending from Ireland and Scotland northeastward through Scandinavia.
Caledonide	The orogenic belt, named by Suess extending from Ireland and Scotland northeastward through Scandinavia formed by the early Palaeozoic.
Cohesive	Said of soil that has relatively high shear strength when air-dried, and high cohesion when wet, e.g. clay-bearing soil.
Connate	Originating at the same time as adjacent material; especially pertaining to waters and volatile materials (such as carbon dioxide) entrapped in sediments at the time the deposits were laid down.
Continental shelf	That part of the continental margin that is between the shoreline and the continental slope (or, when there is not noticeable continental slope, a depth of 200m). It is characterised by its very gentle slope of 0.1°.
Crustal	The outmost layer or shell of the Earth, defined according to various criteria, including seismic velocity, density and composition.
Debris flows	A moving mass of rock fragments, soil, and mud, sometimes more than half of the particles being larger than sand size.
Deltaic	Pertaining to or characterised by a delta; e.g. "deltaic sedimentation". Also constituting a delta; e.g. a "deltaic coast".

Diamicton	A general term for an unsorted sediment
Diapirs	A dome or anticlinal fold in which the overlying rocks have been ruptured by the squeezing-out of plastic ore material. Diapirs in sedimentary strata usually contain cores of salt or shale.
Downwarping	Subsidence of a regional area of the Earth's crust, as in an orogenic belt
Earthquake	A sudden motion or trembling in the Earth caused by the abrupt release of slowly accumulated strain.
Epicentre	The point on the Earth's surface that is directly above the focus of an earthquake.
Eustatic	Pertaining to world-wide changes of sea level that affect all the oceans. Eustatic changes may have various causes, but the changes dominant in the last few million years were caused by additions of water to, or removal of water from, the continental icecaps.
Evaporite	A nonclastic sedimentary rock composed primarily of minerals produced from a saline solution as a result of extensive or total evaporation of the solvent. Examples include: gypsum, anhydrite, rock salt, primary dolomite, and various other nitrates and borates.
Fluvial	Of or pertaining to a river or rivers.
Formation	An assemblage of rocks or soils which have some character in common, whether origin, age, or composition.
Geotechnical	Pertaining to the broad field of geotechnics.
Glacigenic	Originating from glacier or ice sheet.
Groundwater	That part of the subsurface water that is in the zone of saturation, including underground streams.
Halokinesis	A general term for the study of the structure and mechanism of emplacement of salt domes and other salt-controlled structures.
Hiatus	A break or interruption in the continuity of the geologic record, such as the absence in a stratigraphic sequence of rocks that would normally be present but either were never deposited or were eroded before deposition of the overlying beds. (b) A lapse in time, such as the time interval not represented by rocks at an unconformity; the time value of an episode of nondeposition or of nondeposition and erosion together.
Horsts	An elongate, relatively uplifted crustal unit or block that is bounded by faults on its long sides. It is a structural form and may or may not be expressed geomorphologically.
Hydraulic	Pertaining to a fluid in motion, or to movement or action caused by water.
Hydrodynamic	The aspect of hydromechanics that deals with forces that produce motion.
Iapetus Ocean	A sea that existed in the general position of the present Atlantic Ocean before Europe and Africa collided with North America during the Carboniferous and Permian periods.
Intercalated	Said of layered material that exists or is introduced between layers of a different character; or relatively thin strata of one kind of material that alternate with thicker strata of some other kind, such as beds of shale that are intercalated in a body of sandstone.
Littoral	(a) Pertaining to the benthic submarine environment or depth zone between high water and low water, also pertaining to the organisms of that environment.

Magnitude	(Earthquake magnitude) A measure of the strength of an earthquake, or the strain energy released by it, as determined by seismographic observations. C F Ritcher first defined local magnitude as the logarithm to the base 10, of the amplitude in microns of the largest trace deflection that would be observed on a standard torsion seismograph at a distance of 100 km from the epicentre.
Morphology	(a) The shape of the Earth's surface geomorphology (b) The external structure, form and arrangement of rocks in relations to the development of landforms.
Mud	An unconsolidated sediment consisting of clay and/or silt, together with material of other dimensions (such as sand), mixed with water without connotation as to composition.
Outwash	Stratified detritus (chiefly sand and g ravel) removed or "washed out" from a glacier by meltwater streams and deposited in front or beyond the end moraine or the margin of an active glacier. The coarser material is deposited nearer the ice.
Overburden	The upper part of a sedimentary deposit, compressing and consolidating the material below.
Overpressured	Pressure in excess of lithostatic pressure, e.g. from tectonic stress.
Peneplanation	The act or process of formation and development of a peneplain; esp. the decline and flattening out of hillsides during their retreat and the accompanying downwasting of divides and residual hills.
Permeability	The property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid under unequal pressure.
Plate	A torsionally rigid thin segment of the Earth's lithosphere which may be assumed to move horizontally and adjoins other places along zones of seismic activity.
Porosity	The percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected.
Potable	Water which is safe and palatable for human use.
Redbeds	Sedimentary strata composed largely of sandstone, siltstone, and shale, with locally thin units of conglomerate, limestone, or marl, that are predominantly red in colour due to the presence of ferric oxide (hematite) usually coating individual grains
Relict	Said of a topographic feature that remains after other parts of the feature have been removed or have disappeared; e.g. a "relict beach ridge" or a "relict hill".
Rift	A narrow cleft, fissure, or other opening in rock (as in limestone) made by cracking or splitting.
Salt pillows	An embryonic salt dome rising from its source bed, still at depth.
Seismicity	The phenomenon of Earth movements.
Seismograms	An instrument that detects, magnifies, and records vibrations of the Earth, especially earthquakes.
Silesian	European stage: Middle and Upper Carboniferous (above Dinantian below Permian). Concludes Stephanian, Westphalian, and Namurian.
Strike-slip	In a fault, the component of the movement or slop that is parallel to the strike of the fault.

Subsidence	(a) The sudden sinking or gradual downward settle of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved. A sinking or downwarping of a large part of the Earth's crust relative to its surrounding parts, such as the formation of a rift valley or the lowering of a coast due to tectonic movements.
Substrates	The substance, or base or the medium in which, an organism lives and grows, or the surface to which a fixed organism is attached; e.g. soil, rocks
Temperate	Said of a temperature that is moderate or mild. The term is also used to describe temperatures of the middle latitudes, whether moderate or not.
Terrigenous	Derived from the land or continent.
Till	Dominantly unsorted and unstratified drift, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.
Transpressional	Convergent fault.
Turbidites	A sediment or rock deposited from, or inferred to have been deposited from, a turbidity current. It is characterised by graded bedding, moderate sorting, and well-developed primary structures
Unconformity	A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession
Variscan Orogeny	The late Palaeozoic orogenic era of Europe, extending through the Carboniferous and Permian. By current usage, it is synonymous with the Hercynian orogeny.