# North Sea Geology
## A Compilation of Geological Notes

# Contents

# 1.0 A Basic Stratigraphy of the British Isles

## 1.1 Era: None, System: Pre-Cambrian

The Pre-Cambrian covers the period of time from the consolidation of the Earth's crust to the base of the Cambrian and is sub-divided into three main parts, Upper, Middle and Lower. In the past it has also been known as 'Proterozoic', 'Azoic' and 'Arcaean'. Correlation is very hard in the Pre-Cambrian because of the unconformable boundaries and metamorphic state of the contacts. This has given rise to regional stratigraphic sequences and local names for groups of strata, some worldwide correlations have been possible due to radioactive dating. The duration of the Pre-Cambrian is probably no less than 4,000 million years and contains a number of known orogenies. Most Pre-Cambrian rocks have undergone one or more orogenies in the Pre-Cambrian and in subsequent movements. Some relatively un-metamorphosed sediments of Pre-Cambrian age are known in Southern Australia and Leicestershire and some fossils from the era have been described but show 'obscure' affinities.

## 1.2 Era: Lower Palaeozoic, System: Cambrian

The oldest system of rocks in which fossils can be used for dating and correlation. The Period commenced at least 530 million years ago and lasted for approximately 70 million years. In general the base of the Cambrian shows an unconformity with the underlying sediments and is the first sediments to contain fossil remains. In Great Britain there appears to be a marked unconformity between the Cambrian and Pre-Cambrian, even when the Pre-Cambrian has proved to be fossilifereous. The upper limit of the Cambrian is taken to be the top of the Tremadoc series (which in the area of Tremadoc, Wales, is overlain by the Arenig Grits of the Lower Ordovician).

**Lithology**
Cambrian sediments were deposited in two different sedimentary facies. One was due to unstable extra-kratonic basinal deposition, which were massive accumulations of detrital muddy sediments (formerly referred to as the Atlantic Province) and the other was stable deposition of relatively shallow water sediments around the margins of kratons. This deposition characteristically took the form of calcareous sedimentation in clear seas often with an abundance of colloidal silica (formerly refereed to as the Pacific Province).

**Fauna**
The fauna's of the two different areas of deposition differ in many respects, in Great Britain the Pacific facies is represented only by sediments in north-west Scotland, west of the Moine Thrust. Most groups of invertebrates are represented in the Cambrian but only a few occur often enough to be of use for correlation and dating. Trilobites, especially the more primitive forms were abundant and are the main means of zoning the Period, brachiopods were common and graptolites first appear in the Tremadocian.

## 1.3 Era: Lower Palaeozoic, System: Ordovician

The Period extended from 500 to 435 million years ago with a duration of 65 million years. The lower limit is the base of the Arenig Series, which is defined on the first appearance of two-striped extensiform graptolites. The upper limit is the top of the Ashgill Series which is overlain by the lower Llandovery of the Silurian Series, the top of the Ashgillian Series contains the last of the trinucleid trilobites.

**Lithology**
This period showed pronounced vulcanicity and was the start of the Caledonian orogeny. In the North West Scotland the lower part of the Ordovician is represented by limestones which are conformable upon the Cambrian.

**Fauna**
More advanced trilobites were abundant and brachiopods showed more articulate forms. Crinoids became abundant at some horizons and the first tabulate and rugose corals appeared. North America saw the first vertebrates (fish) but the most important fossils of this era were the graptolites, and these are used to zone the Period.

### 1.4 Era: Lower Palaeozoic, System: Silurian

The period extended 435 to 395 million years ago, with a duration of 40 million years. The lowest beds in the series are the Lower Llandovery Series (also known as Valentian); these are defined by the graptolite zone Glyptograptus persulptus. The upper limit is the top of the Downtonian. The Downtonian is included because it contains fauna that are Silurian in aspect, but also contains newer forms. It also lies conformably (in the UK) upon the Upper Ludlow Flags and marks the final phase of Silurian sedimentation. The Silurian marks the final stage in the filling of the Lower Palaeozoic basins of deposition.

**Lithology**
The Scottish mountains provided detritus that went south to the postulated continental margin and lapetus Ocean. The sediments are generally, limestones, lithic arenites, mudstones and conglomerates. In the Midland valley are found lithic wackes, laminated siltstones and grey or grey/green mudtones.

**Fauna**
The top of the Valentian contains the first jawed fishes, trilobites were abundant and brachiopods were represented by all the main groups. Crinoids were present in sufficient numbers to provide limestones. Graptolites, which were represented by varieties of Monograptids died out in the type area but continued into the Lower Devonian in central Europe. The first land plants appeared in this period.

### 1.5 Era: Upper Palaeozoic, System: Devonian

The Devonian extended from 395 to 345 millions years ago and had a duration of 50 million years. The upper limit of the marine Devonian is the top of the Famennian and the upper limit of the continental facies of the Devonian is variable as the overlying Lower Carboniferous is diachronous upon it. Higher zones of the continental Devonian are represented in Greenland but not in Great Britain.

**Lithology**
The Devonian includes the oldest widespread phanerozoic continental deposits; these are deposits that contain obvious and abundant remains of animals and plants. These deposits interdigitate with marine deposits in a number of areas and the continental deposits are referred to as Old Red Sandstone. The climax of the Caledonian orogeny occurred during the Devonian and gave rise to widespread vulcanicity.

**Fauna**
The majority of Devonian zoning is done using fossilifereous deposits of the Ardennes, Belgium. The marine Devonian is zoned on early ammonoid cephalopods (molluscs), where the Old Red Sandstone is zoned largely on brackish or freshwater fish. No new fossil groups are represented in the marine Devonian but some of the more common groups of the Lower Palaeozoic sediments become rare or extinct i.e., Graptolites died out in the early period and trilobites became generally rare. Corals became abundant, especially in the Middle Devonian where reefs occurred. Ammonoid cephalopods became relatively common but nautiloids became unimportant. Crinoids still flourished as did brachiopods and this era saw the emergence of the first marine fish.

In the Old Red Sandstone fish, plants and freshwater molluscs are now found as fossils. The fish underwent considerable development, starting with primitive armored, jawless forms which developed into advance jawed forms. These, at the top of the Old Red Sandstone, developed lungs and were teetering on the edge of being amphibious life.

Plants developed initially as unspecialized swamp forms, rarely exceeding 60cms in height, these later evolved to large tree like ferns at the close of the period. The most abundant of the freshwater molluscs were lamellibranchs that are very similar in form to modern freshwater molluscs.

### 1.6 Era: Upper Palaeozoic, System: Carboniferous

Named after widespread occurrence of carbon in the form of coal in these beds. It covers 345 to 280 million years ago and had a duration of 65 million years. It is divided into two sub-systems, the Lower Carboniferous (Mississippian) and Upper Carboniferous (Pennsylvanian) with the boundary being approximately 325 million years. The lower limit of the Carboniferous is taken where the Devonian faunas are replaced by the fauna of Productid brachiopod and corals. The upper limit is difficult to interpret. A marine sequence occurs in Russia and North America and the Foraminifera Pseudoschwagerina marks the beginning of the Permian.

**Lithology**
A major transgression during the late Devonian to early Carboniferous times flooded the southern margin of the Old Red Sandstone continent. Block and basin areas were established, with many basins taking the form of gromorphic gulfs during the early Dinantian. Carbonate sediments dominated Dinantian deposition in most area, with major, eustatically controlled cyclicity responsible for regional facies change. Extensive lime-mudbank accretion occurred in many basinal areas, with a major phase of associated 'stratiform' lead-zinc mineralisation. Northern areas show evidence of repeated introductions of fluvio-deltaic clastics and alkali-basaltic volcanism. An extensive hinterland uplift phase in late Dinantian times (recogniseable from Silesia to Illinois) was followed by a copious introduction of clastic debris (Namurian Millstone Grit). By upper Carboniferous times an enormous low-lying fluvio-deltaic pain lay over much of NW Europe, causing many coal bearing cycles.

The period experienced widespread vulcanicity and minor igneous intrusions. Toward the end it saw the commencement of the Variscan orogeny and widespread glaciation became established in the southern hemisphere, especially near what is now the present day equator.

**Fauna**
In Great Britain the Lower Carboniferous marine sediments predominate and generally two faunal provinces can be seen.

The Lower Carboniferous facies are usually detrital organic limestones, often with the development of coral reefs, these sometimes show abundant crinoids and brachiopods. The other environment is one of black shales containing a reduced fauna of brachiopods and often goniatites, especially in the upper part of the succession. The Upper Carboniferous in Britain is mainly represented by fresh water or lacustrine sediments containing occasional marine bands. The flora of the Upper Carboniferous consisted mainly of primitive vascular plants that could reach a height of 15-20m and were the main contributors of today's Carboniferous coal seams.

Economically the Carboniferous is very important as it contains the bulk of the Worlds coal reserves and important reserves of iron ore, oil shale and oil.

## 1.7 Era: Upper Palaeozoic, System: Permian

The Permian covered 280 to 225 million years ago with a duration of 55 million years. It marks the end of the Palaeozoic era. Because of the widespread occurrence of continental conditions during the late Carboniferous, Permian and Triassic times defining the upper and lower limits are often difficult. Where marine deposits occur the incoming of large Foraminifera (Pseudoschwagerina) marks the base. The upper limit of the continental facies has been defined as the top of a 'zone' of reptile (Cisticephalus) but is not suitable for general use.

**Lithology**
The continental facies of the Permian is represented by red marls and arkosic sandstone, dolomitic limestones and evaporites. There was limited vulcanicity through this period although the Variscan orogeny was still ongoing and there was the climax of glaciation in the southern hemisphere.

**Fauna**
Many important fossil groups became extinct in the Permian, this included the trilobites and tabulate and rugose corals. The only new group to become widely represented were the reptiles, who were the first vertebrates to sever their connection with water. Flora underwent a marked change in the Permian, the large primitive ferns of the Carboniferous were largely replaced by more advance conifers.

Often the Permian and the Triassic are grouped together as a single Permo-Triassic system, a synonym connected with this grouping is 'New Red Sandstone'.

### 1.8 Era: Mesozoic, System: Triassic

He Triassic extends from 225 to 195 million years with a duration of 30 million years and it marks the beginning of the Mesozoic Era. Widespread continental conditions persisting from the preceding Permian Period make a definition of the lower boundary difficult. The upper limit is marked by a sharp change at the start of the rhaetic (a transitional series between the Triassic and Lower Jurassic). The rhaetic series is included with the Jurassic by British stratigraphers, it marks the period of time after the first marine transgression in the Mesozoic and before the deepening of the seas which led to the deposition of the Lower Jurassic.

**Lithology**
Throughout Permian times the area lay in a trade wind belt, having a hot and arid climate. Ephemeral streams cut wadis in the highland massifs, which became fringed with talus. The Triassic in Northern Europe opened with a phase of uplift that affected many of the massif areas. Periodically, transgressions occurred from the south that raised humidities and permitted temporary establishment of lagoonal communities.

**Fauna**
The Triassic in Great Britain is entirely continental deposits but marine intercalations do occur elsewhere. The continental deposits are largely unfossiliferous except for the occasional reptilian footprint. In Europe, where marine sediments occurs the fauna was mainly lamellibranchs, crinoids and advanced ammonoids. Some very early dinosaur remains occur.

### 1.9 Era: Mesozoic, System: Jurassic

The Jurassic covers the period of time from 195 million years to 135 million years, having a duration of 60 million years. It is divided into the Lower Jurassic (Lias), Middle Jurassic (Dogger) and Upper Jurassic (Malm), the boundaries are at 172 and 162 million years respectively. Further very small divisions have been made based on over a hundred fossil zones which have been grouped into eleven stages with the lower limit being the pre-Planorbis zone and the upper zone being marked by a zone containing Cypridea punctata (Ostracopd).

**Lithology**
In Great Britain all the sediments are shallow water facies with fauna derived from the Tethyan basin. Sedimentary iron ores are widespread at several horizons and in southern Europe the first stages of the Alpine orogeny were being felt.

**Fauna**
The Jurassic had very diverse fauna, the main members were the ammonites, and the period is zoned using these, hexacorals, echinoids and brachiopods were also abundant as were lamellibranchs and gastropods. Dominant terrestrial animals were the dinosaurs with reached their maximum size in the Jurassic and the first birds appeared in the Upper Jurassic. Birds had been known since the rhaetic but were rarely large. The flora included many types that are still seen today, such as cyads, gingkoes, conifers and ferns.

### 1.10 Era: Mesozoic, System: Cretaceous

The Cretaceous Period lasted about 72 million years, between 136 to 64 million years ago. The division between Upper and Lower is approximately 100 million years. Each of the main divisions are further divided into six stages, the lower limit of the period is the base of the Craspedites zone and the upper limit is the top o the Maastrichtian. Some stratigraphers include the Danian, either whole or in part as the uppermost stage. The end of the Cretaceous marks the end of the Mesozoic Era.

Lower Cretaceous sediments continue the pattern of Jurassic sedimentation. In Britain this was primarily lacustrine, deltaic and esturine facies. The beginning of the Upper Cretaceous saw a widespread marine transgression (the Cenomanian Transgression), which at its greatest produced the largest proportion of sea relative to land on the Earths surface since the Palaeozoic.

**Lithology**
In Northern Europe and part of the mid-western United States the Upper Cretaceous is represented by a white limestone (Chalk). In Tethys, the early stages of the Alpine orogeny occurred, in the trough that was produced substantial thicknesses of marine sediments were deposited.

**Fauna**
As expected the early Cretaceous fauna carries on from that of the Jurassic with ammonites and other molluscs being abundant. The ammonites become rarer as the Cretaceous progresses and are extinct by the end of the Period, as are belemnites. Brachiopods flourished in the early Cretaceous but suffer a marked reduction by the end of the Period. Molluscs are used as zone fossils wherever possible and echinoderms and lamellibranchs are locally important, these are usually used as zone fossils where ammonites are absent. Corals are generally less prevalent than the previous Era's.

On land dinosaurs were dominant, but became extinct toward the end of the period, some Cretaceous mammals are known but not significant in size and numbers. The flora matured to produce flowering plants through the Period.

### 1.11 Era: Cainozoic, System: Tertiary

The Tertiary covers the period of time from the end of the Cretaceous to the present day and covers approximately 65 million years. The majority of Tertiary sediments are shallow water in origin and tend to cut across time boundary's making them difficult to define.

#### 1.11.1 Palaeocene

Usually the Montian is taken to be the lowest stage of the Palaeocene but some stratigraphers consider it to be the equivalent of the Upper Cretaceous Danian stage. The Montian and the Thanetian constitute the Palaeocene and generally shows fauna of the Cretaceous (survival forms) before the onset of Tertiary fauna proper.

#### 1.11.2 Eocene

The Eocene begins with the Sparnacian, which contains true Tertiary faunas for most of the world. A general increase in world temperatures occurred in the Eocene, which reached a peak in the Bartonian stage and was mainly characterised by tropical and sub-tropical forms.

#### 1.11.3 Oligocene

Following the Eocene was the Oligocene, which commenced with the Sannoisian and a general reduction in worldwide temperature. The United Kingdom only exhibits the lowest part of the Oligocene but elsewhere the upper section shows a regression of the seas which left a number of isolated basins, each with its own characteristics and fauna.

#### 1.11.4 Miocene, Pliocene and Pleistocene

During the Miocene and Pliocene times the withdrawal of the seas continued, resulting in an absence of the Miocene in Great Britain and only a meager representation of the Pliocene. Elsewhere the Miocene and Pliocene are represented by either freshwater sediments in basins or by marine sediments deposited near to the existing coastlines. The gradual reduction in temperatures continued throughout this time. Through the Pliocene the drop in average temperatures caused the extinction of many groups of mammals and the migration of others to warmer regions. Pliocene deposits are represented in Great Britain by accumulations of shallow water gravel's in East Anglia, together with some high level gravel's in the southern part of Britain and occasional basin deposits in the southwest. Between 80-90% of fossils forms occurring in this country still exist today. The gradual deterioration of climate through this period eventually led to the ice ages of the Pleistocene. In Great Britain it is not possible to draw a line between the Pliocene and Pleistocene although it can be done in some European areas such as Italy.

The glacial period can be separated into two parts, separated by the Great Interglacial, which lasts about 300,000 years. It can be seen that two periods of glaciation occurred before and after the Great Interglacial and between the glaciations the climate was warmer than it is today. The last ice sheet to cover Britain receded about 11,000 years ago and the average annual temperature gradually increased to reach a climax about 5,000 years ago when the bulk of Britain was covered by deciduous forest. Since then the climate has gradually, and is continuing to deteriorate. The periods between glaciation were probably characterised by high rainfall and it was under these conditions that man gradually evolved.

During this time glacial debris accumulated north of a line from Bristol to London where Pleistocene sediments are seen as large spreads of gravel and river terraces which represent the resorting debris from ice sheets. It was during this period that the majority of major landforms in Great Britain today were formed. Fossils from this period include, horses, elephants and pigs.

### 1.11.5 Holocene

Holocene is the term for post-glacial deposits, and the Quaternary generally refers to Pleistocene and Holocene deposits.

# 2.0 General Geology and Structural Framework

## 2.1 Introduction

The composition of the sedimentary fill in the North Sea Basin as a whole is the result of a complex series of structural events that have affected the Northwest European shelf since the Palaeozoic Era. The main effect of these structural events has been a highly variable influx of sediment into the basin, both in direction and magnitude. This changing influx reflects the changing positions and relative elevations of the structural units that acted as source areas in adjustment to the stress patterns that effected them. The relative elevation of most of the structural units has changed over geological time to such an extent that almost all have been both source and receiving area. Complete sedimentary sequences representing the entire time span of the North Sea basinal evolution are therefore not found anywhere, however more or less complete sequences over shorter periods can be found in many areas. The most complete sequences are found in the basinal centre.

Two major sedimentary basins are present, the Southern North Sea Basin, and the Northern/Central North Sea Basin. The two basinal areas are separated by a NW-SE trending series of relatively high areas, the Mid North Sea High is the most important high feature in the area of interest to exploration, production and development.

In The Northern/Central North Sea Basin the most important structural features are three buried graben systems, the Viking Graben, Witch Ground Graben and the Central Graben, and their margins. These three graben features, almost intersecting in the northern area of Block 22, represent the areas with the thickest sedimentary fill of the areas where exploration, production and development is currently active.

In the Southern North Sea Basin the most important features of the area of exploration, production and development are the NW/SE trending Sole Pit Basin, and Inde Shelf and the Silver Pit Basin to the north of these areas.

It should be realised that the sequence present in the different areas is a layer cake of sediment with each recognisable unit formed to a set of paleo controls uniquely its own. Correlation over large distances and sometimes through the entire basin is usually only possible for those layers or intervals formed in response to major events affecting the entire area.

From the viewpoint of basin development the following stages can be recognised:

- Caledonian Phase (Cambrian to Devonian)
- Hercynian Phase (Devonian to Carboniferous)
- Permo-Triassic Intracratonic Phase
- Rifting (Late Triassic to Early Tertiary)
- Post Rifting (Tertiary)

## 2.2 Caledonian Phase

The Caledonian orogenic (mountain building) phase resulted in the collision and fusion of the North American-Greenland plate and the Northwest European plate along the Appalachian and Scottish-Norwegian foldbelts. The massive volume of eroded sediment from the highly uplifted areas of this floodbelt forms the first sedimentary fill on top of the folded, metamorphosed and in places granite intruded rocks of Caledonian age. These Caledonian rocks form the economic basement of the North Sea basin from a hydrocarbon exploration point of view.

The paleogeographical situation near the end of the Caledonian orogeny is very roughly as follows; a high rapidly eroding SW-NE trending Scottish-Norwegian mountain chain sheds sediment to the S and SW onto a large floodplain and onto a wide, shallow marine shelf that reached as far as the Central North Sea. The London-Brabant Massif forms a high area bounding the basing to the SW.

Sediments from this period reflect the mainly continental environment of sedimentation in their red colours, indicative of the oxidising, continental conditions. Coarse sandstones and conglomerates interbedded with finer sandstones/siltstones and claystone indicate that rapid runoff of water (no land vegetation exists during this period) caused string flow and erosion and rapid switching of runoff channels over a floodplain and a high influx of sediment into a shallow sea.

### 2.3 Hercynian Phase

The second phase (Hercynian Phase) was marked by a major uplift of the areas that still form the southern margin of the North Sea Basin. The London Brabant Massif which was a major stable block during the preceding Caledonian orogenic phase was uplifted and fused with the Hercynian mountain chain which formed in a East-West direction across Southern Britain, France and Central Europe. The North Sea basin became enclosed on all sides with connections to other basins and oceanic areas narrow and perhaps intermittently closed as a results of the various orogenic phases of the Hercynian phase.

The wide shelf that occupied most of the North Sea during the Lower Carboniferous was characterised by shallow marine carbonate and claystone deposition with marine ingressions reaching far to the north into the degraded Caledonian mountain chains. Coal bearing sequences were locally deposited in the Central North Sea and Northern England.

As the basin gradually shallowed sedimentation lost much of its marine character and the thick coal deposits deposited in this period are the source rocks for the gas reservoirs both onshore and offshore in the southern basin.

These upper Carboniferous coal sequences do not extend into the central and northern North Sea. The Carboniferous deposits in the central and northern North Sea were laid down in intramontane basins that had limited or no connection to adjacent basins. As later erosion has removed much of the sediment uncertainty remains on the exact nature and distribution of the deposits of Carboniferous age in these areas. Devonian sediments form most of the Pre-Permian subcrop in the area. Some deposits of Carboniferous age have been drilled, limestone, shale and sandstone have been encountered.

### 2.4 Permo–Triassic Intracratonic Phase

At the end of the Hercynian phase the mountain chains formed to the south of the North Sea basin had been consolidated with the craton to the north, with this compressive stresses ceased to work on the area. A new tectonic framework characterised by an extensional setting developed in the Permian. Two large intracratonic basins formed separated by a newly formed series of west-east trending high areas. Of these the Mid North Sea high is the most important in the exploration, production and development area of interest.

The first signs of rifting became apparent in the central and northern North Sea at the end of the Permian and became more pronounced in the Triassic providing the base for the sedimentation patterns of the Jurassic period that followed. The continuing extension and subsidence of the basins throughout the Permian and especially the Triassic lead to thick sediment cover in the two basins and a thinner but still substantial cover over the Mid North sea high.

In the southern basin influx from the eroding Hercynian mountain chain and the high areas rimming the basin lead to a great thickness of sediment. Widespread deposition of redbeds (dunesands) and evaporites around the edges of an inland sea characterises the Lower Permian. These sands (Rotliegendes) are primary reservoirs (gas) in the southern North Sea basin. The rates of deposition vary considerably in the various subbasins. The sands grade into shales and evaporites further northward in the southern basin. In the northern North Sea basin the Rotliegendes sediment is thinner but similar in its composition. Continued subsistence and eventually a relatively low position relative to the ocean level caused a rapid marine transgression once a connection was established to the ocean.

The dark shales of the Kupferschiefer formation mark a break in the sedimentation from the Rotliegendes sands to the Zechstein evaporites and carbonates.

The deposition of carbonates and sulphate sequences characterises the basin margins and very thick halite (rockshaft) deposits the basin centre of both basins. The cyclic nature of the Zechstein can be ascribed to eustatic sea level changes and/or periodic influxes across a physical barrier (tectonically controlled) in the connection to the open ocean. The Zechstein carbonates contain significant quantities of gas in the onshore areas of the eastern rim of the southern basin but do not form significant reservoirs in the offshore areas.

The movement of the salt deposited in the Zechstein during subsequent periods strongly influenced sedimentation patterns and played an important role in the generation of high pressure in the reservoirs of younger age especially in the central area.

### 2.5 Triassic Phase

The start of the Triassic period was characterised by a return to continental type of deposition with fluvial and alluvial sediments being deposited on top of the Zechstein fill. The source of the influx was probably from a northern as well as a southern direction, the Zechstein was eroded to a large extent in the northern basin but is well preserved in the southern basin. The salt deposits act as an impermeable seal for many of the gas reservoirs in the southern basin.

An important new feature was the subsidence of the areas where rifting was to follow, the Central and Viking Graben, and the uplift and erosion of high areas flanking the developing grabens. The sedimentation in the southern basin was more or less continuous into the Triassic, The Bunter Sandstone Formation and sandy deposition of similar age are found rimming the southern and western edges of the North Sea basins. The basin centers were characterised by more shaly sequences (Smith Bank Formation and Cormorant Formation). The main sediment source throughout the Triassic was the Scandinavian shield with smaller contributions from the high areas to the south and the west of the North Sea basin.

A regional tectonic pulse (Hardegsen pulse) had a considerable impact on the basin by triggering the first salt deformation and uplifting some major tectonic blocks in the basin amongst which the Mid North ea high. Erosion followed the uplift and subsequently the basin subsided and was filled by a very fine rained muddy sediments. At the end of the intracratonic phase the entire area is marked by a very low relief. The middle and upper Triassic sediments are not considered to be of great interest for hydrocarbon exploration.

### 2.6 Rifting Phase

In response to large scale rifting movements in the Atlantic and later in the rifting phase also far to the east of the area there was a large increase of tectonic activity in the North Sea basin. The crustal stability was severely affected and the incipient rifts of the Triassic developed into large rift systems which in turn affected the adjacent areas and changed the sedimentation pattern in a major way.

Several pulses of what has been termed the Cimmerian cycle affected the area and the sediment was deposited in clearly recogniseable sequences. Several regressive-transgressive clastic sedimentary cycles, truncated by an erosion surface can be recognised.

The first pulse caused increased rifting, uplifted several areas marginal to the North Sea basin but on the whole affected the high areas more than the basinal centre where sedimentation continued with only a small hiatus. In the developing rifts Triassic fluvial and deltaic/near shore deposits are buried beneath increasingly fine grained sediments (e.g., Dunlin Group in the Viking Graben overlying the Triassic Statfjord Formation) as a widespread transgression of the sea over land occurred.

In the southern North Sea, Lower Jurassic (Liassic) clays conformably overlie older Triassic deposits and a carbonate shoal rimmed the London-Brabant Platform, the high point of the transgression was reached in the lower Jurassic (Dogger Formation). After the high point of the transgression deltaic complexes started to spread into the basin from the margins, and these deltas developed especially in the north of the basin. The sediments that were laid down during this periods contain some of the largest oil reservoirs in the North Sea basin (Brent, Dunlin, Cormorant).

The second major tectonic pulse, during the Callovian (Upper Dogger), had much more impact and set off another round of subsidence and some uplift of other tectonic blocks. As very deep holes developed in the Viking and Central Graben volcanism (Ratteray Formation) became a locally important source of sediment. Deformation of buoyant salt was very string during this time in the areas underlain by Zechstein salt. In the southern North Sea basin the salt structures control to a considerable extent the distribution of Jurassic sediments. The Jurassic sediment left is very much the sum of regional and local erosion and sedimentation.

During and after the second major (Callovian) pulse the high blocks are subject to erosion and the basins are filled partly by the material derived from this erosion. Thick sequences of sediments accumulate in the deeper part of the basin which have a distinct coarsening upward component and consist of a mix of sandy detritus from the high areas (turbiditic) and clays originating in the basin itself (pelagic). High areas and more distal parts of the basin did not receive much sediment, the sediment fill shallowed the basins and the regression reached its maximum at the end of the Jurassic.

The third pulse of the Cimmerian cycle occurred at the end of the Jurassic and caused further warping, rifting an wrenching. Along the southern rim of the North Sea the Wealden basins underwent rapid subsidence. During the Lower Cretaceous a gradual transgression characterised the North Sea basin, deposition of shallow water shales and carbonates occurred in the central parts of the basin, deeper water deposition of shales took place in the rifts and the basin margins were characterised buy deposition of coarse sediment (especially the Moray Firth area).

The transgression marks the final stage of the Cimmerian tectonic activity and tectonic activity decreased markedly during the Cretaceous. The basinal area became covered by a shallow sea with a predominantly carbonate sedimentation, notably chalk. In the grabens the sedimentation was more clayey. Great thicknesses of sediment accumulated during the Cretaceous in most of the North Sea basin, sedimentation cycles were controlled by eustatic sea level changes, the sediment deposited consists mainly of limestones (chalk) and marls.

At the end of the Cretaceous – early Tertiary a final phase of tectonic activity in response to Atlantic plate movements affected the North Sea (Laramide phase). Uplift and erosion along the margins of the Viking Graben was accompanied by down faulting and warping and the removal of much of the chalk from high blocks near the margins. In the central North Sea the effects were minor but in the southern basin the effects were very pronounced. Inversion of the Weald basins and major uplift caused the formation of complex structures and massive erosion. Most of the Cretaceous and Jurassic (what was left after the Cimmerian pulses) cover was eroded and Tertiary sediment is found on top of sediments of Triassic age. The detritus of the erosion was resedimented in he central part of the North Sea basin and formed the Danian deposits. Several huge oil fields are found in these resedimented deposits (Ekofisk and Dan).

### 2.7 Post Rifting Phase

After the Laramide pulse strong basin subsidence occurred in response to Atlantic rifting and the resulting south-eastward movement of the European plate. The movement decreased during the middle Tertiary however basin subsidence continued.

A notable event was the enormous volcanic activity at the Eocene-Paleocene boundary which caused a basin wide cover of volcanic sediment (Balder Tuff). The main sources of the volcanic sediment were the major eruptions which occurred throughout Western Scotland and the Atlantic region.

As subsidence continued sedimentation into the basin proceeded at a rapid rate and very thick Tertiary sequences are present, especially in the basin centre. During the Paleocene and Eocene a large influx of sand and finer grained material from the north-west formed a shelf along the Scottish coast and a series of deep-sea fans in the centre of the basin. The sandy sediments of these deep-sea fans now form the reservoirs for the majority of Tertiary fields of the North Sea (e.g., Forties, Petrel, Gannet, Frigg).

As continued Atlantic rifting removed the western source areas of the material the remainder of the Tertiary is marked by finer grained deposition.

*Reference: "Introduction to The Petroleum Geology of the North Sea" K.W. Glennie*

# 3.0 Stratigraphy and Reservoir Geology

## 3.1 Southern North Sea

The source for all the reservoirs in the southern North Sea area are Carboniferous coals and shales deposited in a range of environments (shallow/deep marine, lagoon, delta, lake). The gas migrated into Permian sand bodies sealed by Zechstein evaporites, or Carboniferous sands sealed by Lower Permian clays.

### 3.1.1 Carboniferous Reservoirs

Westphalian and Stephanian reservoirs occur in the Silverpit area where fluvial sand/shale sequences lie unconformably below sealing shales of the Lower Permian Silverpit formation. The Westphalian consists of a mixture of interbedded coastal, swamp (coal), fluvial and shallow marine deposits.

Above the Westphalian deposits is a further sand/shale sequence called the Barren Red Beds, of indeterminate age (but considered to be Westphalian D and/or Stephanian) due to the lack of coal seams and destruction of spores by oxidation.

High sand to shale ratios occur at two levels in the Carboniferous and these form the best reservoirs.

- Barren Red Beds (Westphalian D/Stephanian)
- Middle Coal Measures (Lower Westphalian B)

These comprise high energy, laterally extensive braided river deposits. Sands in intermediate shale rich horizons were generally laid down in low energy meandering rivers and tend to be local, laterally discontinuous and in poor communication. Some of the ticker shales are thought to be intra-formational seals.

A period of uplift and erosion occurred at the end of the Carboniferous. In general reservoir quality decreases away from the unconformity thus formed. The stratigraphic level of good reservoir sands at any one locality varies depending on the structural level of the unconformity.

### 3.1.2 Lower Permian Reservoirs

Sedimentation recommenced in the Lower Permian, predominantly in sub-aerial conditions in an arid environment. Red colouration of arenaceous parts of the succession is the result of post depositional diagenesis causing ferrous iron to be oxidised to the red ferric state. Later hydrocarbons cause reduction, thus the gas bearing part of the reservoir is often greenish grey.

Four depositional environments can be recognised.

1. **Desert Lake (north)**
   Shales and occasional halites and these form the seal in the Silverpit area where they have been named the Silverpit Formation.
   Elsewhere coarser clastic deposits dominate. These constitute the Leman Sandstone Formation although often referred to as Rotliegendes.
2. **Marginal Lacustrine Environment**
   Lacustrine (sabkha) deposits of poorly sorted sandstones, siltstones and claystones representing the reworking of the lake sediments in an ephemeral desert lake. Poorest reservoir quality overall but very variable, especially in the sandstones.
3. **Aeolian Environment (south east)**
   Aeolian dune and interdune sandsheet consisting of well sorted sands. This facies possesses the best reservoir quality of the four, reflecting the high degree of sorting and lack of sediment types other than sand.
4. **Fluvial Deposits (south to south west)**

Fluvial (wadi) sheet flood deposits comprising homogeneous sandstones and laminated sandstones and siltstones. The reservoir quality is poorer than aeolian deposits due to poorer sorting and higher proportions of detrital and diagenetic clays.

Differences in the character of the reservoir thus developed depending on the relative position of an area with respect to the main dune field etc. Therefore, Leman which is more to the west of Indefatigable shows a greater portion of wadi facies, the Sole Pit area has more sabkha than either, and in the Silverpit area, desert lake shales form the cap rock.

The reservoir in the Sole Pit basin has been divided vertically into three zones depending on the relative proportion of the three sandy lithofacies:

1. **C Sands**
   The lowermost division of the reservoir lying unconformably on the Carboniferous consists of wadi deposits intercalated with minor dune sand bodies. The sandstones are slightly argillaceous and conglomeratic with frequent calcite cements. Alluvial fan and flood plain deposits derived their sediments from the southern Variscan Highlands through deep canyons and gorges.
   Transport took place during sporadic flood events. Ephemeral streams dried out and evaporation of groundwater resulted in carbonate sedimentation. In the succeeding dry period, wind transport occurred and dunes migrated into the area. Repetition of this pattern created the alternation of water lain and aeolian sediments. Reservoir characteristics are generally poor except in the dune sands but the sequence is generally below the gas water contact.
2. **B Sands**
   Aeolian deposits. Clean dune sands with minor anhydrite or dolomitic cement. Sand was derived from unconsolidated alluvial fan/wadi deposits fringing the Southern Highlands by prevailing easterly winds. Some reworking by floods occurred resulting in interbeds of argillaceous and conglomeratic deposits. The sandstones have steeply sipping foresets which show up well in dipmeter logs. At the time of deposition, porosities would have been approximately 42%. With increasing burial, compaction, cementation and pressure solution reduced porosity such that today the typical Leman porosities range from 10% to 18%. In the Sole Pit area isolated wadi deposits tend to be commoner.
3. **A Sands**
   Water lain and dune sands. In the Leman area the bulk of the A Sands are dune sands similar to those of the B zone but with a greater degree of cementation. However, of the top 20 to 100ft tend to be structureless with only a few slump structures or irregular laminations visible. Their homogeneity is believed to be due to the transgressing Zechstein Sea which reworked most of the Rotliegendes. The top zone is termed the Weissliegendes due to its grey colour and it generally displays poor reservoir qualities.

In the Sole Pit area the influence of the desert lake is seen. The A Sands are defined by the presence of interbedded sabkha sands within the dunes. Again the Weissliegendes is present at the top. There is some variation between the fields in the area. In the Clipper aeolian deposits dominate, with rare, think sabkha and local, usually isolated wadi units. Barque being even closer to the desert lake is dominated by sabkha deposits.

### 3.1.3 Upper Permian Reservoirs

Carbonate reservoirs are relatively rare but form a feature of interest in the area. High overpressure can be encountered from rafted carbonates (dolomites) in the salt sequences.

The Zechstein was deposited in an evaporitic marine basin, after subsidence of the low lying Lower Permian floodplains had caused the area to be submerged.

The Zechstein comprises five evaporitic cycles, but only four are well developed in the southern North Sea. Each cycle marks the replenishing and progressive drying out of the Zechstein Sea. Within each cycle the influence of increasing salinity through evaporation can be seen following an initial marine incursion occurring in response to a global change in sea level. The following represents an ideal sequence:

- Marine Shale

- Limestone
- Dolomite
- Anhydrite
- Halite
- Potassium Salts

Not all members need to be present in a cycle and smaller cycles are evident within the major ones. Potassium salts have not been accorded Members status. In general carbonates thin towards the centre of the basins whereas halite sequences thicken. Local variations in halite thickness occur due to halokinitic movements. The basal deposit of the Zechstein sequence, the Kupferschiefer (or Copper Shale), is a thin (approximately 5ft) black bituminous claystone. It is a regional marker horizon.

The sequence in the Southern North Sea is:

Zechstein, Z5
    Grenzanhydrit (rare)
Zechstein, Z4
    Aller Halite
    Pegmatitanhydrit
    Roter Salzton
Zechstein, Z3
    Leine Halite
    Hauptanhydrit
    Plattendolomit
    Grauer Salzton
Zechstein, Z2
    Deckanhydrit
    Stassfurt Halite
    Basalanhydrit
    Hauptdolomit
Zechstein, Z1
    Werraanhydrit (with occasionally the Werra Halite)
    Zechsteinkalk
    Kupferschiefer

### 3.1.4 Triassic Reservoirs

The Triassic represents a return to clastic sedimentation. It is divided into the Bacton, Haisborough and Rhaetic Groups. The Bacton Group consists of continental deposits with fluvial and playa lake deposits forming in a hot arid climate. The upper two groups are of marine origin.

The basal member of the Bacton Group, the Brockelschiefer, is typically a siltstone and represents the extension of marginal clastic sediments into the Zechstein basin as the sea retreated. The overlying clay rich Bunter and Rogenstein members probably accumulated in a shallow inland sea or playa lake.

The upper half of the Bacton Group is the Bunter Sandstone formation, this sandstone is the major reservoir found in the Triassic in the area. The Bunter Sandstone consists of fluvial sheet sands which migrated into the basins from its southern edge. There is some evidence of cyclicity with silt rich horizons at various levels, in general the upper Bunter Sandstone is a potential reservoir (Esmond, Forbes and Gordon fields), where it is charged from the Rotliegendes via faults which cut through the succession where halokinesis has thinned or removed the Zechstein.

The overlying Haisborough Group consists of a number of clay and evaporite interbeds which represent a further period of shallow marine deposition. It is possible that the lateral impersistence and range of thicknesses observed for the Keuper Halite represent an interval of sedimentation in scattered saline lakes rather than in the more continuous bodies of water postulated for the Dowsing Dolomitic formation halites (Rot and Muschelkalk Halites).

The Rhaetic shales and sandstones indicate a return to more normal marine conditions. The Rhaetic Sandstone member is well developed and is a distinctive marker for correlation purposes. It is overlain by a grey shale marking the transition to Liassic sediments.

#### 3.1.5 Mesozoic to Recent

In most southern North Sea areas some or all of the Mesozoic is absent. In some blocks the only Jurassic sediments seen are shallow marine Liassic clays. These may be missing where erosion has led to Cretaceous or Tertiary sediments being deposited on a Triassic surface. No reservoirs are found in these Mesozoic deposits.

The Cretaceous again represents a period of marine deposition with the clastics of the Speeton Clay passing through the marls of the Red Chalk formation into the chalk. The chalk is a fine white limestone which, especially towards the bottom, contains hard siliceous concretions (chert). Soft marine Tertiary and Recent sediments complete the succession in many places.

### 3.2 Central North Sea

The features of most interest to the operational geology in the central North Sea are the very high overpressures in the Central Graben. The overpressures are in the main due to the salt movement in the area.

The principal source rock is the Kimmeridge Clay formation which is well developed in the Central Graben area. The reservoirs on the fringes of the graben were mainly charged by the updip migration of hydrocarbons from the source rock in the graben.

The Kimmeridge Clay is developed in a similar facies as in the northern North Sea, the top section of the formation can be expected to be a clean ‘hot’ shale, the thickness can be very variable.

Reservoirs exist in both the pre-Cretaceous section and in the Cretaceous/Tertiary section.

The pre-Cretaceous reservoirs are the upper Jurassic Piper and Fulmar formations, the middle Jurassic Hugin and Pentland formations and the Triassic Skagerrak formation. The lower Permian Rotliegendes group forms the reservoir in the Auk area.

The Cretaceous–Recent reservoirs include the Danian age Chalk group reservoirs in the Norwegian Ekofisk area, the Paleocene-Oligocene Andrew, Lyell, Ninian and Frigg formations.

### 3.3 Northern North Sea

The principal source rock in the northern North Sea is the organic rich dark Kimmeridge Clay which was deposited in a restricted basin environment. The Kimmeridge Clay is mature for both oil and gas and acts as a top seal for many of the reservoirs as well as being the source rock for the hydrocarbons.

The thickness of the formation can vary markedly. Very thick sequences are found in the grabens, where over 500ft of Kimmeridge can be present, erosion can have removed all or left only a few feet on high blocks. The difference is thought to have been caused by syndepositional fault movement coupled with erosion on the high blocks.

The top section of the Kimmeridge Clay is often developed as a clean ‘hot’ shale without the thin siltstone and sandstone lenses and stringers found in the bottom part of the formation. The gamma ray signature of the Kimmeridge is characteristic. It is very high in the ‘hot’ shales and high compared to the underlying silts of the Heather formation for the lower ‘non-hot’ shales.

The intra Kimmeridge sands of the Magnus, Brae and Kimmeridge sandstone members form important reservoirs in the area. These sands have been deposited as subsea mass flow deposits.

In the Middle Jurassic Hugin and Pentland formations the intra formation shales can be a source rock for the formation sands. The source rocks are mature for gas/condensate. Typical are the coal contents of the source rocks. No source rock of significance is present in Triassic or older deposits in the northern North Sea (UK sector). Minor source rocks are the Scottish Oil Shale and the Devonian lacustrine shales.

Tertiary shales/organic claystones can act as source rock for the Paleocene/Eocene sands of the Andrew, Lyell, Heimdall and Ninian formations. These source rocks are mostly gas prone (lignitic).

# 4.0 Formation Identification

These guidelines are intended to aid identification of formation tops and to provide general information on the stratigraphy of the area. The descriptions are very general, describing briefly the main points of some of the more diagnostic lithologies that comprise a stratigraphic unit. Faulting and/or unconformities may remove part of the sequence of any well.

## 4.1 Southern North Sea

### 4.1.1 Pleistocene Sediments

Dark grey glutinous clay containing pebbles and/or bands of chert, igneous rock, loose sand grains, coal, limestone, shell fragments etc.

### 4.1.2 North Sea Group

Predominantly soft grey clays with occasional sand horizons, shell fragments, glauconite, the clays can be micromicaceous. Firmer mottled green grey deposits found near the base of the group in the Silverpit area are volcanic tuffs (Balder formation).

### 4.1.3 Chalk Group

#### 4.1.3.1 Chalk

White, pure, fine grained limestone (IIA) formed of microfossils. Occasional shell fragments. Increasing amounts of hard grey cryptocrystalline silica material known as chert, occur at the base of the formation.

#### 4.1.3.2 Plenus Marl

Rarely described in cuttings, the Plenus Marl is a dark grey/black carbonaceous claystone about 5ft thick. It can be seen in petrophysical logs as a high gamma ray spike about 50ft above the Cromer Koll Group.

#### 4.1.3.3 Hidra

Predominantly white to light grey, hard, dense limestone and white chalk. Basal section is often tinged pink and can contain grey/black shale partings. Minor chert is found, the transition to the Cromer Knoll Group is sharp.

### 4.1.4 Cromer Knoll Group

#### 4.1.4.1 Red Chalk

Pink chalk to red-brown marls and calcareous claystones which may be grey/white mottled. The top is not always easy to determine but is seen on petrophysical logs as a sharp increase in gamma ray and a distinct break on the sonic.

#### 4.1.4.2 Speeton Clay

Medium to dark grey claystones and shales. Slightly to very calcareous and occasionally glauconitic. Some silty sandstone bands might be found near the base. The lower boundary is a pronounced log/lithological break with the Jurassic/Triassic sequences.

#### 4.1.4.3 Spilsby Sandstone

Very fine to medium grained sandstone, colourless to grey white unconsolidated grains with some cemented bands. The formation is found along the Dowsing fault zone in the south-west of the area.

#### 4.1.5 Lias Group

Predominantly a grey clay/claystone. Sand grains, siltstone, chert limestone, shell fragments etc. may all be present at various levels. A brown clay has been described from near the base of the group. Hydraulic limestone which occurs in bands just above the base of the group is rarely seen in cuttings.

#### 4.1.6 Rhaetic Group

##### 4.1.6.1 Winterton

Typically red or grey-green non-calcareous claystones.

##### 4.1.6.2 Rhaetic Sandstone

Fine to medium grained, clean sandstone often associated with dolomite or dolomitic limestone stringers.

#### 4.1.7 Haisborough Group

##### 4.1.7.1 Triton Anhydritic

Wellsite descriptions and programmes have often called all of this formation Upper Keuper Claystone. It may however be broken up into the following members:

- Upper Keuper Member
- Dolomite and Keuper Red Claystone
- Keuper Anhydrite Member
- Middle Keuper Member

The various members are difficult to distinguish from cuttings alone until the whole sequence has been drilled when the old Keuper Dolomite and Anhydrite members can be distinguished by the pattern of anhydrite and dolomite distribution. The dominant lithology in all cases is a red-brown claystone with subordinate amounts of grey-green claystone. Traces of anhydrite and dolomite may occur throughout but tend to be concentrated in the old Keuper Anhydrite and Keuper Dolomite members.

##### 4.1.7.2 Dudgeon Saliferous

**Keuper Halite**
May dissolve in drilling fluids and only be observed as an increase in salinity of the water phase.

**Lower Keuper Member (Lower Keuper Claystone)**
Dominantly a red-brown claystone with lesser amounts of grey-green claystone and traces of anhydrite and dolomite.

##### 4.1.7.3 Dowsing Dolomitic

**Upper Dowsing Member (Upper Muschelkalk Claystone)**
Difficult to differentiate from the Lower Keuper Claystone from cuttings, although it tends to contain slightly more dolomite. Dolomite tends to be more abundant than pyrite.

**Muschelkalk Halite**
Rock salt with thin red-brown clay interbeds and anhydritic dolomites. The halite may dissolve in drilling fluids and only be observed as an increase in the salinity of the water phase.

**Lower Dowsing Member**
Comprises the former Lower Muschelkalk Claystone and Rot Claystone which were difficult to differentiate from cuttings and drilling parameters alone. Dominant red-brown claystone with traces of grey-green claystone and siltstone. Dolomite and anhydrite stringers.

**Rot Halite**
Rock salt with thin red-brown clay interbeds. The halite may dissolve in drilling fluids and only be observed as an increase in the salinity of the water phase.

**Rot Claystone (Lower Rot Claystone)**
Thin red-brown silty clay sequence. Not always seen or differentiated from the Rot Halite/Bunter Sandstone.

### 4.1.8 Bacton Group

#### 4.1.8.1 Bunter Sandstone

Dominantly red-brown, very fine to medium grained sandstone. Often interbeds of siltstone and anhydritic claystone which tend to be commoner near the top. The upper silts can be very hard and ROP tends to increase with increasing depth. Anhydritic sandstone or anhydrite is common. Occasional trace of claystone.

#### 4.1.8.2 Bunter Shale

**Rogenstein**
Dominant red-brown claystone, often silty or associated with minor amounts of grey-green siltstone and anhydrite. Limestone oolith beds are present but rarely seen in the cuttings (seen as low gamma ray spikes). Reduced ROP compared to pure Bunter Sandstones.

**Bunter Claystone**
Difficult to pick top from cuttings alone. Red-brown claystones predominate and in places may be silty. Traces of dolomite and anhydrite present. Overall, less silty than the Rogenstein.

**Brockelschiefer**
Red-brown clays and siltstones with occasional fine grained sandstones. Claystones often grade to silt. It is generally coarser that the Bunter Claystone but it is not often clear in cuttings until the whole sequence has been drilled. ROP may also be reduced in this member. Seen on petrophysical logs as a reduced gamma ray level.

### 4.1.9 Zechstein Group

Halokinesis can lead to considerable thickening or thinning of the salt, especially the Stassfurt Halite. In some instances a halite may be completely missing. Associated with halokinesis is the break-up and rafting of the Hauptdolomit and Plattendolomit. These members may be completely absent or floating at any level or angle in the salts and may sometimes be thrust over each other such that parts of the succession are repeated.

#### 4.1.9.1 Zechstein Z5 Cycle

**Grenzanhydrit**
Rarely seen.

#### 4.1.9.2 Zechstein Z4 Cycle

**Aller Halite**
Clear to pink halite. Orange/deep pink/red potassium and magnesium salts occur, generally in the upper half of the member. Anhydrite also occurs (and hence the possibility of polyhalite as an anhydrite alteration product). The halite may also dissolve in water based drilling fluids. If so, top Zechstein may be picked from a positive drilling break, decrease in torque, increase in salinity of the water phase of the drilling fluid and the possible occurrence of orange-brown clay.

**Pegmatitanhydrit**
Light grey/white anhydrite and reduced ROP. Not always seen in cuttings.

**Roter Salzton (Red Salt Clay)**
Thin band of red or red-brown claystone or clay-rich halite. Not always seen in cuttings.

#### 4.1.9.3 Zechstein Z3 Cycle

**Leine Halite**
Similar to Aller Halite and difficult to define it top Pegmatitanhydrit and Roter Salzton are absent. A dark green clay is often present near the top. Potassium and magnesium salts are again concentrated in the upper half. A 20-30ft band of anhydrite is commonly found near the base.

**Hauptanhydrit**
Negative drilling break. Off white, cream, light grey anhydrite.

**Plattendolomit**
Possible further negative drilling break. Upper portion dark grey/dark brown dolomite or dolomitic limestone which may grade down into a marly dolomite with traces of clay or silt. Very rare ooliths are found near the top. Increase in background gas is generally seen. The Hauptanhydrit cuttings may persist through the Plattendolomit.

**Grauer Salzton (Grey Salt Clay)**
Thin grey claystone/siltstone (often carbonaceous). May not be seen in cuttings.

#### 4.1.9.4 Zechstein Z2 Cycle

**Deckanhydrit**
Thin anhydrite band. May not be seen in the cuttings or is difficult to tell apart from the Hauptanhydrit cavings.

**Stassfurt Halite**
Dominant rock salt with potassium and magnesium salts, especially in the upper portion. Anhydrite also commonly occurs in the basal 200ft of the member where it may form the dominant cuttings.

**Basalanhydrit**
A thin bed of anhydrite which may be seen as an increase in anhydrite cuttings. However, it is not always easy to define from cuttings especially if the base Stassfurt Halite is anhydrite rich. A negative drilling break should be seen.

**Hauptdolomit**
Its occurrence is generally marked by a negative drilling break and the first re-appearance of carbonate cuttings. Grey/dark grey, argillaceous dolomite, dolomitic limestone or limestone. Some anhydrite cuttings may persist but should soon die out. Core shows the formation to comprise interbedded dolomitic mudstone, limestone and dolomitic limestone. An increase in gas levels is also commonly seen. Can be a common drilling fluid loss zone if fractures are encountered.

#### 4.1.9.5 Zechstein Z1 Cycle

**Werraanhydrit**
Possible slight positive drilling break. The top is marked by the re-appearance of anhydrite in the cuttings (or increase in anhydrite if Basalanhydrit persisted through the Hauptdolomit). Cores of this member show it to comprise calc-dolomite, dolomitic limestone interbedded with anhydrite stringers. The proportion of anhydrite tends to increase downward although the basal 10ft may be more dolomitic. The base of the formation in cores is marked by the final occurrence of anhydrite. Considerable thickness differences in this member are seen across the southern North Sea.

**Werra Halite**
Found in the Leman field in the middle of the Werraanhydrit member. It is formed of interbedded halite and anhydrite.

**Zechsteinkalk**
A possible slight drilling break and increase in gas levels. Its top is generally marked by a marked increase in dolomitic/dolomitic limestone cuttings. Core shows the lower part of the Zechsteinkalk to be dolomites interbedded with anhydrite stringers and nodules.

**Kupferschiefer (Copper Shale)**
Possible negative drilling break. This band of black carbonaceous, possibly micaceous shale. May not be seen in the cuttings however it displays a characteristically strong gamma ray peak.

### 4.1.10 Rotliegendes

#### 4.1.10.1 Leman Sandstones

Clear white or light grey fine to medium grained sand and sandstone which generally coarsens and reddens with depth. Occasional red-brown siltstone and claystone bands occur. Positive drilling break below the Kupferschiefer. It can be difficult to spot the top if drilling with a PDC bit which can pulverise the sand to rock flour. The torque should be monitored and a break/change in trend should be checked for penetration of the Leman Sandstone. Some sand grains may persist (especially in mud cleaner samples), and the size and amount of any residual anhydrite cuttings will both decrease. There should be an increase in gas levels.

#### 4.1.10.2 Silverpit

The lateral equivalent of the Leman Sandstone which is found in the Silverpit area. It comprises red-brown claystones and siltstone interbedded with halites in the lower section. At the top of the formation a thin Upper Leman Sandstone is often seen.

### 4.1.11 Carboniferous

The Carboniferous tends to be hard with reduced ROP throughout. Any sands may be gas bearing. The Carboniferous lies unconformably below the Rotliegendes and may be entered at any level down to the Westphalian A.

#### 4.1.11.1 Barren Red Beds

Interbedded red-brown sandstones, siltstones and shales of the Stephanian. Occasional gravel and pebble beds. The barren Red Beds may be subdivided into three zones:

- Zone 3 - Sand Prone
- Zone 2 - Shale Rich
- Zone 1 - Sand Rich

#### 4.1.11.2 Westphalian

Typically white to grey in colour (with the finer sediments being darker) as opposed to the Barren Red Beds. Similar lithologies with the addition of coals and fragments. A transition zone exists above the top coal and the top is difficult to define from cuttings.

#### 4.1.11.3 Namurian

Interbedded Sandstones, Siltstones and Shale cyclothems. Medium to dark grey, dark blue-grey, hard, blocky, silty, carbonaceous and micromicaceous Claystones. Very pale grey to pale yellow-brown, very fine to medium , rarely coarse grained Sandstones. Non or very rare Coal seams.

## SOUTHERN NORTH SEA STRATIGRAPHY

| ERA / PERIOD | SUPER GROUP | GROUP | FORMATION | MEMBER | LITHOLOGY | DESCRIPTION | AGE Ma |
|---|---|---|---|---|---|---|---|
| PLEISTOCENE | | | UNDIFFERENTIATED | | | Dark grey glutinous clay containing pebbles and/or bands of chert, igneous rock, loose sand grains, coal, limestone, shell fragments etc. | 0.0 |
| TERTIARY | | NORTH SEA | UNDIFFERENTIATED | | | Soft grey clay with occasional sand horizons, shell fragments, glauconite, the clays can be micromicaceous. | 1.6 |
| CRETACEOUS | | CHALK | UNDIFFERENTIATED | | | White to pale grey Chalk, becoming pink to red near the base. Often with abundant chert. | 65.0 |
| | | | PLENUS MARL | | | Dark grey/black carbonaceous Claystone. | |
| | | | HIDRA | | | White to light grey Chalk, becoming pink towards base. Minor Chert. | |
| | | CROMER KNOLL | RED CHALK | | | Pink Chalk to red-brown Marls and calcareous Claystones. | |
| | | | SPEETON CLAY | | | Medium to dark grey Claystones and Shales | |
| | | | SPILSBY SANDSTONE | | | Very fine to medium grained, unconsolidated Sandstone. | |
| JURASSIC | | HUMBER | KIMMERIDGE CLAY | | | Grey to dark grey Claystone. | 152.1 |
| | | | CORALLIAN LIMESTONE | | | Pale grey and oolitic Limestone. | |
| | | | OXFORD CLAY | | | Grey Claystone with ironstone nodules. | |
| | | WEST SOLE | UNDIFFERENTIATED | | | Grey Claystone with beds of Siltstone and thin Sandstone. | |
| | | LIAS | UNDIFFERENTIATED | | | Variably light grey, grey, dark grey and greyish green, micromicaceous and pyritic Claystones. | 209.5 |
| TRIASSIC | | RHAETIC | WINTERTON | | | Typically red or grey-green non-calcareous Claystones. | |
| | | | | RHAETIC SANSTONE | | Fine to medium grained Sandstone often with Dolomite or Dolomitic Limestone stringers. | |
| | | | | | | Typically red or grey-green non-calcareous Claystones. | |
| | | HAISBOROUGH | TRITON ANHYDRITIC | UPPER KEUPER | | Red-brown Claystone with subordinate amounts of grey-green Claystone. Traces of Anhydrite and Dolomite may occur throughout. | |
| | | | | KEUPER ANHYDRITIC | | | |
| | | | | MIDDLE KEUPER | | | |
| | | | DUDGEON SALIFEROUS | KEUPER HALITE | | Halite, colourless or pale yellow orange. | |
| | | | | LOWER KEUPER | | Red-brown Claystones with nodules and thin beds of anhydrite. | |
| | | | DOWSING DOLOMITIC | UPPER DOWSING | | Red-brown Claystones with nodules and thin anhydrites. Slightly more Dolomitic than above. | |
| | | | | MUSCHELKALK HALITE | | Colourless or pale yellow orange Halite. | |
| | | | | LOWER DOWSING | | Red-brown Claystone with grey-green Claystone and Siltstone. Dolomite and Anhydrite beds. | |
| | | | | ROT HALITE | | Colourless or pale yellow orange Halite. | |
| | | | | ROT CLAYSTONE | | Thin red-brown silty Claystones. | |
| | | BACTON | BUNTER SANDSTONE | | | Red brown, fine to medium grained, often friable Sandstone, interbedded with red brown claystones. | |
| | | | BUNTER SHALE | ROGENSTEIN | | Red-brown claystone, often silty or associated with minor amounts of grey-green siltstone and anhydrite. | |
| | | | | BUNTER CLAYSTONE | | Red-brown claystones predominate and in places may be silty. Traces of dolomite and anhydrite present. Overall, less silty than the Rogenstein. | |
| | | | | BROCKELSCHIEFER | | Red-brown clays and siltstones with occasional fine grained sandstones. Claystones often grade to silt. | |
| PERMIAN | ZECHSTEIN | Z5 | GRENZANHYDRIT | | | White to light grey, hard Anhydrite. | 250.0 |
| | | Z4 | ALLER HALITE | | | Halite and various other salts such as carnalite, sylvite and polyhalite. Variably colourless, yellow, pink, red and orange. | |
| | | | | ALLER POTASH | | Potassium and magnesium salts. | |
| | | | PEGMATITANHYDRIT | | | White to light grey, hard Anhydrite. | |
| | | | ROTER SALZTON | | | Red or red-brown Claystones. | |
| | | Z3 | LEINE HALITE | | | Halite with various other potassium and magnesium salts such as Carnalite, Sylvite and Polyhalite. Variably colourless, yellow, pink, red and orange. | |
| | | | HAUPTANHYDRIT | | | Off white to cream, light grey Anhydrite. | |
| | | | PLATTENDOLOMIT | | | Light brownish grey to dark grey, dark grey-brown Dolomite and Dolomitic Limestone. | |
| | | | GRAUER SALZTON | | | Thin grey Claystone / Siltstone. | |
| | | Z2 | DECKANHYDRIT | | | Thin white to off white, cream Anhydrite. | |
| | | | STASSFURT HALITE | | | Colourless to pale pink and orange Halite. | |
| | | | | STASSFURT POTASH | | Potassium and magnesium salts, especially polyhalite. | |
| | | | BASALANHYDRIT | | | White to off white, pale cream to pale grey Anhydrite. | |
| | | | HAUPTDOLOMIT | | | Grey/dark grey, tan, argillaceous Dolomite, Dolomitic Limestone or Limestone | |
| | | Z1 | WERRAANHYDRIT | | | White to cream, pale grey, hard Anhydrite with occasionally Dolomite interbeds and lenses. | |
| | | | ZECHSTEINKALK | | | Dark grey, brown black Dolomite with thin Anhydrite stringers and nodules. | |
| | | | KUPFERSCHIEFER | | | Black, carbonaceous, micaceous, pyritic Shale. | |
| | | ROTLEIGENDES | UPPER LEMAN SANDSTONE | | | Thin red-brown and greenish-grey, fine to medium and occasionally coarse grained Sandstone. Variably poor to good porosity. | 268.8 |
| | | | SILVERPIT | | | Red-brown Claystones and Siltstones. | |
| | | | | SILVERPIT HALITE | | Halite, colourless or pale yellow orange. | |
| | | | LOWER LEMAN SANDSTONE | | | Thin red-brown and greenish-grey, fine to medium and occasionally coarse grained Sandstone. Variably poor to good porosity. | |
| CARBONIFEROUS | UPPER | STEPHANIAN | BARREN RED BEDS | ZONE 3<br>ZONE 2<br>ZONE 1 | | Interbedded red-brown Sandstones, Siltstones and Shales. Occasional Gravel and Pebble beds. | 295.1 |
| | | WESTPHALIAN | COAL MEASURES | D COAL MEASURES | | Typically white to grey in colour with finer sediments being darker. Thin Coal seams, Sandstones and Siltstones. | 304.0 |
| | | | | C COAL MEASURES | | | |
| | | | | B COAL MEASURES | | | |
| | | | | A COAL MEASURES | | | |
| | | NAMURIAN | MILLSTONE GRIT | NAMURIAN B | | Interbedded Sandstones, Siltstones and Shale cyclothems. Medium to dark grey, dark blue-grey, hard, blocky, silty, carbonaceous and micromicaceous Claystones. Very pale grey to pale yellow-brown, very fine to medium , rarely coarse grained Sandstones. Non or very rare Coal seams. | 313.0 |
| | | | | NAMURIAN A | | | |

## 4.2 Central North Sea

### 4.2.1 Nordland Group *(Miocene to Recent)*

A mixed sequence of soft to firm sands, gravel and clays.

### 4.2.2 Hordaland Group

Shales, light grey to brown, soft and fossiliferous. Thin brown limestone and dolomite stringers.

### 4.2.3 Tay Group

#### 4.2.3.1 Tay Shale

Grey-green occasionally red-brown silty claystones alternating with calcareous siltstones. Streaks of dolomitic limestone and fine grained light brown sandstones can be found.

#### 4.2.3.2 Tay Sand

Very fine to very coarse sometimes lithic sandstones with grey silty claystones.

#### 4.2.4.1 Rogaland Group

The group consists generally of carbonaceous shales at the base (Sele formation) overlain by tuffs, siltstones and shales (Balder formation). Sandstones are present in the form of streaks, if the Central Sand formation is distinguished.

#### 4.2.4.1 Balder *(Early Eocene)*

Laminated varicoloured fissile shales with interbedded grey, green or buff, often pyritic, sandy tuffs. Occasionally stringers of limestone and dolomite are encountered. Green-blue glaucophane, brick red tufa particles and minute, clear, volcanic glass shards are often found in the Balder formation. The gamma ray and sonic log response has a typical bell shape.

#### 4.2.4.2 Sele *(Late Paleocene to Early Eocene)*

Finely laminated carbonaceous, tuffaceous, dark-green to black shales and siltstones. Fine sandstone streaks can be present. The claystones are generally non-calcareous. A characteristic high gamma ray response and low sonic velocity.

#### 4.2.4.3 Rogaland Sand

Light brown sandstones, the sorting and grain size range is large, grey-green silty claystones are interbedded.

### 4.2.5 Montrose Group *(Paleocene)*

The group consists of a mixed sequence of lithologies, the base of the group consists of marls, re-deposited limestones of the Chalk Group, sandstones and shales. The major part of the group consists of a sequence of sands and shales. The sands are the dominant lithology in this sequence.

#### 4.2.5.1 Lista *(Late Paleocene)*

A sequence of grey, silty claystones and shales with minor interbeds of limestone. Sandstone beds can occur locally. A synonym sometimes used is Heather Clay formation. Laterally the formation grades into sandy formations, (Forties and Fergus) the boundary is arbitrarily set at the Lista formation containing less than 50% sandstone.

#### 4.2.5.2 Lower Forties / Forties

Sandstones, firm, friable, very fine grained, poorly to moderately sorted, light brown to light grey micaceous and slightly to non-calcareous. The sandstones can be silica and calcite cemented and tuffaceous material can be present. Grey-green non-calcareous claystones are interbedded with the sandstones, these claystones may be carbonaceous and micromicaceous. The top of the Forties formation can be developed as shale.

#### 4.2.5.3 Fergus

Poorly sorted very fine to very coarse sandstones alternating with grey shales. Hard well cemented sandstone and limestone stringers are found.

#### 4.2.5.4 Andrew

Fine to medium to coarse sandstones, locally coarse to sub angular to sub rounded grains, moderately sorted, white to very light grey. Grey, firm, sub fissile claystones are interbedded with the sandstones. The formation has a characteristic log response, a low gamma ray and a blocky sonic. This log differs considerably from the heterolithic lithologies of the underlying Maureen formation. Laterally the Andrew formation grades into the Lista formation at 50% sandstone content. Pyrite, carbonaceous debris and some glauconite are found in the formation.

#### 4.2.5.5 Maureen

Mixed lithologies with irregular distribution patterns. Dark grey shales, grey-brown siltstones and fine to medium sandstones for a matrix for pebbles and larger clasts of reworked limestone. Laterally the Maureen formation grades into the Maureen Marl (Central Graben).

#### 4.2.5.6 Maureen Marl

Grey marls and calcareous claystones.

### 4.2.6 Chalk Group *(Upper Cretaceous)*

#### 4.2.6.1 Ekofisk *(Danian)*

A sequence of cream to white, occasionally light green, pink and pale red chalks and chalky limestones and hard microcrystalline limestones. Red-brown calcareous claystones can be interbedded with the limestone. Chert may be present in the formation.

#### 4.2.6.2 Tor

White to light grey, tan and pink hard chalky limestones, the limestones can be earthy and less firm in places, on the whole the formation is homogeneous. The top of the formation can be locally earthy.

#### 4.2.6.3 Hod

White to light grey, cryptocrystalline to microcrystalline hard limestones which are locally chalky or argillaceous. Thin silty claystones and dark grey to black micaceous shales can be present. Orange pink limestone layers may be found. The formation is more glauconitic in the lower part. The lateral equivalent of the Hod formation is the Flounder formation which is more marly/clayey in composition.

#### 4.2.6.4 Flounder

A sequence of light to dark grey, pink or pale red very calcareous claystones and argillaceous limestones with thin shale and clean limestone stringers. The formation is distinguished on log by its lower gamma ray and slower sonic values than the over and under lying more calcareous formations.

#### 4.2.6.5 Herring

White to light grey, very hard, dense, crystalline limestones. The limestones are occasionally pinkish grey and sometimes chalky.

#### 4.2.6.6 Plenus Marl

Varicoloured shaly claystones, often very pyritic and glauconitic and sometimes with recrystallised argillaceous limestones at the top of the formation. The formation is usually difficult to spot in cuttings as its thickness is limited. On a log however, it has a characteristic high gamma ray peak and an increase in sonic values.

#### 4.2.6.7 Hidra

White to light grey, hard, dense limestones and dolomites interbedded with calcareous claystones and black shales. The limestones can be pinkish grey and marly.

### 4.2.7 Cromer Knoll Group *(Lower Cretaceous)*

The group consists of mainly fine grained, argillaceous and marly sediments with some limestones. Sandstones are present near the base.

#### 4.2.7.1 Valhall

A monotonous sequence of grey to brown shales, calcareous claystones with thin interbedded sandstones and limestones. This name is only used when no further subdivision of the Cromer Knoll is possible.

#### 4.2.7.2 Upper Valhall

This formation is subdivided into the Rodby and Sola formations. Where these formations can be recognised, the formation consists of a monotonous sequence of brown grey-light grey claystones interbedded with red-brown claystones and dark brown to black shales. The shales are more common in the lower half of the formation, marly and chalky limestones can be present near the top of the formation. The top of the formation is on the whole more calcareous, the bottom is more shaly.

#### 4.2.7.3 Rodby

Grey-brown often silty claystones and pink-grey to red marls and calcareous claystones with marly and chalky limestones found near the top of the formation.

#### 4.2.7.4 Sola

The formation consists of dark grey to black generally non-calcareous shales and grey-brown calcareous claystones and marls. The lower boundary is usually a prominent shale bed. The formation is characterised on log by a high gamma ray/low sonic response.

#### 4.2.7.5 Kopervik

A sequence of sandstones interbedded with shales, marls and limestones. The sandstones are very light to dark grey, the grain sizes vary from very fine to very coarse and are non or very poorly sorted.

#### 4.2.7.6 Lower Valhall

A composite sequence consisting of limestones and marls and the top, a monotonous sequence of shales and calcareous claystones forming the main body of the formation, and argillaceous limestones and grey to red-brown calcareous shales and marls in the bottom part of the formation. In some areas a basal limestone member of the formation is present.

#### 4.2.7.7 Devils Hole

Grey sandstone, slightly calcareous and micaceous. Anhydrite nodules can be found (Auk area). The lower Cretaceous found on high areas can be conglomeratic with clasts of various lithologies embedded in a sandy or gravelly matrix.

### 4.2.8 Humber Group *(Upper Jurassic)*

#### 4.2.8.1 Kimmeridge Clay

Dark grey to black micromicaceous, carbonaceous claystones and shales, very slightly to non-calcareous. The very high gamma ray signature is characteristic. Thin limestone, siltstone and sandstone beds are present.

#### 4.2.8.2 Kimmeridge Sandstone

Very fine to very coarse, pebbly, poorly to well sorted sandstone interbedded with dark grey silty claystone. The member is found embedded in the shales of the Kimmeridge Clay formation.

#### 4.2.8.3 Heather

A monotonous sequence of grey-brown claystones and shales. The claystones can be moderately calcareous and thin sandstones can be present and are more common towards the base. The middle member of the formation can be developed as grey-brown to black non-calcareous, carbonaceous claystones. Gamma ray normally below 100api.

#### 4.2.8.4 Piper

Fine to medium sometimes coarse to very coarse well sorted sandstone. Hot shales might be present. Brown siltstone and very silty shales can be found near the top of usually well defined cycles.

#### 4.2.8.5 Fulmar

Massive fine to medium grained well sorted sandstones becoming finer and moderately sorted with very fine sands and silts towards the base of the formation. A pebbly lag deposit can be present at the base of the formation, the top can be developed as silty very fine grained sandstones.

#### 4.2.8.6 Hugin

A sequence of massive fine to coarse grained argillaceous well sorted sandstones and brown-grey shales and claystones. The claystones can be silty. The sandstone beds can be capped by coal and well cemented sandstone (calcite, siderite, baryte) can be found, usually near the top of sequences. Coal is usually found dispersed in the sandstone instead of being found in in-situ layers.

### 4.2.9 Fladen Group *(Jurassic)*

#### 4.2.9.1 Pentland

An alternation of fine to medium rarely pebbly/conglomeratic poorly sorted sandstones, grey-brown carbonaceous siltstones and claystones with in-situ coal beds. These coal beds with think interbedded sandstones can be more than 50ft thick in places. Tuffaceous horizons can be present. The characteristic feature of the formation is the presence of in-situ coal beds, with very low densities seen on log recordings. Distinctive are the high amplitudes on the sonic and gamma ray.

#### 4.2.9.2 Rattray

A sequence of grey to purplish vesicular lavas, interbedded tuffs and aglomerates (volcanic conglomerates). Red-brown to grey-green siltstones and calcareous claystones are found at the base of the formation. The

Rattray formation laterally passes into the Pentland formation with the boundary being defined at 50% volcanic lithologies.

#### 4.2.9.3 Fladen Sandstone

Very fine to very coarse grained, poorly sorted, pyritic, micaceous sandstones alternating with dark grey carbonaceous, non-calcareous shales and siltstones. Tuff layers and coal seams may be present in the top of the formation. The formation passes laterally into the Pentland formation (lateral equivalent of the Tarbert formation found further to the north).

### 4.2.10 New Red Group *(Triassic)*

The sequence is characterised by the presence of redbeds in most of the formations.

#### 4.2.10.1 Skagerrak

Upward coarsening sequence of claystones, siltstones and sandstones with local conglomeratic layers found in the top of the formation. The sediments are mostly red coloured, at the top of the formation white-grey sandstone and grey to green claystone can be encountered.

#### 4.2.10.2 Smith Bank

Brick red silty claystones, siltstones and occasional interbeds of fine to medium grained sandstones. Anhydrite and dolomite bands can also be found.

### 4.2.11 Zechstein Group *(Late Permian)*

Sediments of this group underlie the Cormorant formation. Evaporite deposits are widespread in the Central North Sea. Salt movement has been one of the most important structural controls on reservoir development.

#### 4.2.11.1 Zechstein Caprock

Massive crystalline anhydrite sometimes with interbeds of dolomite and halite.

#### 4.2.11.2 Zechstein Salt

Halite sequences with dolomites and anhydrites at the base of the formation. The sequences are normally disturbed by the previous movements of the salt.

#### 4.2.11.3 Argyll

Leached and fractured dolomitic limestones and dolomites. No interbedded shales are present and little anhydrite or halite.

#### 4.2.11.4 Kupferschiefer

Thin layer of dark brown to black organic rich, dolomitic shale. The shale is usually laminated and normally high concentrations of metal sulphides (lead, zinc, copper, pyrite) are present in the shale.

### 4.2.12 Rotliegendes Group *(Permian)*

The sediments consist of red coloured sandstones and claystones with thin interbedded halites.

#### 4.2.12.1 Frazerburgh

Hard and dense dolomitic shales, dark grey to red-brown with interbedded dolomite and micaceous sandstone stringers.

#### 4.2.12.2 Auk

Grey to red-brown sandstones, locally dolomitic and anhydritic, often a conglomeratic layer is found at the base of the formation. The sandstones can be divided into subunits based on the texture (roundness, sorting and grain size).

### 4.2.13 Old Red Sandstone Group *(Devonian)*

A sequence of red coloured, commonly micaceous sandstones of varying grain size and sorting, interbedded with red-brown claystones, siltstones and conglomerates.

## 4.3 Northern North Sea

### 4.3.1 North Sea Group *(Late Eocene to Recent)*

A mixed sequence of soft to firm sands, gravels and clays. Boulder beds or isolated glacial dropstones can be encountered in the sediment, these consist of hard to very hard lithologies which are mostly metamorphic in origin. Two main formations are distinguished.

#### 4.3.1.1 Hutton Sand

Sands of variable grain size, very fine to coarse with occasional granules and pebbles, glauconite and abundant fossil debris. The sands are interbedded with dark grey-green to black silty, slightly calcareous claystones. The formation laterally shales out towards block 211/13, the base of the formation is sandy and can be traced over large areas.

#### 4.3.1.2 Hutton Clay

Claystones and siltstones, light brown to dark grey, micaceous, glauconitic and carbonaceous. Thin beds of brown to red-brown limestone and dolomite. Thin sand layers occur near the top, thin tuff layers can be present near the base. The claystones are sometimes varicoloured and contain traces of pyrite. In the Viking Graben the formation passes laterally into the Hutton Sand formation.

#### 4.3.1.3 Frigg *(Early Eocene)*

Monotonous structureless sands laterally passing into interbedded sandstones and mudstones and into silty claystones with thin fine to medium grained sandstone stringers. The main sandstone development is found mainly in blocks 3/18, 19, 20 and 3/24, 25. The base of the sandstone is taken as the lower boundary with the Balder formation. The lower boundary with the underlying Balder formation might be difficult to pick in the areas with a more shaly development.

### 4.3.2 Rogaland Group

The group consists generally of carbonaceous shales at the base (Sele formation) overlain by tuffs, siltstones and shales (Balder formation). Sandstones are present in the form of streaks, in the Central North Sea they are found as thicker units and the Rogaland formation is distinguished. Westward the group grades into the Moray Group.

#### 4.3.2.1 Balder *(Early Eocene)*

Laminated varicoloured fissile shales with interbedded grey, green or buff, often pyritic, sandy tuffs. Occasionally stringers of limestone and dolomite are encountered. Green-blue glaucophane, brick red and blue tufa particles and minute, clear, volcanic glass shards are often found in the Balder formation. The appearance of the Balder is often speckled. A high gamma ray peak may also be found at the top of the Balder formation. The gamma ray and sonic log response has a typical bell shape.

#### 4.3.2.2 Sele *(Late Paleocene to Early Eocene)*

Finely laminated carbonaceous, tuffaceous, dark green to black shales and siltstone. Some fine sandstone streaks can be present. The claystones are generally non calcareous and can be pyritic. The claystone can be slightly tuffaceous and may be silty near the base. A characteristic high gamma ray response and low sonic velocity. The formation can usually be recognised as far north as block 3/15.

### 4.3.3 Moray Group *(Late Paleocene to Early Eocene)*

A sequence of mixed sandstones and claystones with coal seams near the top. The group is more or less the time equivalent of the Rogaland Group and is found laterally to the west of the Rogaland Group. It is overlain by the North Sea Group. The group contains considerably more clastic sand sized sediment than the Rogaland Group. Two formations, the Beauly and the Dornoch, are distinguished.

#### 4.3.3.1 Beauly

An interbedded sequence of sandstones, siltstones, claystones and lignites. Poorly sorted, silty to very coarse granular or pebbly sub angular to well rounded sands often with abundant lignite. The claystones and shales are often highly carbonaceous and well developed black, red-black, brittle lignites are found. The lignites are the distinctive feature of this formation, the first appearance of lignite beds marks the base of the formation. The upper boundary is unconformable and is marked by a change of log trends.

#### 4.3.3.2 Dornoch

A sequence of sandstones and mudstones. Very coarse, poorly sorted, pebbly sands are found with substantial amounts of pyrite and lignite in the upper portion of the formation, the middle part consists of siltstones and shales and the lower part is an interbedded sandstone/shale sequence. Green-grey to brown-grey lignitic, slightly tuffaceous shales are found but not common. The sands in the bottom unit are fine to medium with grey-green fissile claystones and shales.

### 4.3.4 Montrose Group *(Paleocene)*

The group consists of mixed sequences of lithologies, the base of the group consists of marls, re-deposited limestone of the Chalk Group, sandstones and shales. The major part of the group consists of a sequence of sands and shales. The sands are the dominant lithology in this sequence.

In the Northern North Sea the following formations are encountered: Maureen North, Maureen, Andrew, Lista, Lyell and Ninian.

#### 4.3.4.1 Ninian

Medium to very coarse, granular to pebbly, poorly sorted, thick bedded sandstones. Occasional beds of hard coal and thin clay occur. Both upper and lower boundaries are normally sharp with the shaly/clayey Lista formation and Sele/Balder formation.

#### 4.3.4.2 Lyell / Lower Sand

A widespread sand wedge thinning in an easterly direction present in the North Viking Graben, northern part of the South Viking Graben and adjacent high areas.

The boundaries are normally taken to be first and last significant sand layer in the sequence as the sequence is transitional to the Lista at the base and top.

Two facies can be recognised in this formation:

A. Fine to coarse, sub rounded, unsorted to poorly sorted sandstone, brown silty clay and minor lithic layers. Beds of very coarse gravelly sandstone are generally common throughout the formation and in the east are more common towards the top.

B. Fine to medium, sometimes coarse, poorly sorted sandstone often argillaceous and some layers are calcite cemented. The sandstones are interbedded with shales. Facies B is found in the northern part of the Viking South Graben.

#### 4.3.4.3 **Lista** *(Late Paleocene)*

A sequence of grey, silty claystones and shales with minor interbeds of limestone. Sandstone beds can occur locally. (A synonym sometimes used is the Heather Clay formation). Laterally the formation grades into sandy formation (Andrew, Lyell, Heimdal and Ninian), the boundary is arbitrarily set at the Lista formation containing less than 50% sandstone.

#### 4.3.4.4 **Andrew** *(Late Paleocene)*

Fine to medium, coarse sandstones, locally coarse sub angular to sub rounded grains, moderately sorted, white to very light grey. Grey, firm, sub fissile claystones are interbedded with the sandstones. The formation has a characteristic log response marked by a low gamma ray and a blocky sonic. This log response differs considerably from the heterolithic lithologies of the underlying Maureen formation. Laterally the Andrew formation grades into the Lista formation at 50% sandstone content. Pyrite, carbonaceous debris and some glauconite are found in the claystones. Tuff particles may be found (pale blue) in the claystones. The finer sandstones can be ground to rock flour by bit action.

#### 4.3.4.5 **Heimdal** *(Late Paleocene)*

Fine to coarse, poorly sorted, slightly cemented sandstone, with mica, glauconite and detrital lignite. The formation is found in the South Viking Graben.

#### 4.3.4.6 **Maureen** *(Paleocene)*

Mixed lithologies with irregular distribution patterns. Dark grey shales, grey-brown siltstones and fine to medium sandstones form the matrix for pebbles and larger clasts of reworked limestone. The change from the underlying non clastic Chalk Group of the calcareous mudstones of the Shetland Group is clearly visible on logs as in cuttings. Laterally the Maureen formation can grade into more sandy or more marly formations (Maureen North, Maureen Marl, Heimdal).

#### 4.3.4.7 **Maureen North** *(Early to Late Paleocene)*

A sequence of mainly calcareous claystones and minor limestone stringers. The upper boundary is sharp to the soft shales of the overlying Lista formation.

### 4.3.5 **Shetland Group** *(Upper Cretaceous)*

A mixture of lithologies consisting mainly of claystones, calcareous claystones, limestones and dolomites.

The Shetland Group is found in the Viking North Graben and in the northern part of the South Viking Graben. The group lies unconformably on sediments of the Cromer Knoll Group and passes laterally to the south into the sediments of the Chalk Group. The boundary between the Chalk Group and the Shetland Group lies arbitrarily at 20% limestones. The base of the group is present only in the deeper parts of the basin. The subdivision of the group where subdivisions can be recognised is as follows: Shetland A to E and where no subdivision into A to D can be made as Shetland Clay formation.

#### 4.3.5.1 **Shetland E**

The sequence consists of shales, calcareous claystones and limestones. The formation top may be marked by the presence of massive, chalky limestone with thin light grey shale interbeds. Some red colouration may be found in this top formation of the group. The Shetland E formation is synchronous with the Tor formation of the Chalk Group into which it passes laterally to the south. The Shetland E formation is easily recognisable on log by its low gamma ray signature and high sonic log values.

#### 4.3.5.2 Shetland D

A monotonous sequence consisting o flight to dark grey shales and calcareous claystones with some minor dolomite and limestone stringers. The Chalk Group equivalent is the Flounder formation into which the formation passes to the south.

#### 4.3.5.3 Shetland C

A sequence of interbedded to massive limestones with calcareous shales and claystones. The formation becomes more calcareous to the south and shales out towards the north. The Chalk Group equivalent is the Herring formation. The limestones are hard, crystalline, white to grey and can be found in layers up to 100ft thick. Red-brown claystone and orange brown claystone can be interlayered with the limestone; the main claystone component is dark grey, fissile, calcareous and moderately hard.

#### 4.3.5.4 Shetland B

A thin sequence of shales and claystones, dark grey, fissile and calcareous. The Chalk Group equivalent is the Plenus Marl formation.

#### 4.3.5.5 Shetland A

A mixed sequence of limestone, calcareous claystone and shales becoming more shaly upward and more calcareous to the south where it passes into the Hidra formation of the Chalk Group.

### 4.3.6 Chalk Group *(Upper Cretaceous)*

In the Northern North Sea the Chalk Group is present in the South Viking Graben and Outer Moray Firth. The group is characterised by a mixture of limestones, calcareous claystones and chalk. Shales are only present as a subordinate lithology.

#### 4.3.6.1 Ekofisk *(Danian)*

A sequence of cream to white, occasionally light green, pink and pale red chalks and chalky limestones and hard, microcrystalline limestones. Red-brown calcareous claystone can be interbedded with the limestone. Toward the north the formation becomes more argillaceous. In parts of the South Viking Graben and Witch Ground Graben a sandstone unit is present. The sandstone is fine to medium grained, white and calcareous. Locally chert may be present in the formation. The ROP is variable, reflecting the various lithologies, the trend is to slower penetration than the overlying formations.

#### 4.3.6.2 Tor

White to light grey, tan and pink, hard, chalky limestone. The limestones can be earthy and less firm in places, on the whole the formation is homogenous. The top of the formation can locally be cherty. The limestone is normally hard and ROP and sonic reflect this.

#### 4.3.6.3 Hod

White to light grey, crypto to microcrystalline, hard limestones, which are locally chalky or argillaceous. Thin silty claystones, and dark grey to black micaceous shales can be present. Orange and pink limestone layers may be found. The formation is more glauconitic in the lower part. The lateral equivalent of the Hod is the Flounder formation which is more marly/clayey in composition.

#### 4.3.6.4 Flounder

A sequence of light to dark grey, pink or pale red, very calcareous claystones and argillaceous limestones with thin shale and clean limestone stringers. The formation is distinguished on a log by its lower gamma ray and slower sonic values than the over and underlying more calcareous formations.

#### 4.3.6.5 Herring

White to light grey, very hard, dense, crystalline limestones. The limestones are occasionally pinkish-grey and sometimes chalky. In the South Viking Graben the lower part of the formation is slightly more shaly whereas the top consists of clean limestones.

#### 4.3.6.6 Plenus Marl

Varicoloured, shaly claystones, often very pyritic and glauconitic and sometimes with recrystallised argillaceous limestones at the top of the formation. The formation is usually difficult to pick in the cuttings as its thickness is limited, on log however it has a characteristic high gamma ray peak and increase in sonic values.

#### 4.3.6.7 Hidra

White to light grey hard dense limestones and dolomites interbedded with grey calcareous claystones and black shales. The limestones can be pinkish grey and marly.

### 4.3.7 Cromer Knoll Group *(Lower Cretaceous)*

The group consists of mainly fine grained, argillaceous and marly sediments with some limestones. Sandstones are present near the base of the formation. The top of the formation is usually marked by an increase in ROP, a decrease in calcimetry values and an appearance of red-brown sediment. The gamma ray values increase markedly and the sonic interval transit time increases as softer sediments are penetrated.

#### 4.3.7.1 Valhall

A monotonous sequence of grey to brown shales, calcareous claystones with thin interbedded sandstones and limestones. This name is only used when no further subdivision of the Cromer Knoll is possible.

#### 4.3.7.2 Upper Valhall

This formation is normally subdivided into the Rodby and Sola formations where these can be recognised, in the North Viking Graben, however this distinction is difficult to make. The formation consists of a monotonous sequence of brown-grey to light grey claystones with interbedded red-brown claystones, and dark brown to black shales. The shales are more common in the lower half of the formation, marly and chalky limestone can be present near the top of the formation The top of the formation is on the whole more calcareous the bottom more shaly.

#### 4.3.7.3 Rodby

Grey-brown often silty claystones and pink-grey to red marls and calcareous claystones with marly and chalky limestones found near the top of the formation.

#### 4.3.7.4 Sola

The formation consists of dark grey-black, generally non-calcareous shales and grey-brown calcareous claystones and marls. The lower boundary is usually a prominent shale bed. The formation is characterised on log by a high gamma ray and low sonic response.

#### 4.3.7.5 Kopervik

A sequence of sandstones interbedded with shales, marls and limestones. The sandstones are very light to dark grey, the grain sizes vary from very fine to very coarse and are non or very poorly sorted. Sandstones are coarser and thicker in the Moray Firth area and the formation grades into the Moray Firth formation towards the west. The sandstones are thinner and finer towards the north and east.

#### 4.3.7.6 Lower Valhall

A composite sequence consisting of limestones and marls at the top, a monotonous sequence of shales and calcareous claystones forming the main body of the formation with argillaceous limestones and grey to brown to red-brown calcareous shales and marls in the bottom part of the formation and in some areas a basal limestone member of the formation. In the North Viking Graben the bottom part of the formation, the red-brown marly claystone, is also named the Alwyn Marl. This clearly recognisable member is used as a marker before penetrating the over pressured Jurassic or older formations.

#### 4.3.7.7 Basal Limestone Member

The member consists of white to light grey, hard, partly recrystallised limestones/dolomitic limestones often sandy and argillaceous with marly interbeds. The member is present at the very base of the Cromer Knoll Group (in the North Viking Graben also called the Barremian Limestone).

### 4.3.8 Humber Group *(Upper Jurassic)*

#### 4.3.8.1 Kimmeridge Clay

Dark grey to black, micromicaceous, carbonaceous claystones and shales, very slightly to non-calcareous. The very high gamma ray signature is characteristic. Thin limestone, siltstone and sandstone beds are present. The sandstones can thicken laterally into thicker units of sandstones. The most important sandstone members are the Magnus, Kimmeridge and Brae. Organic rich with organic contents varying between 5% and 10%, often the shales are highly radioactive ('hot').

#### 4.3.8.2 Kimmeridge Sandstone Member

Very fine to very coarse, pebbly, poorly to well sorted sandstones interbedded with dark grey silty claystones. The member is found embedded in the shales of the Kimmeridge Clay formation.

#### 4.3.8.3 Brae Member

A mix of very coarse sandstones, conglomerates and fine sands and shales. The conglomerate is diverse in its components ranging from quartzite to anhydrite.

#### 4.3.8.4 Magnus Member

Light brown, poorly sorted, fine to medium, sometimes coarse grained sandstones interbedded with grey-brown carbonaceous silty claystones. Coal can be present.

#### 4.3.8.5 Heather

Medium to dark grey, micromicaceous, silty claystones and shales. The claystones can be moderately calcareous and thin sandstones can be present and are more common towards the base. The middle member of the formation can be developed as grey-brown to black non-calcareous, carbonaceous claystones. Gamma ray values are normally below 100api which is a marked drop from the very high values of the Kimmeridge shales.

#### 4.3.8.6 Piper

Fine to medium, sometimes coarse to very coarse, well sorted sandstones. Hot shales might be present. Brown siltstones and silty shales can be found near the top of usually well defined cycles.

#### 4.3.8.7 Hugin

A sequence of massive, fine to coarse grained argillaceous, well sorted sandstones and brown-grey shales and claystones. The claystones can be silty. The sandstone beds can be capped by coal and well cemented sandstone (calcite, siderite, baryte) can be found, usually near the top of sequences. Coal if present is usually found dispersed in the sandstone.

### 4.3.9 Brent Group *(Middle Jurassic)*

#### 4.3.9.1 Tarbert

Fine to medium, sometimes coarse-grained, well-sorted micaceous sandstones, the formation is absent in many places due to erosion. Thin siltstones, shales and coal can be intercalated in otherwise massive sandstones.

#### 4.3.9.2 Ness

This unit is divided into two reservoir sections separated by a shale unit.

#### 4.3.9.3 Upper Ness

A sequence of fine to medium grained sands, dark grey shales and coals.

#### 4.3.9.4 Mid Ness Shale

Dark grey-brown to black pyritic shales with often thin sand layers interbedded in the shale. The shales are usually massive.

#### 4.3.9.5 Lower Ness

Fine to medium grained argillaceous sands interbedded with pyritic dark-grey silty shales. Coal layers can be found.

#### 4.3.9.6 Etive

Massive, fine to coarse grained, well sorted, non-micaceous sandstones. Characteristics are the low gamma ray and the low mica content of the sandstones.

#### 4.3.9.7 Rannoch

A sequence of fine grained, well sorted micaceous sandstones and micaceous siltstones. The base of the formation is siltier. Laterally the formation can be developed in a shale facies and grey to dark grey silty and occasionally sandy shales are found. The formation is shalier in the northern part of the Viking Graben and East Shetland Basin. Characteristic is the high mica content of the sandstones. Where the formation is shaly a Rannoch Shale may be distinguished.

#### 4.3.9.8 Broom

Medium to coarse grained, feldspathic sandstone, occasionally pebbly with shale clasts, very poorly sorted. The formation is micaceous and argillaceous. The base is normally sharp with the underlying deposits a distinct log break is observed.

### 4.3.10 Fladden Group *(Jurassic)*

#### 4.3.10.1 Pentland

An alternation of fine to medium rarely pebbly/conglomeratic poorly sorted sandstones, grey-brown carbonaceous siltstones and claystones with in-situ coal beds. These coal beds with thin interbedded sandstones can be more than 50ft thick in places. Tuffaceous horizons can be present. The characteristic feature of the formation is the presence of in situ coal bed with very high amplitudes on the sonic and gamma ray.

#### 4.3.10.2 Rattray

A sequence of grey to purplish vesicular lavas and interbedded tuffs and agglomerates (volcanic conglomerates). Red-brown to grey-green siltstones and calcareous claystones are found at the base of the formation. The Rattray formation laterally passes into the Pentland formation with the boundary being defined at 50% volcanic content.

#### 4.3.10.3 Fladden Sandstone

Very fine to very coarse grained, poorly sorted, pyritic, micaceous sandstones alternating with dark grey carbonaceous non-calcareous shales and siltstones. Tuff layers and coal steaks can be present in the top of the formation. The formation passes laterally into the Pentland formation (lateral equivalent of the Tarbert formation found further to the north).

### 4.3.11 Dunlin Group *(Jurassic)*

The group consists of two thinning and fining upwards cycles consisting of sandstones, siltstones and dark shales. The Drake and Burton formations have in general a relatively even gamma ray signature compared to the more serrated gamma ray trace of the Cooke and Amundsen formations.

#### 4.3.11.1 Drake

A monotonous sequence of dark grey micromicaceous shales with some thin sandstone stringers. The base is more calcareous.

#### 4.3.11.2 Cook

Dark grey, micromicaceous siltstones and slightly calcareous shales with interbedded fine to coarse grained calcareous sandstones. Sandy limestones can be found.

#### 4.3.11.3 Burton

Grey non-calcareous slightly silty carbonaceous shales.

#### 4.3.11.4 Amundsen

Grey, silty shales and grey, non-calcareous siltstones. The siltstones dominate and are pyritic and carbonaceous. Streaks of calcareous iron rich sandstone and limestone are present.

#### 4.3.11.5 Dunlin Shale

In the South Viking Graben and Beryl embayment the Dunlin Group is represented by the Dunlin Shale formation, this formation consists of light to dark grey non-calcareous shales with sandstones stringers.

#### 4.3.11.6 Nansen

The base Nansen formation is included in the Dunlin Group and forms its base. The formation consists of massive medium to coarse, poorly to fairly well sorted, light grey sandstone interbedded with thin dark grey shale layers. The sandstones can be pebbly at the base and are calcite cemented in the top of the formation. This Nansen formation is also known as Unit 1 of the Statfjord reservoirs but as it was deposited in a marine environment as a transgressive sheet sand it should be included in the Dunlin Group opposed to the strictly fluvial deposits of the underlying Statfjord formation. The Nansen formation is developed as a marine limestone/calcareous sandstone/shale sequence further to the north, the limestones can be microcrystalline and dense with low porosities. The sandstone can be tightly calcite cemented. Dolomite nodules can be found in the shale.

### 4.3.12 New Red Group *(Triassic)*

The whole sequence is characterised by the presence of redbeds in most of the formations.

### 4.3.12.1 Statfjord

An upward coarsening sequence of fluvial sediments consisting of sandy shales interbedded with siltstone, sandstones and finally pebbly conglomerates. Two members can be distinguished.

### 4.3.12.2 Raude Member

Sandy shale with interbedded sandy siltstones and sandstone. Very light grey-white calcareous sands and carbonate streaks can be present. The shales can be red-grey at the base.

### 4.3.12.3 Eirikson Member

Massive blocky locally conglomeratic light brown, light grey sandstones interbedded with sandy claystones. The sands are well cemented and fairly poorly sorted.

### 4.3.12.4 Beryl

Fine to coarse grained, moderately well sorted sandstones, interbedded with argillaceous siltstones and grey-brown to black claystones. A basal conglomeratic sandstone might be present. The formation is a lateral equivalent of the Statfjord formation.

### 4.3.12.5 Cormorant

A complex of red coloured sediments including claystones, siltstones, sandstones and conglomerates. The top is usually gradually gradational to the overlying Beryl and Statfjord formations which contain some red-grey shales and claystones at the base.

### 4.3.12.6 Skagerrak

An upward coarsening sequence of claystones siltstones and sandstones with local conglomeratic layers found in the top of the formation. The sediments are mostly red coloured, at the top of the formation white grey sandstone and grey to green claystone can be encountered.

### 4.3.12.7 Smith Bank

Brick red, silty claystones, siltstones and occasional interbeds of fine-medium sandstones. Anhydrite and dolomite bands can be found.

### 4.3.13 Zechstein Group *(Late Permian)*

Sediments of this group underlie the Cormorant formation. Evaporites are found in the Northern North Sea, halites can be developed in the South Viking Graben. No clear cycles can be differentiated in the northern basin, the Zechstein deposits mainly consist of anhydrites, dolomites and limestones. The distribution of the Zechstein is relatively unknown compared to the overlying deposits. Its depth and general lack of reservoir quality sediments in the Northern North Sea do not make it a zone of interest.

### 4.3.13.1 Fringe Zechstein

A mixed clastic-carbonate sequence consisting of conglomerates, sandstones of various texture and sorting and grey mottled claystones. Red-brown to grey, hard limestones and dolomites alternate with these clastics. The carbonates are usually microcrystalline, sometimes sandy. The formation is found near the basin edges (Inner Moray Firth).

### 4.3.13.2 Turbot Bank

White crystalline anhydrite interbedded with red-brown silty shales and hard, microcrystalline dolomites. The Turbot Bank formation directly underlies the New Red Group in the Viking Graben.

#### 4.3.13.3 Halibut Bank

Light brown-grey, microcrystalline, often vuggy dolomites, occasionally anhydritic or argillaceous, interbedded with grey-green dolomitic shales. The boundaries are distinct lithologically and on the log. The top lies at the base of the first anhydrite bed of the Turbot Bank formation, the base at the gamma ray break on log and the appearance of dark-brown to black shales with the Kupferschiefer formation.

#### 4.3.13.4 Kupferschiefer

Thin layer of dark brown to black organic rich, dolomitic shale. The shale is usually laminated and normally high concentrations of metal sulphides (lead, zinc, copper, pyrite) are present in the shale.

### 4.3.14 Rotliegendes Group *(Permian)*

The group has not been subdivided in the northern North Sea, the sequence found is usually far from complete and datings are difficult. The sediments consist of red coloured sandstones and claystones with some thin interbedded halites.

### 4.3.15 Carboniferous Limestone Group *(Visean)*

Some scattered deposits have been encountered in the northern North Sea. The limestones are recrystallised, very hard and can in places be very vuggy. Thin black shale partings are found in the limestone.

### 4.3.16 Firth of Forth Group *(Early Carboniferous)*

Carbonaceous vary coloured shales with interbedded coal seams, silty shales and sandstones.

### 4.3.17 Old Red Sandstone Group *(Devonian)*

A sequence of red coloured commonly micaceous sandstone’s of varying grain size and sorting interbedded with red-brown claystones, siltstones and conglomerates.

# NORTH SEA STRATIGRAPHY

## Stratigraphy of the North Sea

| | | | | |
|---|---|---|---|---|
| Quaternary | Holocene *Holozan* | | | |
| Quaternary | Pleistocene *Pleistozan* | | | |
| Tertiary | Pilocene *Pliozan* | | | |
| Tertiary | Miocene *Miozan* | Upper | *Obermiozan* | |
| | | Middle | *Mittelmiozan* | |
| | | Lower | *Untermiozan* | |
| | Oligocene *Oligozan* | Upper | *Oberoligozan* | |
| | | Middle | *Mitteloligozan* | |
| | | Lower | *Unteroligozan* | |
| | Eocene *Eozan* | Upper | *Obereozan* | |
| | | Lower | *Untereozan* | |
| | Palaeocene *Palaozan* | Upper | | |
| | | Lower | *Danian* | |
| Cretaceous | Upper Cretaceous | *Oberkreide* | Sennonian | Maastrichtian |
| | | | | Campanian |
| | | | | Santonian |
| | | | | Coniacian |
| | | | | Turonian |
| | | | | Cenomanian |
| | Lower Cretaceous | *Unterkreide* | Albian | Upper *Oberalbian* |
| | | | | Middle *Mittelalbian* |
| | | | | Lower *Unteralbian* |
| | | | | Aptian |
| | | | | Barremian |
| | | | | Hauterivian |
| | | | | Valanginian |
| | | | Ryazanian | (Wealden) |
| Jurassic | Upper Jurassic | *Malm (Oberer Jura)* | Volgian / Portlandian | Oberer Malm |
| | | | Kimmeridgian | |
| | | | Oxfordian | |
| | Middle Jurassic | Dogger (Mittlerer Jura) | Callovian | *Zeta* |
| | | | Bathonian | *Epsilon* |
| | | | Bajocian | *Delta* |
| | | | Aalenian | *Gamma* |
| | | | | *Beta* |
| | | | | *Alpha* |
| | Lower Jurassic | Lias (Unterer Jura) | Toarcian | *Zeta* |
| | | | Pliensbachian | *Epsilon* |
| | | | Sinemurian | *Delta* |
| | | | Hettangian | *Gamma* |
| | | | | *Beta* |
| | | | | *Alpha* |
| Triassic | Upper Triassic | Keuper | Rhaetian | *Rhat* |
| | | | Norian | *Mittlerer Keuper* |
| | | | Carnian | *Unterer Keuper* |
| | Middle Triassic | Muschelkalk | Ladinian | *Oberer Muschelkalk* |
| | | | | *Mittlerer Muschelkalk* |
| | | | Anisian | *Muschelkalk Salinar* |
| | | | | *Unterer Muschelkalk* |
| | Lower Triassic | Bundsandstein | Scythian | *Rot* |
| | | | | *O. Bundsandstein* |
| | | | | *M. Bundsandstein* |
| | | | | *U. Bundsandstein* |
| Permian | Upper Permian | Zechstein Supergroup | Z5 Group | Grenzanhydrit Fm. |
| | | | Z4 Group *Aller Halite* | Aller Halite Fm. |
| | | | | Pegmatitanhydrit Fm. |
| | | | Z3 Group *Leine Series* | Roter Salzton Fm. |
| | | | | Leine Halite Fm. |
| | | | | Hauptanhydrit Fm. |
| | | | | Plattendolomit Fm. |
| | | | | Grauer Salzton Fm. |
| | | | Z2 Group *Stassfurt Series* | Deckanhydrit Fm. |
| | | | | Stassfurt Halite Fm. |
| | | | | Basalanhydrit Fm. |
| | | | | Hauptdolomit Fm. |
| | | | Z1 Group *Werra Series* | Werraanhydrit Fm. |
| | | | | Zechsteinkalk Fm. |
| | | | | Kupferschiefer Fm. |
| | Lower Permian | | Rotliegendes Group | U. Leman Sandstone Fm. |
| | | | | Silverpit Fm. |
| | | | | L. Leman Sandstone Fm. |
| arboniferou | Upper Carboniferous | | Stephanian | Barren Red Beds |
| | | | Westphalian | Coal Measures |
| | | | Namurian | Millstone Grit |

## UK Sector Southern North Sea

| | | |
|---|---|---|
| | Red Crag *Coralline Crag* | |
| | London Clay Fm. | |
| | Sele Fm. | |
| | Lista Fm. | |
| Chalk Group | Undifferentiated | |
| | Plenus Marl Fm. | |
| | Hidra Fm. | |
| Cromer Knoll Group | Red Chalk Fm. | |
| | Speeton Clay Fm. | |
| | Spilsby Sandstone Fm. | |
| Humber Group | Kimmeridge Clay Fm. | |
| | Oxford Clay Fm. | |
| West Sole Group | Undifferentiated | |
| Lias Group | Undifferentiated | |
| Penarth Group | Winterton Fm. | Rhaetic Sand Mbr. |
| Haisborough Group | Triton Anhydritic Fm. | Keuper Anhydritic Mbr. |
| | Dudgeon Saliferous Fm. | Keuper Halite Mbr. |
| | Dowsing Dolomitic Fm. | Muschelkalk Halite |
| | | Upper Rot Halite Mbr. |
| | | Rot Claystone Mbr. |
| | | Main Rot Halite Mbr. |
| Bacton Group | Bunter Sandstone Fm. | |
| | Bunter Shale Fm. | Rogenstein Mbr. |
| | | Bunter Claystone Mbr. |
| | | Brockelschiefer Mbr. |
| Z5 Group | Grenzanhydrit Fm. | |
| Z4 Group *Aller Halite* | Aller Halite Fm. | |
| | Pegmatitanhydrit Fm. | |
| Z3 Group *Leine Series* | Roter Salzton Fm. | |
| | Leine Halite Fm. | |
| | Hauptanhydrit Fm. | |
| | Plattendolomit Fm. | |
| | Grauer Salzton Fm. | |
| Z2 Group *Stassfurt Series* | Deckanhydrit Fm. | |
| | Stassfurt Halite Fm. | |
| | Basalanhydrit Fm. | |
| | Hauptdolomit Fm. | |
| Z1 Group *Werra Series* | Werraanhydrit Fm. | |
| | Zechsteinkalk Fm. | |
| | Kupferschiefer Fm. | |
| Rotliegendes Group | U. Leman Sandstone Fm. | |
| | Silverpit Fm. | |
| | L. Leman Sandstone Fm. | |
| Stephanian | Barren Red Beds | Zone 3 |
| | | Zone 2 |
| | | Zone 1 |
| Westphalian | Coal Measures | D Coal Measures |
| | | C Coal Measures |
| | | B Coal Measures |
| | | A Coal Measures |
| Namurian | Millstone Grit | Namurian B |
| | | Namurian A |

## Beryl Area Block 9/13

| | | |
|---|---|---|
| Nordland Group | Undifferentiated | |
| Stronsay Group | Horda Fm. | Grid Sandstone Mbr. |
| | | Frigg Sandstone Mbr. |
| Rogaland Group | Balder Fm. | |
| | Sele Fm. | |
| Montrose Group | Lista Fm. | Heimdal Sandstone Mbr Units II & I |
| | Maureen Fm. | |
| Near Cretaceous (Danian?) | | |
| Shetland Group | Jorsalfare Fm. | |
| | Herring Fm. & Plenus Marl | |
| | Hidra Fm. | |
| Cromer Knoll Group | Rodby Fm. | |
| | Valhall Fm. | |
| Humber Group | Base Cretaceous Unconformity (BCU) | |
| | Kimmeridge Clay Fm. | Brae Mbr. |
| | Heather Fm. | Katrine Mbr, Nevis Mbr, Angus Mbr. |
| Beryl Embayment Group | Beryl Fm. | Units V, VI, III, II, I |
| | Linnhe Fm. | Units I & II |
| Missing | | |
| Dunlin Group | Burton Fm. / Amundsen Fm. | Units I & II |
| | Nansen Fm. | |
| Statfjord Group | Eiriksson Fm. | |
| | Raude Fm. | |
| Cormorant Group | Lewis Fm. | Unit IV |
| | | Units III & II |
| | | Unit I |
| | Undifferentiated | |

# 5.0 Drilling Problems

## 5.1 Drilling Problems in the Southern North Sea

### 5.1.1 Stuck Pipe

Claystones of the North Sea Group and Haisborough Group.
Halites of the Haisborough Group, Zechstein Halites and Silverpit Formation.

### 5.1.2 Mud Losses

Mud losses in top hole drilling, up to 200ft below the seabed.
Porous zones may be encountered in the carbonates of the Chalk Group.
Losses into the Bunter Sandstone and Brockelschiefer formations.
Mud losses into fractured Zechstein Carbonates.
Losses into fractured or depleted Rotliegendes.
Losses into depleted Silverpit sandstones.

### 5.1.3 Washouts

Notably in the North Sea Group and in the salts of the Zechstein Group.

### 5.1.4 Kicks / Flows

Magnesium brine flows within the Zechstein salts.
Gas, water or brine flows in Zechstein carbonates.
Gas kicks within the reservoir formation.

### 5.1.5 Hydrogen Sulphide ($H_2S$)

Potential for hydrogen sulphide in the Zechstein carbonates.

### 5.1.6 Nodule Bands

Chert nodules and bands in the Chalk Group, especially Lower Chalk.
Pyrite in the Kupferschiefer.

## 5.2 Drilling Problems in the Central North Sea

### 5.2.1 Stuck Pipe

Clay swelling/caving in the Horda formation, Tay shale and the Lista formation. This problem is severe in the Fulmar area. OBM has been used to reduce the risk of stuck pipe but does not offer complete protection against swelling clays. The problem lies with the very high swelling clay (montmorrilite) content of the claystones.

### 5.2.2 Mud Losses

Weak tuff layers in the Balder formation.
Porous zones may be encountered in the carbonates of the Chalk Group.
Thin Sands in the Kimmeridge formation.
Losses into weaker zones with high mud weights in the Heather formation.
Mud losses into fractured Zechstein carbonates.
Losses into fractured or depleted Rotliegendes.

### 5.2.3 Washouts

Washouts can occur in the poorly consolidated Tertiary sands and in the Zechstein salts.

#### 5.2.4 Hydrogen Sulphide ($H_2S$)

High concentrations of hydrogen sulphide can be present in the Piper formation of blocks 15 and 21.
High concentrations of hydrogen sulphide can be present in the Brae sands in block 16.
High to very high concentrations of hydrogen sulphide can be present in the Hugin formation in block 16 and in low concentrations in other blocks.
Low concentrations can be encountered in the Pentland formation.
Low to very low concentrations can be encountered in the Skagerrak formation and Zechstein carbonates.

#### 5.2.5 Nodule Bands

Chert, mainly in the Chalk Group. Chert may be encountered near or at the top of formations especially where hardgrounds developed. Chert is commonly found in the Tor and Hod formations.

### 5.3 Drilling Problems in the Northern North Sea

#### 5.3.1 Stuck Pipe

Clay swelling and caving problems are encountered in the Hutton Clay and the Balder formation (very severe in places, notably North Cormorant, Dunlin, severe on Eider, Tern, Cormorant and moderate on Brent). The clay swelling/caving is more pronounced in the northern part of the Brent field. The Balder formation is very variable in thickness and is dependent on the swelling clay component content of the claystones. The Lista formation and the Shetland Group show less pronounced swelling behaviour.

#### 5.3.2 Washouts

Washouts can occur in the Tertiary sections, especially where loose sands are present, (Frigg, Tay, Forties, Ninian) and where claystones are tectonically fractured (Balder, Hutton Clay).

#### 5.3.3 Mud Losses

Mud losses can be encountered in the Ninian formation, Chalk Group, Statfjord formation, Heather formation and limestones of the Carboniferous.

#### 5.3.4 Hydrogen Sulphide ($H_2S$)

Moderate to high concentrations can be encountered in the Brae Sands and Hugin formation. Low concentrations can be encountered in the Pentland and Kimmeridge formations.

#### 5.3.5 Nodule Bands

Chert can be encountered in the Chalk Group, especially near or at formation tops. Pyrite nodules and bands can be encountered in the Kimmeridge Clay and in the shales of the Ness formation of the Brent Group. Siderite nodules can be found in the Hugin formation, Cormorant formation and Old Red Sandstones.

# 6.0 A Guide to North Sea Geology

## 6.1 Cormorant Formation

### 6.1.1 Lithology

A sandstone dominated sequence of red beds showing great lateral variation; lithologies include red, silty, locally calcareous claystones, siltstones, pinkish to white argillaceous sandstones, usually fine to medium grained. Conglomerates are present along the graben margins. Red claystones are dominant in the upper part of the formation.

### 6.1.2 Boundaries

The lower boundary corresponds to the Base New Red Unconformity; it is taken at the base of the red bed sequence, at the contact with the underlying massive anhydrites of the Turbot Bank formation. Where the Cormorant formation overlies the Fringe Zechstein formation, the contact is usually not clearly recogniseable on the logs and circumstantial evidence is required to identify the lower boundary. The boundary with the overlying Statfjord and Beryl formations is gradational and conformable. It is taken at the top contact between the monotonous red claystones of the Cormorant formation and the overlying red and grey claystones interbedded with thin blocky sandstones (fluvial channel and crevasse splay/sheet sands). This boundary is usually taken at the base of the first sandstone bed and corresponding log break. The Cormorant formation is often unconformably overlain by younger formations.

### 6.1.3 Distribution

Viking Graben.

### 6.1.4 Environment

Continental, fluvio-lacustrine under semi-arid (to humid?) climatic conditions.

### 6.1.5 Age

Triassic (limited biostratigraphic control). The distal alluvial plain red shales immediately underlying the Statfjord formation have been dated as Norian to Early Rhaetian (*Fisher, 1984*).

### 6.1.6 Oil Field

### 6.1.7 Remarks

The Cormorant formation has been deposited in the rapidly subsiding/rifting Viking Graben; sedimentation has been greatly influenced by local tectonic activity, resulting in great thickness/facies variations from one fault block to another. Oil bearing in Cormorant Block II.

### 6.1.8 Synonyms

Hegre Group

## 6.2 Beryl Formation

### 6.2.1 Lithology

A sequence of fine to coarse grained, moderately to well sorted, locally argillaceous sandstones, interbedded with variegated claystones, argillaceous siltstones and locally with poorly to well sorted conglomeratic sandstones. A laterally continuous black claystone horizon is recognised in many wells of the Beryl Field.

### 6.2.2 Boundaries

The boundary with the underlying Cormorant formation is usually taken at the base of the first, broad, blocky sandstone, as identified on the gamma ray log. A conspicuous, intra-Beryl, black claystone horizon can be used for correlation and for establishing the formations lower boundary in wells where the basal sandstone sequence is not properly developed. Hence, the basal contact with the Cormorant formation is either conformable or marked by an unconformity. In block 9/28, the Beryl formation is marked by a hiatus (Base Dunlin or Base Fladen Unconformity) expressed by an abrupt change in the gamma ray and sonic logs.

### 6.2.3 Distribution

Beryl Embayment area/South Viking Graben.

### 6.2.4 Environment

Continental, fluvial (alluvial plain crossed by fluvial interpretation channel complex).

### 6.2.5 Age

Rhaetian to Hettangian (limited biostratigraphic control in wells 9/13-2, 5, 7; 9/19-3; 16/29-4).

### 6.2.6 Oil Field

Beryl

### 6.2.7 Remarks

The Beryl formation is, in part, the lateral equivalent of the Skagerrak, Gassum and Statfjord formations. The onset of the fluvial Beryl deposits corresponds to the Late Triassic/Earliest Jurassic change from semi-arid to humid, resulting in increased precipitation and in the development of wide spread alluvial sediments.

### 6.2.8 Synonyms

Crawford Member (*Bolliger, 1982*).

### 6.3 Statfjord Formation

Subdivisions:

- Eirikson Member
- Raude Member

#### 6.3.1 Lithology

A coarsening-upward sequence of variegated, often sandy shales, interbedded with thin siltstones, sandstones of increasing bed thickness (multi-storey channel sand bodies) and occasionally pebbly conglomerates. Carbonate streaks (calcrete) have also been reported.

#### 6.3.2 Boundaries

The base of the Statfjord Formation should be taken below the first blocky channel and sand body (circa 3m thick) and/or at the boundary between relatively sandy shales (=highly serrate, moderate negative separation of the FDC/CNL overlay) and 'clean' shales (=relatively smooth logs with wide separation of the FDC/CNL overlay) (*Johnson & Wonink, 1982*).

The upper boundary corresponds locally to an unconformity (Base Dunlin Unconformity) and is taken at the base of the overlying marine sandstones of the Nansen Formation (now included in the Dunlin Group); in many wells, the upper boundary is transitional. Vail & Todd (1981) indicate tilting and truncation of the Statfjord formation prior to deposition of the Nansen formation.

Note that the boundaries as defined here depart from the original definition of the formation by Deegan & Scull (1977).

#### 6.3.3 Distribution

North Viking Graben / eastern margin of the East Shetland Basin.

#### 6.3.4 Environment

Continental, fluvial (distal to proximal alluvial plain); under marginal marine influence in the upper part.

#### 6.3.5 Age

Rhaetian to Hettangian (limited biostratigraphic control).

#### 6.3.6 Oil Field

Statfjord, Alwyn

#### 6.3.7 Remarks

The Statfjord formation is, in part, the lateral equivalent of the Beryl and Skagerrak Formations. The onset of the fluvial Statfjord deposits corresponds to the Late Triassic/earliest Jurassic climatic change from semi-arid to humid, resulting in increased precipitation an in the development of widespread alluvial sediments. The Statfjord river system was flowing from south to north.

The formation definition is amended here in the sense that the overlying transgressive and onlapping marine sandstone (Nansen formation) is now included in the Dunlin Group.

#### 6.3.8 Synonyms

## 6.4 Dunlin Group

Subdivisions:

- Broom Formation
- Dunlin Shale Formation
- Drake Formation
- Cook Formation
- Burton Formation
- Amundsen Formation
- Nansen Formation

### 6.4.1 Lithology

Three thinning upwards mega-cycles (Nansen-Amundsen-Burton cycle, Cook-Drake cycle and Dunlin-Broom cycle) consisting of grey to white sandstones, siltstones and grey to grey-brown, occasionally black shales.

### 6.4.2 Boundaries

The lower boundary is taken at the base of the first massive, marine sandstone of the Nansen Formation. This boundary represents in places an unconformity (Base Dunlin Unconformity), while, in the centre of the basin, the boundary is conformable and in depositional continuity with the underlying Statfjord formation, The upper boundary is marked by either a sharp break of Broom Sandstone and overlying Rannoch formation.

### 6.4.3 Distribution

East Shetland Basin and Viking Graben down to the Beryl Embayment. The formation is thickest in the Viking Graben and thins out towards the western part of the East Shetland Basin and towards the South Viking Graben.

### 6.4.4 Environment

Two successive, depositional cycles, ranging from marginal marine nearshore to offshore, low energy environments.

### 6.4.5 Age

Hettangian?/Sinemurian to Aalenian.

### 6.4.6 Oil Fields

Statfjord, Brent, Gullfaks.

### 6.4.7 Remarks

Thickness variations within the Dunlin Formations provide evidence for a N-S trending fault system within the Graben; it includes tilting of individual fault blocks to the west superimposed on a gradual plunge of the Graben to the North (*Bolliger et al., 1979*).

### 6.4.8 Synonyms

## 6.5 Nansen Formation

### 6.5.1 Lithology

A sequence of massive, medium to coarse-grained, poorly to fairly well sorted, light grey sandstones, occasionally glauconitic, interbedded with thin shale layers; pebble horizons are present at the base. The sandstones become distinctly calcareous cemented in the upper part and occasionally grade into siltstones; presence of marine fossils.

### 6.5.2 Boundaries

The Formation's boundaries are taken at the limits of the massive, marine sandstones. The lower boundary is sharp; it represents in places an unconformity (Base Dunlin Unconformity), while, in the centre of the basin it rests conformably and in depositional continuity on the underlying Statfjord formation. Vail & Todd (1981) indicate that the Nansen Formation rests unconformably on truncated and tilted strata.

### 6.5.3 Distribution

North Viking Graben/Eastern part of the East Shetland Basin. The Formation thins towards the East.

### 6.5.4 Environment

Transgressive, marginal to shallow marine (bar sands/nearshore sheet sands).

### 6.5.5 Age

Early Sinemurian.

### 6.5.6 Oil Fields

Statfjord, Brent, Gulfaks.

### 6.5.7 Remarks

The Nansen sandstones and the stratigraphically underlying non-marine Statfjord formation can be distinguished on the basis of their unconformable, onlap relationship as seen in the East Shetland Basin.

### 6.5.8 Synonyms

### 6.6 Amundsen Formation

#### 6.6.1 Lithology

A siltstone dominated sequence consisting of grey, silty shales and greyish, non-calcareous siltstones, in part carbonaceous and pyritic. Streaks of fine to coarse grained, glauconitic, calcareous sandstones, locally rich in siderite, chamosite and siderite ooliths; occasional presence of limestone stringers

#### 6.6.2 Boundaries

The lower boundary is taken at the base of the sub linear, slightly serrate gamma ray and sonic logs, at the contact with the underlying sandstones of the Statfjord or Nansen formations. A calcareous member is locally present at the base of the formation and is characterised by a bell-shaped response on the gamma ray and sonic logs. The boundary with the underlying Nansen formation is always expressed by a distinct log break. The upper boundary is taken at the base of the monotonous shales of the Burton formation, characterised by smooth, linear, almost constant gamma ray and sonic log readings, and wider separation between the FDC and CNL logs.

#### 6.6.3 Distribution

North Viking Graben and East Shetland Basin.

#### 6.6.4 Environment

Slowly subsiding basin under marginal to shallow marine conditions. The lack or sporadic presence of marine fossil assemblages indicate partial restriction of the offshore depositional environment.

#### 6.6.5 Age

Sinemurian.

#### 6.6.6 Oil Fields

#### 6.6.7 Remarks

Vail & Todd (1981) indicate onlap of the Amundsen Formation onto the Statfjord/Cormorant formation towards the basin margins.

#### 6.6.8 Synonyms

## 6.7 Burton Formation

### 6.7.1 Lithology

A monotonous sequence of grey, non-calcareous occasionally slightly silty and carbonaceous shales.

### 6.7.2 Boundaries

The Burton formation is characterised by smooth linear, parallel gamma ray and sonic log responses with lower sonic log readings and wider FDC/CNL log separations than in the underlying and overlying formations. 'The upper and lower boundaries are taken where this log character changes' (*Deegan & Scull, 1977*).

### 6.7.3 Distribution

North Viking Graben and East Shetland Basin.

### 6.7.4 Environment

Distal marine, offshore system; under low energy conditions. The Burton shales reflect the furthest southward transgression of the Arctic Seas and the concomitant gradual deepening of the basin.

### 6.7.5 Age

Late Sinemurian to Early Pliensbachian.

### 6.7.6 Oil Fields

### 6.7.7 Remarks

Vail & Todd (1981) indicate tilting and truncation at the top of the Burton formation; towards the basin margins, the formation is found to be onlapping onto the Statfjord/Cormorant formations.

### 6.7.8 Synonyms

## 6.8 Cook Formation

### 6.8.1 Lithology

A siltstone dominated sequence consisting of light to dark grey, micromicaceous, locally calcareous shales and siltstones, interbedded with fine to coarse-grained, occasionally glauconitic and calcareous sandstones. Sandy limestones containing chamosite-ooliths are locally present at or close to the top formation.

### 6.8.2 Boundaries

On logs, the lower boundary is taken at the top of the monotonous, smooth, parallel gamma ray and sonic log responses, characteristic for the underlying Burton formation. According to Vail & Todd (1981), it corresponds to a major unconformity, involving locally tilting and truncation of the underlying strata. The upper boundary is taken at the top of the siltstone-dominated sequence; on logs, it corresponds to the top of the roughly bell-shaped Sonic log response, at the contact with the low-velocity shales of the overlying Drake formation.

### 6.8.3 Distribution

North Viking Graben and East Shetland Platform.

### 6.8.4 Environment

Marginal to shallow marine; with renewed detritus supply following a drop in sea level (and rotation of fault blocks).

### 6.8.5 Age

Late Pliensbachian to Early Toarcian.

### 6.8.6 Oil Fields

Gulfaks.

### 6.8.7 Remarks

### 6.8.8 Synonyms

## 6.9 Drake Formation

### 6.9.1 Lithology

A monotonous sequence of dark grey, micromicaceous shales with occasional sandstone stringers; near its base the sequence is more calcareous and occasionally glauconitic. Rare shell fragments and belemnites.

### 6.9.2 Boundaries

The lower boundary is taken at the log break corresponding to the base of the higher gamma ray - lower velocity shales of the Drake formation. Based on well correlations, Vail & Todd (1981) argue that this boundary is unconformable in places i.e. with an onlap to the Burton formation. The upper boundary of the formation is well defined by a gamma ray log break at the base of the Broom sandstones. In the northerly basinal areas, shale sedimentation has been continuous and the Rannoch shales overlie (conformably?) the Drake formation (e.g. northern part of blocks 211/12, 14, 19).

### 6.9.3 Distribution

East Shetland Basin/North Viking Graben.

### 6.9.4 Environment

Offshore "prodelta" basinal system under low energy conditions.

### 6.9.5 Age

Toarcian to Aalenian.

### 6.9.6 Oil Fields

### 6.9.7 Remarks

'During deposition of the Drake formation, major fault zones became active. The newly created fault blocks started to rotate to the west, thus allowing thickest sedimentation near the down throw sides of the major faults' (*Bolliger et al., 1979*). Intra-Drake sandstones in well Norsk Hydro 33/5-2 are interpreted to represent the regressive stage of cycle UAB-4.6.

### 6.9.8 Synonyms

## 6.10 Dunlin Shale Formation

### 6.10.1 Lithology

A sequence of light to dark grey non-calcareous, locally carbonaceous and micaceous shales and siltstones with stringers of sandstones.

### 6.10.2 Boundaries

The lower boundary is taken at the contact with the underlying red beds of the Beryl or Cormorant formations; it is an abrupt lithological and facies change marking the Base Dunlin Unconformity. The Dunlin Shale formation overlies an undated sandstone unit, supposedly part of the underlying Beryl formation (see *Bolliger et al 1982*). The upper boundary is taken at the contact with the lowest sandstone of the overlying coal-bearing Pentland formation. This boundary is expressed by a hard kick on the sonic log.

### 6.10.3 Distribution

Beryl Embayment.

### 6.10.4 Environment

Marine, open shelf.

### 6.10.5 Age

Pliensbachian to Aalenian.

### 6.10.6 Oil Fields

### 6.10.7 Remarks

This formation includes the marine Liassic shales in the Beryl Embayment.

### 6.10.8 Synonyms

Basal Shale Member (*Bolliger et al., 1982*).

## 6.11 Broom Formation

### 6.11.1 Lithology

Medium to very coarse grained, poorly sorted feldspathic sandstone with occasional pebbles and shale clasts. The matrix is very argillaceous and may contain significant amounts of mica. A generally massive appearance with minor planer cross lamination, much of the primary sedimentary structure has been destroyed by intense bioturbation.

### 6.11.2 Boundaries

Four Broom sequences have been identified (Giles et al., 1989) of which the most typical has a generally blocky to bell- shaped gamma ray and Sonic log response. In this case the boundaries are sharp, especially the lower one which rests on Dunlin Group shales. In the other cases the sequence is frequently gradational and boundaries may be difficult to pick without core data especially as the Broom formation may be represented as a very thin layer of coarse sand granules.

### 6.11.3 Distribution

East Shetland Basin; Tampen Spur and North Viking Graben.

### 6.11.4 Environment

Syn-rift fan delta system which pro-graded from the west and which appear to young to the south (*Giles et al., 1989*).

### 6.11.5 Age

Aalenian to Earliest Bajocian.

### 6.11.6 Oil Fields

### 6.11.7 Remarks

Broom sequences show distinct proximal-distal relationships (*Giles et al., 1989*) with a marked thickening across faults, forming distinct wedges which thin to the west. In the northern areas (blocks 211/13, 14) the Broom formation is very thinly developed or absent and may pass laterally into deeper marine shales of the Dunlin Group. The relationship with the overlying Rannoch formation is complex; the Broom formation appears to be reworked by the Rannoch Sands in the south and to be directly overlain by the Rannoch Shale Member in the north.

### 6.11.8 Synonyms

## 6.12 Heather Formation

**Subdivisions:**
- Upper Heather Member
- Middle Heather Member
- Lower Heather Member

### 6.12.1 Lithology

A monotonous sequence of medium to dark grey, micromicaceous to silty claystones and shales, moderately calcareous, locally with streaks of sandstones and/or carbonates. In the East Shetland Basin, a unit of non-calcareous, carbonaceous (SOM-rich), dark grey-brown to black claystones (Middle Heather Member) is intercalated in a sequence of otherwise silty, calcareous claystones. Beds of carbonaceous claystones, characterised by a 'soft' expression on the sonic log, occur at the base of Heather sequences in the Inner Moray Firth.

### 6.12.2 Boundaries

The Heather claystones are usually characterised by a sub linear, almost parallel gamma ray and sonic log curves, with gamma ray log values below 100api. Hence, the formations boundaries are taken where this character changes. Distinct log breaks usually separate the Heather formation from the underlying coarser clastic units (e.g. Brent Group) and from the overlying Kimmeridge Clay formation.

### 6.12.3 Distribution

The formation can be recognised over most of the North Sea.

### 6.12.4 Environment

Shallow marine to outer shelf and bathyal low energy setting.

### 6.12.5 Age

Bathonian to Berriasian.

### 6.12.6 Oil Fields

### 6.12.7 Remarks

Carmichael (1979) demonstrated the cyclic pattern of deposition for the Heather shales in the East Shetland Basin. Cyclic patterns, in part correlative with those of the East Shetland Basin, can be recognised in the Heather sequences throughout the North Sea. In the Inner Moray Firth, 'regressive' Piper sandstones occur in the middle of the Heather Shales, however, no formal subdivisions of the Heather formation is thought advisable at this stage.
Angular unconformities (related to synsedimentary tectonism), submarine hiati and condensed sequences are frequently recorded in the Heather formation.
Units of re-deposited sandstones are occasionally present within the Heather Shales and have been related in part to the Hugin formation. Due to the limited number of occurrences, no formal member is proposed yet.

### 6.12.8 Synonyms

Ampthill Clays, Viking Shales (previously included in the Kimmeridge Clay formation in the Central Graben).

## 6.13 Lower Heather Member

### 6.13.1 Lithology

'Grey, calcareous silty claystones with occasional thin limestones, particularly near the base and at the top. The log expression is typically a blocky sonic and FDC with high density and velocity values' (*Carmichael 1979*).

### 6.13.2 Boundaries

The lower boundary corresponds to a sharp log break at the contact with the sandstones of the underlying Brent Group. In a few cases (see Tarbert formation), this boundary may be gradational and the lithostratigraphic limits are set on individual criteria.
The upper boundary with the Middle Heather Member corresponds to a sharp decrease in sonic and density log values.

### 6.13.3 Distribution

East Shetland Basin.

### 6.13.4 Environment

Shallow marine, low energy, mainly inner shelf.

### 6.13.5 Age

Latest Bajocian? to Bathonian.

### 6.13.6 Oil Fields

### 6.13.7 Remarks

See Upper Heather Member.

### 6.13.8 Synonyms

## 6.14 Middle Heather Member

### 6.14.1 Lithology

A sequence of dark grey brown to black, non-calcareous carbonaceous (SOM-rich) claystones.

### 6.14.2 Boundaries

'The contact with the underlying Lower Heather Member is marked by a relatively sharp increase in density and velocity and a relative increase in FDC/CNL separation. In wells with a thick Heather development (e.g. 211/21-5), this contact may be transitional, in which case the boundary is picked at the point where the velocity starts to decrease.' (*Carmichael, 1979*). The upper boundary is an unconformable contact (Mid Callovian Unconformity) expressed by a log change towards higher velocities and densities.

### 6.14.3 Distribution

East Shetland Basin.

### 6.14.4 Environment

Marine, outer shelf setting under very low energy conditions (no oxygenation of the bottom waters).

### 6.14.5 Age

Latest Bathonian-Earliest Callovian.

### 6.14.6 Oil Fields

### 6.14.7 Remarks

### 6.14.8 Synonyms

## 6.15 Upper Heather Member

### 6.15.1 Lithology

'The lithology of this interval consists of grey calcareous claystones with frequent thin interbedded limestones' (*Carmichael, 1979*), and rare sandstone intercalations.

### 6.15.2 Boundaries

The lower boundary corresponds to an unconformable contact (Mid Callovian Unconformity) expressed on the logs by an abrupt change towards higher log densities and velocities and a relative decrease in FDC/CNL log separation, as compared to the underlying Middle Heather Member.
The upper boundary, with the Kimmeridge Clay formation, is expressed by a decrease in velocity and density log values and an increase in the gamma ray and resistivity log readings.

### 6.15.3 Distribution

East Shetland Basin.

### 6.15.4 Environment

Marine, outer shelf to bathyal setting under low energy conditions, with occasional turbidite deposition.

### 6.15.5 Age

Callovian to late Oxfordian.

### 6.15.6 Oil Fields

### 6.15.7 Remarks

### 6.15.8 Synonyms

## 6.16 Kimmeridge Clay Formation

Subdivisions:
- Upper Kimmeridge Clay Member
- Kimmeridge Sandstone Member
- Magnus Sandstone Member
- Claymore Sandstone Member
- Brae Member
- Lower Kimmeridge Clay Member

### 6.16.1 Lithology

A sequence of organic rich claystones and shales, dark grey to black in colour, micromicaceous to silty, carbonaceous, slightly to non-calcareous. Thin beds of siltstones and sandstones are present locally, which may develop laterally into thicker units of sandstones (Kimmeridge Sandstone Member). Stringers of carbonates (mostly dolomite) occur, mostly in the lower part of the formation.

### 6.16.2 Boundaries

When overlying the Heather formation, the lower boundary corresponds to a log break expressed by higher gamma ray values (usually above 100api), a decrease in sonic and density log readings. When overlying the Brae, Helmsdale, Piper or Fulmar formations, the lower boundary is a marked log break at the top of the sandstones. An abrupt facies, log and lithological break (unconformity?) is also recorded at the base of the Kimmeridge Clay formation when in contact with the Corallian formation.
The upper boundary corresponds to a regional, North Sea wide unconformity (Late Kimmeridgian Unconformity or Base Cromer Knoll Unconformity), expressed by a major log break. The contact with the overlying Cromer Knoll Group is taken at the top of the shales characterised by low sonic and density log values, and high gamma ray log readings (in excess of 100api).

### 6.16.3 Distribution

The Kimmeridge Clay formation can be recognised over most parts of the North Sea region. It pinches out towards the inner parts of the Western Platform and is absent over some paleo high features of the Central North Sea.

### 6.16.4 Environment

Marine, bathyal/outer neritic (Central Graben areas) to inner neritic (Graben margin/platform); under restricted bottom circulation/stagnant conditions.

### 6.16.5 Age

Late Oxfordian to Intra-Late Berriasian. The most regional, North Sea-wide development of the formation was reached during Portland and Berriasian times.

### 6.16.6 Oil Fields

### 6.16.7 Remarks

The Kimmeridge Clay formation, mainly in its upper part, has a very high organic carbon content and is considered as the main source rock for the hydrocarbon accumulations in the Central and Northern North Sea. Accounting for the fact that organic-rich shales were deposited throughout the North Sea during Late Jurassic/Early Cretaceous times, the name ‘Kimmeridge Clay Formation’ is retained here, against the proposals of Vollset & Dore (1984).

### 6.16.8 Synonyms

Draupne Formation, Mandal formation, Helmsdale Sandstone Member.

## 6.17 Lower Kimmeridge Clay Member

### 6.17.1 Lithology

A sequence of dark to black, micromicaceous to silty claystones and carbonaceous shales, very slightly to non-calcareous; stringers of dolomites and occasionally, minor interbeds of sandstones. In the Inner Moray Firth, thicker units of sandstones are interbedded in shales which tend to have higher gamma ray log values towards the base of the member.

### 6.17.2 Boundaries

The lower boundary corresponds to the formations lower boundary. The upper boundary is taken either at the top of the shaly sequence, at the contact with the first massive sandstone member, or, if present, to the first sonic log break (cycle boundary) in the shales immediately underlying the sandstones. In the Inner Moray Firth the boundary with the overlying Kimmeridge Sandstone Member is expressed by a soft sonic log break, at or near the top of the hot shales/clastics sequence.

### 6.17.3 Distribution

Approximately same distribution as the Kimmeridge, Magnus, Helmsdale and Claymore Sandstone Members.

### 6.17.4 Environment

Marine bathyal/outer neritic under restricted bottom circulation/stagnant conditions.

### 6.17.5 Age

Kimmeridgian.

### 6.17.6 Oil Fields

### 6.17.7 Remarks

In the Inner Moray Firth, proximal active fault scarps supply coarse clastics.

### 6.17.8 Synonyms

Black Shale.

## 6.18 Cromer Knoll Group

Subdivisions:

- Valhall Formation
- Upper Valhall Formation
- Lower Valhall Formation
- Kopervik Formation
- Moray Firth Formation
- Devils Hole Formation
- Red Chalk Formation
- Speeton Clay Formation
- Spilsby Sandstone Formation

### 6.18.1 Lithology

The Group consists mainly of fine grained, argillaceous and marly sediments with some limestones; sandstones are locally present at the base and within the sequence (e.g. Moray Firth formation, Devils Hole formation, Spilsby Sandstone formation, Kopervik formation).

### 6.18.2 Boundaries

The lower boundary corresponds to a major North Sea wide unconformity (Base Cretaceous or Late Kimmerian Unconformity), usually expressed by a strong contrast on the Sonic log (i.e. increase of the velocities), whereby the group unconformably overlies the Humber or older groups.
The Boundary with the overlying Chalk or Shetland Group is in places gradational and conformable, with minor lithological or log contrast at the contact, requiring biostratigraphic analysis and log correlations to identify the boundary. Where the upper boundary is sharp (e.g. on the basis of a sonic log break), it often coincides with an unconformity.

### 6.18.3 Distribution

Witch Ground Graben; South Halibut Basin; Inner Moray Firth; Outer Moray Firth.

### 6.18.4 Environment

Inner/outer shelf to bathyal; mainly under normal marine, low energy conditions.

### 6.18.5 Age

Latest Berriasian to earliest Cenomanian.

### 6.18.6 Oil Fields

### 6.18.7 Remarks

### 6.18.8 Synonyms

## 6.19 Upper Kimmeridge Clay Member

### 6.19.1 Lithology

A sequence of dark grey to black, micromicaceous and carbonaceous claystones and shales, very slightly to non-calcareous.

### 6.19.2 Boundaries

The lower boundary corresponds to the base of the 'hot shale' sequence, at the contact with the first major sandstone unit of the underlying Kimmeridge Sandstone Member, or when present, to the first sonic log break (cycle boundary) in the shales immediately overlying the sandstones.
The upper boundary corresponds to the upper boundary of the formation and group.

### 6.19.3 Distribution

Same distribution as the Kimmeridge Sandstone Member.

### 6.19.4 Environment

Bathyal/Outer neritic to inner neritic; under restricted bottom circulation/stagnant conditions.

### 6.19.5 Age

Late Kimmeridgian to Intra-Late Berriasian.

### 6.19.6 Oil Fields

### 6.19.7 Remarks

### 6.19.8 Synonyms

'Hot Shales', Radioactive Clay, Kimmeridge Clay Formation.

## 6.20 Kimmeridge Sandstone Member

### 6.20.1 Lithology

Very fine to very coarse, occasionally pebbly, poorly to well sorted sandstones, interbedded with dark grey to brown mudstones. The sandstones vary from blocky, with no or poorly defined bedding, to vertically graded units, the most common facies consisting of interbedded, thin graded sandstones (turbidites) and finely laminated dark grey shales which give a high frequency/high amplitude response on the gamma ray log. Slumped ad contorted sandstones and mudstones have locally been recognised in cored sections. At the base and at the top of the member, the shales are often well developed, to the extent that the sandstones occasionally constitute the secondary lithology.

### 6.20.2 Boundaries

The Kimmeridge Sandstone Member is embedded in the shales of the Kimmeridge Clay Formation; both its boundaries are transitional, reflecting he gradual development of the submarine fan and its subsequent abandonment.
The lower boundary is either taken at the base of the first distinct sandstone bed or, if recognisable, at a deeper sonic log break marking the onset of the new sedimentation regime. In such a case, the lower boundary may not correspond to a change in lithology.
In some cases (Beryl Embayment), the Kimmeridge Sandstone Member possibly lies directly on top of the Heather formation.
The upper boundary is taken either at the top of the uppermost sandstone bed or, if recognisable, at a shallower sonic log break marking the return to the 'hot shale' sedimentation regime.

### 6.20.3 Distribution

South Halibut Basin, Moray Firth Basin, Witch Ground Graben, Viking Graben, Beryl Embayment and Magnus Embayment.

### 6.20.4 Environment

Submarine fan systems. The gravity flow deposits originated in response to relative sea-level low-stands.

### 6.20.5 Age

Kimmeridgian to Berriasian.

### 6.20.6 Oil Fields

Bruce, Ettrick, Claymore, Magnus.

### 6.20.7 Remarks

The Helmsdale Sandstone Member, the Claymore Sandstone Member and the Magnus Sandstone Member are local equivalents of the Kimmeridge Sandstone Member. The 'Bruce Sandstone' in part is also a local equivalent, included here into the Kimmeridge Sandstone Member.
In the absence of cores, the differentiation between the submarine fan deposits of the Kimmeridge Sandstones Member and those of the shallow marine Piper formation may not always be possible on lithology and logs only; palynofacies analysis will help to differentiate the lithostratigraphic units.

### 6.20.8 Synonyms

### 6.21 Lower Valhall Formation

Subdivisions:
- Lower Valhall C Member
- Lower Valhall B Member
- Lower Valhall A Member
- Main Lower Valhall Member
- Lower Valhall Sand Member

#### 6.21.1 Lithology

The Formation consists of interbedded calcareous claystones and marls grading, in places, into argillaceous limestones especially at the base. Occasionally dolomite and siltstones/sandstones are developed locally. Over structural highs and on basin margins carbonate facies are developed.

#### 6.21.2 Boundaries

The lower boundary is generally the groups boundary (Base Cretaceous or Late Kimmerian Unconformity), corresponding to an abrupt lithological/log break, and recognised by a sharp increase in sonic log velocities.
Where the Lower Valhall formation overlies the Moray Firth or Devils Hole formation, the lower boundary is taken at the top of the uppermost sandstone bed, or, if present at a level immediately above it, at a character change/break on the sonic log.
The upper boundary corresponds to an intra-Early Aptian event; it is taken at the base of the high gamma ray/low sonic log velocity shale marker, at the contact with the overlying Upper Valhall formation. When overlain by the Kopervik formation, the upper boundary is taken either at the base of the first distinct sandstone bed, or, if present at a level immediately underneath, at a character change/break on the sonic log.
The lateral boundary with the Moray Firth or Devils Hole formation is taken where the sequence becomes predominantly shaly.

#### 6.21.3 Distribution

Inner/Outer shelf to bathyal; mainly under normal marine conditions.

#### 6.21.4 Environment

#### 6.21.5 Age

#### 6.21.6 Oil Fields

#### 6.21.7 Remarks

#### 6.21.8 Synonyms

## 6.22 Lower Valhall A Member

### 6.22.1 Lithology

A sequence of white to light grey, hard, partly recrystallised limestones/dolomitic limestones, often sandy and argillaceous, with marly interbeds.

### 6.22.2 Boundaries

The lower boundary corresponds to the Base Cretaceous Unconformity, usually an abrupt log/lithological change, characterised by an upward shift to lower gamma ray log values and high sonic log readings. The upper boundary is taken at the top of the uppermost limestone bed, which is indicated by a distinct up hole decrease in sonic log velocities.

### 6.22.3 Distribution

Patchy distribution, mainly in the Viking Graben and in the Greater Moray Firth Area. Often encountered on paleo high features.

### 6.22.4 Environment

Transgressive, shallow marine; normal, oxygenated bottom conditions (*Rawson & Riley, 1982*).

### 6.22.5 Age

Latest Berriasian to Early Valanginian.

### 6.22.6 Oil Fields

### 6.22.7 Remarks

Gas shows in the type well.

### 6.22.8 Synonyms

## 6.23 Upper Valhall Formation

Subdivisions:
- Upper Valhall B Member
- Upper Valhall A Member

### 6.23.1 Lithology

The formation consists of calcareous claystones and marls sometimes grading into limestone towards the top of the formation. Non-calcareous claystones are also developed during periods when dysaerobic bottom conditions persisted.

### 6.23.2 Boundaries

The boundary with the Chalk Group is often unconformable (Base Cretaceous Unconformity) and marked by an abrupt upward increase in sonic log velocities indicative of the onlap of the Chalk carbonates. Where the Lower/Middle Cenomanian Lower Hidra Member is present, the log/lithological contrast between the two formations is attenuated, often corresponding to a slight increase in sonic log velocities; in these cases, the position of the boundary is best established on the basis of log correlations.
In the Northern North Sea the upper boundary with the Shetland Group is best established using a combination of biostratigraphic evidence and log correlation.
The lower boundary is taken at the base of a prominent shale bed (Basal Aptian Shale Marker) characterised by high gamma ray and low sonic log values.

### 6.23.3 Distribution

### 6.23.4 Environment

Inner/Outer shelf to bathyal; mainly under normal marine, low energy conditions.

### 6.23.5 Age

Early Aptian - earliest Cenomanian.

### 6.23.6 Oil Fields

### 6.23.7 Remarks

The Upper Valhall formation is used primarily when the individual A and B members cannot be differentiated (e.g. condensed sequences); in this instance biostratigraphic correlation is essential.

### 6.23.8 Synonyms

Rodby formation, Sola formation; Valhall B and Valhall A (upper part); Valhall Units B2, B1, A2 and A1 (uppermost part); CK V, IV and III (*Ribis, 1983*); Alwyn Marl Member (*Shell Expro, 1977*); Cromer Knoll Shale formation.

## 6.24 Shetland Group

**Subdivisions:**

- Shetland F Formation
- Shetland E Formation
- Shetland D Formation
- Shetland C Formation
- Shetland B Formation
- Shetland A Formation
- Shetland Clay Formation

### 6.24.1 Lithology

The Shetland Group is characterised by a mixture of lithologies. It consists mainly of fine grained sediments, marls, claystones, shales with some chalk, limestone and dolomite. Arenaceous deposits are extremely rare.

### 6.24.2 Boundaries

The lower contact with the Cromer Knoll Group is mainly unconformable (Base Upper Cretaceous Unconformity); it is expressed by a distinct log break, with lower gamma ray and higher sonic log values, reflecting the higher calcareous content of the Shetland Group.
The Shetland Group is overlain, in part unconformably by the Montrose Group. The upper boundary is taken at the top of the dominantly calcareous sequence, it corresponds to a log break, with higher gamma ray and lower sonic log readings in the units immediately overlying the Shetland Group.
Near the Beryl Embayment the Shetland Group passes southwards into the equivalent Chalk Group; the cut off point is arbitrarily defined where the Tor/Shetland E formation contains less than 20% limestones and also where the Shetland E Marl Member is recognisable.

### 6.24.3 Distribution

### 6.24.4 Environment

Marine, deep water shelf to slope and basin. The absence of coarse clastics reflects the general high sea-level stand throughout the deposition of the Group.

### 6.24.5 Age

Cenomanian to Maastrichtian.

### 6.24.6 Oil Fields

### 6.24.7 Remarks

The main source of data for the description of the Shetland Group is an unpublished exploration report (*A lithostratigraphic study of the Cretaceous in the U.K. part of the Viking Graben*).

### 6.24.8 Synonyms

## 6.25 Shetland A Formation

### 6.25.1 Lithology

A sequence of interbedded limestones, marls, claystones and shales in the south, grading into calcareous claystones and siltstones in the north.

### 6.25.2 Boundaries

The lower contact with the Cromer Knoll Group is mainly unconformable (Base Upper Cretaceous Unconformity); it is expressed by a distinct log break, with lower gamma ray and higher sonic log readings and a less quiet log response as compared with the one of the underlying shales of the Cromer Knoll Group. The upper boundary is usually distinct, with lower gamma ray and a higher sonic log responses than the overlying formation (Shetland B, C and D formations). The boundary becomes less distinct northwards.
The boundaries are the best established on the basis of log correlations.

### 6.25.3 Distribution

Deeper parts of the North Viking Graben and East Shetland Basin; absent from the highs, the Shetland Platform and the Magnus trends, although it is traceable up to the End-of-the-World fault-zone in the deeper areas. Southwards, this Formation passes into the equivalent Hidra formation of the South Viking Graben.

### 6.25.4 Environment

Marine, deep water shelf to slope and basin. Mass flow deposits are probably present, adjacent to paleo high areas.

### 6.25.5 Age

Cenomanian.

### 6.25.6 Oil Fields

### 6.25.7 Remarks

### 6.25.8 Synonyms

## 6.26 Shetland B Formation

### 6.26.1 Lithology

A thin unit of mainly shales and claystones.

### 6.26.2 Boundaries

The Shetland B Formation is characterised by relatively high gamma ray and low sonic log values. The Upper boundary with the Shetland C formation is often transitional.

### 6.26.3 Distribution

The Shetland B formation is only 20-50 ft thick and is present only in the deeper parts of the North Viking Graben, with a distribution very similar to that of the Shetland A formation. Southwards, the Shetland B formation passes laterally into the equivalent Plenus Marl formation.

### 6.26.4 Environment

Marine, deep water shelf to basin; under partial dysaerobic conditions; low rates of sedimentation.

### 6.26.5 Age

Late Cenomanian to Mid Turonian.

### 6.26.6 Oil Fields

### 6.26.7 Remarks

### 6.26.8 Synonyms

## 6.27 Shetland C Formation

Subdivisions:

- Upper Shetland C Member
- Basal Shetland Limestone Member
- Lower Shetland C Member

### 6.27.1 Lithology

A sequence of bedded to massive limestones with calcareous shales, claystones and marls.

### 6.27.2 Boundaries

The lower boundary is distinct in so much that the top of the Shetland A formation with a lower gamma ray response and a higher sonic log reading can be easily picked. The boundary with the Shetland B formation can rarely be easily picked and must be established on the basis of log correlations. In places the Shetland C formation unconformably overlies the Cromer Knoll Group.
The upper boundary is distinct; except in the far north, where the Shetland C formation is relatively calcareous and characterised by a relatively low gamma ray and high sonic log expression as compared to the overlying shalier Shetland D formation. North of Quadrant 3, the Shetland C formation becomes less calcareous, especially in the lower part, until only a few calcareous stringers remain to mark the upper boundary - even these eventually die out to the northeast where the Shetland C formation is not distinguishable. North of Quadrant 3 a stronger marker becomes evident just below the calcareous stringers which has a high gamma ray and low sonic log response. This marker is thought to be roughly equivalent to the probably diachronous boundary between the shalier lower part and the more calcareous upper part of the Herring formation in the South Viking Graben, which becomes progressively higher in the section going northwards. Although this lower marker represents a strong boundary north of Quadrant 3, it is felt for consistency reasons that it is better to maintain the original boundary. Although it is not so well marked, it can still be picked at the top of the calcareous stringers.
In the far northeast, the formation becomes undistinguishable from the Shetland D formation.
Towards the south, the formation passes laterally into the Herring formation of the Chalk Group.

### 6.27.3 Distribution

Larger part of the South Viking Graben; absent from many of the highs, the Magnus Trend, the Unst Basin, the Shetland Platform and the marginal areas of the Shetland Platform.

### 6.27.4 Environment

Marine, deep water shelf, slope (mass flows) to basin.

### 6.27.5 Age

Middle Turonian?

### 6.27.6 Oil Fields

### 6.27.7 Remarks

The formation becomes relatively calcareous to the South and adjacent to the Shetland Platform and the high areas, where part of the formation may consist of mass-flow limestones.

### 6.27.8 Synonyms

## 6.28 Lower Shetland C Member

### 6.28.1 Lithology

As for the Formation.

### 6.28.2 Boundaries

The upper boundary corresponds with the base of the Basal Shetland Limestone Member and the lower one is identical to the base of the formation.

### 6.28.3 Distribution

East Shetland Basin.

### 6.28.4 Environment

Open marine shelf.

### 6.28.5 Age

Middle Turonian (lower)?

### 6.28.6 Oil Fields

### 6.28.7 Remarks

### 6.28.8 Synonyms

## 6.29 Basal Shetland Limestone Member

### 6.29.1 Lithology

A unit consisting of hard to moderately hard limestone (wackestone - packstone), sometimes argillaceous, white to grey. Within the unit one or more thin marl beds can be present. Losing its typical, well defined character to the south.

### 6.29.2 Boundaries

The characteristically low gamma ray and high sonic log responses made this unit easily distinguishable from the underlying and overlying shaly sequences. The boundaries are usually sharp, but are less well defined towards the south.

### 6.29.3 Distribution

Widespread in the East Shetland Basin, typically in the Tern - Eider area, probably into the NW Magnus Embayment and Alwyn Slope areas. Could be limited to structural highs.

### 6.29.4 Environment

Marine, relatively shallow, middle-outer neritic shelf with clear, well oxygenated conditions.

### 6.29.5 Age

Middle Turonian (middle)?

### 6.29.6 Oil Fields

### 6.29.7 Remarks

### 6.29.8 Synonyms

## 6.30 Upper Shetland C Member

### 6.30.1 Lithology

As for the formation.

### 6.30.2 Boundaries

The upper boundary is identical too the one for the formation. The lower boundary is usually well defined by the underlying carbonate succession belonging to the Basal Shetland Limestone Member.

### 6.30.3 Distribution

East Shetland Basin.

### 6.30.4 Environment

Open marine shelf.

### 6.30.5 Age

Middle Turonian (upper)?

### 6.30.6 Oil Fields

### 6.30.7 Remarks

### 6.30.8 Synonyms

## 6.31 Shetland D Formation

### 6.31.1 Lithology

A fairly monotonous sequence consisting of marls, shales and claystones with minor dolomite and limestone stringers.

### 6.31.2 Boundaries

The lower boundary is variable. In the shallower areas, the formation lies unconformably on the Cromer Knoll Group which in general has a high gamma ray and low sonic response. In deeper areas, it overlies the Shetland C formation with a distinct log break, i.e. with lower gamma ray and higher sonic log signatures in the underlying formation.
In the far north, the Shetland C formation is undistinguishable from the lower part of the Shetland D formation; here, the Shetland D formation directly overlies the Shetland B and A formations. The upper boundary corresponds to a relatively good break, the Shetland A formation having a lower gamma ray and a higher sonic log expression.
North of the End-of-the-World fault, the Shetland D formation is not always distinguishable from the Shetland E formation.
Southwards, the Shetland D formation passes laterally into the Flounder formation of the Chalk Group.

### 6.31.3 Distribution

Entire North Viking Graben area, with the probable exception of a small area adjacent to the Unst Basin, the Unst Basin itself and the Shetland Platform.

### 6.31.4 Environment

Marine, deep water shelf to basin.

### 6.31.5 Age

Late Turonian to Late Campanian (?)

### 6.31.6 Oil Fields

### 6.31.7 Remarks

### 6.31.8 Synonyms

## 6.32 Shetland E Formation

Subdivisions:
- Shetland E Limestone Member
- Shetland E Main Member

### 6.32.1 Lithology

The Shetland E formation can be divided into the following two members:
- Shetland E Limestone Member: massive chalky limestone with occasional shaly intervals.
- Shetland E Main Member: interbedded grey marls, shales and thin bedded argillaceous limestones getting less calcareous and grading away into grey shales towards the base.

### 6.32.2 Boundaries

The relatively low gamma ray and high sonic log responses of the Shetland E Main Member produces in general a good break at the contact with the underlying Shetland D formation; however, north of the End-of-the-World fault, this boundary is not always recognisable.
The upper boundary is usually distinct with the formation being overlain, in part unconformably, by the Maureen North formation, which has a higher gamma ray and a lower sonic log response.
A thin argillaceous limestone is also often present at the top of the Shetland E formation. Near the Shetland Platform, the Shetland E Limestone Member is present, having a characteristic low gamma ray and a high sonic log signature. Southwards, the Shetland E formation passes laterally into the Tor formation of the Chalk Group (see Shetland Group).

### 6.32.3 Distribution

North Viking Graben.

### 6.32.4 Environment

Marine, deep water shelf, slope to basin.

### 6.32.5 Age

Late Campanian to Maastrichtian.

### 6.32.6 Oil Fields

### 6.32.7 Remarks

The previously distinguished Shetland E Marl Member is now regarded as a synonym of the Shetland E Main Member.

### 6.32.8 Synonyms

Shetland Marl Formation.

## 6.33 Shetland E Main Member

### 6.33.1 Lithology

A unit of interbedded grey marls, shales and thin bedded argillaceous limestones becoming less calcareous and grading into grey shales towards the base.

### 6.33.2 Boundaries

The characteristic low gamma ray and high sonic log values makes this rock unit easily distinguishable from the underlying and overlying sequences.

### 6.33.3 Distribution

As for the formation.

### 6.33.4 Environment

### 6.33.5 Age

### 6.33.6 Oil Fields

### 6.33.7 Remarks

This rock unit comprises all Shetland E sequences consisting of marls and shales. Massive chalky limestone is absent. It includes the previously distinguished Shetland E Marl Member.

### 6.33.8 Synonyms

Shetland E Marl Member.

## 6.34 Montrose Group

**Subdivisions:**

- Forties Formation
- Teal Formation
- Lista Formation
- Andrew Formation
- Heimdal Formation
- Maureen Formation
- Maureen Marl Formation
- Maureen North Formation

### 6.34.1 Lithology

The group typically comprises, at the base, a mixed sequence of marls, shales, sandstones and re-deposited blocks of chalk, overlain by a shaly sequence with interbedded sandstones, where the sandstones often constitute the main lithology.

### 6.34.2 Boundaries

The lower boundary is a widespread unconformity (Base Tertiary Unconformity), associated with a change from dominantly calcareous (Chalk Group) to dominantly siliclastic sediment. In general, it is expressed by an often abrupt, upward decrease in the Sonic log response. In the northern part of the South Viking Graben, the Montrose Group unconformably overlies the Cromer Knoll or Humber Group. In the areas where the Maureen Marl or Maureen North formation are developed, the lower boundary with the Chalk or Shetland Group may be transitional. The upper boundary with the Rogaland Group is taken at the base of the organic-rich shales of the Sele formation to their time correlative sediments (e.g. Rogaland Sand formation).

### 6.34.3 Distribution

The Group is present throughout the Central and Northern North Sea. In the Southern North Sea, its identification is sometimes difficult and the corresponding sediments are often referred to as the (undifferentiated) North Sea Clay Formation.

### 6.34.4 Environment

'Deep Marine' (circa. 100 to 800 metres), hemipelagic depositional environment experiencing episodes of mass flow sedimentation. Initially, the mass flows are mainly slumps and debris flows, which are then gradually replaced by more mature turbidites. Two major depositional sequences can be recognised, the first of which deposited the Andrew and Heimdal submarine fans, the second one the Forties and Teal fans. Both fan systems are generally separated by claystones of the Lista formation, which was deposited during a transgression phase of sedimentation.

### 6.34.5 Age

Paleocene (mainly late part).

### 6.34.6 Oil Fields

Forties, Montrose, Nelson, Gannet (part), Maureen, Andrew, Balmoral, Everest, Lomond.

### 6.34.7 Remarks

The Ninian Sand formation has been re-interpreted as belonging to the Moray Group rather than to the Montrose Group. The Lyell Sand formation has been renamed Heimdal formation. The Lower Forties formation has been re-interpreted as the upper part of the Andrew formation.

### 6.34.8 Synonyms

## 6.35 Maureen Formation

### 6.35.1 Lithology

'The formation consists of mixed lithologies with rather irregular distribution patterns. It is frequently conglomeratic and contains pebbles and clasts of reworked limestones and shales of Danian and late Cretaceous age, in a matrix of, or interbedded with, brown and dark grey shales, siltstones and sandstones.' (*Deegan & Scull, 1977*).

### 6.35.2 Boundaries

'The Maureen Formation rests on the Chalk Group or Shetland Group and the change from the primarily non-clastic deposits of the Chalk Group, or the calcareous mudstones of the Shetland Group, to the heterogeneous deposits of the Maureen formation is well shown on the sonic, gamma and dipmeter logs. The upper boundary is marked by the change from variably sandy deposits containing reworked limestone fragments, to the commencement of submarine fan and turbidite deposits. This boundary can be difficult to identify as the first deposits of the fan wedges may also be calcareous in nature.' (*Deegan & Scull, 1977*).
Laterally, the Formation passes into the Maureen Marl formation (parts of the Central North Sea) and into the Maureen North formation (Viking Graben).

### 6.35.3 Distribution

'The generally coarse Maureen formation deposits were mainly derived from erosion and reworking of underlying Danian and Cretaceous rocks, although fragments of pre-Cretaceous rocks may be locally present. This coarse detrital facies is mainly developed in the Central Graben and Southern Viking Graben, particularly around intra-basinal highs. It thins to the northwest in the Moray Firth Basin. A marl facies equivalent of the Maureen formation is present over highs, and away from sand sources where the underlying rock is marly'. (*Deegan & Scull, 1977*).

### 6.35.4 Environment

The Maureen formation contains abundant slumps, debris flows and "slurry deposits" interpretation with frequent reworking from the Chalk Group. These reworked strata were deposited in response to a rapid drop in relative sea level, which is correlative with a rapid uplift of the Shetland Platform/Scottish Highlands area. This uplift is associated with sudden northward progradation of Atlantic spreading and volcanism west of the Shetlands.

### 6.35.5 Age

Paleocene.

### 6.35.6 Oil Fields

### 6.35.7 Remarks

### 6.35.8 Synonyms

## 6.36 Andrew Formation

### 6.36.1 Lithology

'The Andrew formation consists of sandstones, showing a characteristic cylindrical wireline log response, with minor interbeds of claystones. The sandstones are composed of fine to medium, locally coarse, sub angular to sub rounded grains, are moderately sorted, white to very light grey, locally calcareous and rarely tuffaceous. The claystones are firm, sub fissile to blocky, medium grey, greenish grey and olive grey, micromicaceous, locally silty add non-calcareous. Pyrite, carbonaceous debris, and rare amounts of glauconite are present as accessories, Tuffaceous deposits occur in association with the claystones and sandstones forming fairly thick layers within the Andrew formation in the north western portion of the study area. These tuffaceous beds may be bonded sub aerial tuffs or concentrations of reworked older volcanics, possibly Middle Jurassic'. (*RRI. 1987*).

### 6.36.2 Boundaries

The boundaries correspond to identified seismic markers (D11.6 and D12 for the Central North Sea area). 'On log shape the Andrew formation is characterised by a low gamma ray response and a high box-shape, sonic velocity, in contrast to the more irregular log response of the overlying unit'. (A*lberts & Speelman. 1986*). 'The formation overlies the Maureen formation, the boundary being conformable and marked by an upward change from the heterolithic lithologies with reworked limestones of the Maureen formation to the interbeds of sand and claystone of the Andrew formation. There is a gradual upward increase in gamma ray response across the boundary". (*RRI, 1987*). In places, the Andrew formation unconformably overlies the Maureen formation or the Chalk Group. 'The upper boundary is identified on the sonic log as the break between the generally high velocity Andrew Formation and the overlying sandstones and siltstones (Fergus formation), which have a distinctly lower velocity'. (*Deegan & Scull, 1977*).
Laterally and upward the Andrew formation grades into the shales of the Lista formation, the boundary being arbitrarily taken when the sequence contains less than 50% sandstones.

### 6.36.3 Distribution

South Viking Graben, Outer Moray Firth, Central Graben.

### 6.36.4 Environment

The Andrew formation forms a large sand-dominated submarine fan, which spread over most of the Moray Firth/Central Graben area. The high sand content causes turbidites in the Andrew fan to have a proximal aspect. Maximum water depth is estimated to have been about 600 metres. The fan was deposited after the rapid fall in relative sea level, which initially triggered deposition of the Maureen formation. Subsequent relative sea level rise caused abandonment of the Andrew fan, with a gradual change from Andrew sands into Lista shales as a result.

### 6.36.5 Age

Late Paleocene.

### 6.36.6 Oil Fields

Oil fields: Andrew, Maureen, Balmoral, Gannet D, Mabel, Maggie.
Gas/condensate fields: Everest (part), Judy, Joanne.

### 6.36.7 Remarks

### 6.36.8 Synonyms

Unit 1, Sequence A (*Alberts & Speelman, 1986*). Halibut Sand formation. The 'Lower Forties Formation' corresponds to the upper part of the Andrew Formation.

## 6.37 Lista Formation

Subdivisions:
- Upper Lista Member
- Lower Lista Member

### 6.37.1 Lithology

A sequence of claystones and shales, grey, micromicaceous to silty, usually poorly to non-calcareous. Minor interbeds concretions of carbonate, occasionally including reworked chalk. Sandstone beds may be locally quite common, although the overall sand content must be less than 50%. Bioturbidation is common in the lower part of the Lista formation (typically Chondrites, Planolites), and becomes increasingly rare upward. This upward change is associated with a colour change from greenish grey to dark grey (Forties formation equivalent).

### 6.37.2 Boundaries

The Lista formation is characterised on logs by higher gamma ray and lower sonic readings and larger negative FDC/CNL log separations than the surrounding formations. The most common occurrence of the Lista formation is a ‘transgressive’ claystone between the Andrew and Forties formations or between the Heimdal and Teal formations. However, the Lista formation can be a lateral clay-equivalent of all these turbidite-bearing formations.

### 6.37.3 Distribution

Widely distributed throughout the North Sea.

### 6.37.4 Environment

Deep marine, hemipelagic with occasionally distal turbidites. Well oxygenated in the lower part, becoming increasingly restricted towards the top.

### 6.37.5 Age

### 6.37.6 Oil Fields

### 6.37.7 Remarks

### 6.37.8 Synonyms

## 6.38 Balder Formation

### 6.38.1 Lithology

'The Balder formation is composed of laminated varicoloured fissile shales with interbedded grey green or buff, often pyritic, tuffs and occasional stringers of limestone, dolomite and siderite'. (*Deegan & Scull, 1977*).
In cores, the tuffs can be observed as discrete blue-grey or green-grey bands, typically 1-5cm thick, with very sharp, flat boundaries. The tuffs in these bands are mostly very angular, interlocking crystals of volcanic glass, quartz and plagioclase with abundant smectite in the pore spaces. The crystals are fine sand to silt-sized and often display a perfect fining-up within the tuff band, due to the more rapid sinking of coarser ash particles. The colour of the tuff bands contrasts strongly with the background sedimentation of dark, grey-black hemipelagic clay.

### 6.38.2 Boundaries

'The upper boundary is placed at the change from the laminated shales of the Balder formation to the non-laminated, often glauconitic, occasionally reddish, overlying sediments. The lower boundary with the Sele formation is generally identified on wireline logs as the upward change from higher to lower gamma ray response and lower to higher sonic velocity readings, probably corresponding to the sharp increase in the tuffaceous component of the Balder formation'. (*Deegan & Scull, 1977*). This effectively means, that both the lower and the upper boundary are picked on gamma ray log maxima. In the absence of sand, the Balder formation can often be recognised on seismic as a double black loop which can be followed over large distances.

### 6.38.3 Distribution

'This Formation is distributed over most of the North Sea and may correspond in part to the Mo Clay Formation in Denmark'. (*Deegan & Scull, 1977*).

### 6.38.4 Environment

Marine, outer shelf to bathyal setting with restricted water circulation. Strong input of volcaniclastics (tuffs). The bloom of siliceous diatoms (Coscinodiscus) at that time is indicative of an abnormally low pH of the surface waters (silica-enrichment related to Thulean volcanism).

### 6.38.5 Age

Early Eocene.

### 6.38.6 Oil Fields

### 6.38.7 Remarks

### 6.38.8 Synonyms

The Scaup formation, forms the upper part of the Balder Formation.

## 6.39 Hutton Clay Formation

Subdivisions:
- Upper Hutton Clay Member
- Lower Hutton Clay Member

### 6.39.1 Lithology

Claystone and siltstone, light brown, grey green or dark grey, non-to slightly calcareous, micaceous, glauconitic, carbonaceous. Contains thin beds of brown, red brown limestone and dolomite. May have thin beds of sandstone at the top (transition to Hutton Sand) or at the base (lateral equivalent of Frigg Sand).

### 6.39.2 Boundaries

The upper boundary is taken at the base of the lower most prominent sandstone in the Hutton Sand formation. This is quite a clear boundary in most areas but in some eastern sectors this is less clear due to shaling out of the lower sands of the Hutton Sand formation. The base is taken at the top of the Frigg Sandstone, where present, or at the top of the Balder tuff sequence.
The joint Central North Sea equivalents of the Hutton Clay formation are the Tay Shale, Horda and Lark formations, which are lithologically identical to the Hutton Clay formation.
In the Viking Graben, the Hutton Sand Formation progrades over the Hutton Clay formation. This progradation occurs in advancing cycles, and during the Late Miocene the entire North Sea was covered. The boundary between the formations is taken at an overall sand content of 20%. The transition is frequently marked by a gradual coarsening-up sequence.

### 6.39.3 Distribution

Northern North Sea.

### 6.39.4 Environment

Marine; moderately deep basin.

### 6.39.5 Age

Eocene to Miocene.

### 6.39.6 Oil Fields

### 6.39.7 Remarks

The Hutton Clay formation is a composite unit comprising several depositional sequences, sequences E – I. (*Alberts & Speelman, 1986*).

### 6.39.8 Synonyms

## 6.40 Upper Hutton Clay Member

### 6.40.1 Lithology

As for the Formation.

### 6.40.2 Boundaries

The upper boundary is taken at the base of the lowermost prominent sandstone in the Hutton Sand formation. The lower boundary is taken at the top of the highest sand bed of the Alba North formation.

### 6.40.3 Distribution

Viking Graben. East Shetland Basin.

### 6.40.4 Environment

Marine, moderately deep basin.

### 6.40.5 Age

Oligocene to Miocene.

### 6.40.6 Oil Fields

### 6.40.7 Remarks

### 6.40.8 Synonyms

### 6.41 Hutton Sand Formation

#### 6.41.1 Lithology

Sands of variable grain size, very fine to coarse, with occasional granules and pebbles, glauconite, with abundant fossil debris (corals, bryzoa, gastropods, forams, bivalves at some levels, also lignitic beds. Interbedded with claystones, grey green to black (carbonaceous), silty and slightly non-calcareous.

#### 6.41.2 Boundaries

The top of the formation is generally assumed to be the seabed, although the lithology of the first few hundred feet is usually poorly known. The lowermost prominent sand is taken to be the base, which sometimes lends to the inclusion of thick intervals of shale in the Hutton Sand formation. The basal sand unit, however, can be traced over large areas and can be observed to thin and effectively pass into the Hutton Clay formation. Because of this interfingering with the Hutton Clay the base of the Hutton Sand formation is diachronous. Lateral equivalents of the Hutton Sand formation are the sandy parts of the Lark formation and the Nordland Group in the Central North Sea, and the North Sea Sand formation in the Southern North Sea. Lithologically, these are all identical.

#### 6.41.3 Distribution

Most parts of the Northern North Sea.

#### 6.41.4 Environment

Marine, shallow to intermediate shelf, shallowing up to marginal marine and glacial.

#### 6.41.5 Age

Oligocene to Recent.

#### 6.41.6 Oil Fields

#### 6.41.7 Remarks

The Hutton Sand formation is a composite unit comprising several depositional sequences.

#### 6.41.8 Synonyms

## 6.42 North Sea Clay Formation

### 6.42.1 Lithology

In the type well, this rock unit consists of a sequence of grey to light brown, micromicaceous, in places silty/sandy, soft clays grading downward into claystone. Occasional streaks of dolomitic limestones.

### 6.42.2 Boundaries

A composite unit, the lower boundary of which is usually picked at the top of the Balder tuff sequence, where the tuffs are not recognisable (e.g. parts of the Southern North Sea), the North Sea Clay formation may extend down to the top of the Chalk Group.
The upper boundary is taken at the unconformable contact with the overlying North Sea Sand formation.

### 6.42.3 Distribution

Southern North Sea.

### 6.42.4 Environment

Marine, mainly middle to outer shelf.

### 6.42.5 Age

Eocene to Miocene.

### 6.42.6 Oil Fields

### 6.42.7 Remarks

### 6.42.8 Synonyms

## 6.43 North Sea Sand Formation

### 6.43.1 Lithology

This formation consists of a sequence of very fine to medium (coarse), poorly to moderately sorted loose sands becoming very argillaceous and carbonaceous towards the base. Occasional streaks of limestones and shell fragments. In places thick lignite beds are present.

### 6.43.2 Boundaries

A composite unit, the lower boundary of which is taken at the base of the sand sequence, at the contact with the clays/claystones of the underlying North Sea Clay formation, or at the contact with older groups (e.g. Chalk Group, Lias Group, Haisborough Group). The upper boundary is the seafloor.

### 6.43.3 Distribution

Southern North Sea and Mid North Sea High.

### 6.43.4 Environment

Shallow marine, marginal marine and glacial.

### 6.43.5 Age

Pliocene to Recent.

### 6.43.6 Oil Fields

### 6.43.7 Remarks

The North Sea Sand formation is apparently separated from the underlying North Sea Clay Formation by a regional unconformity (*Veeken, 1987*) and as such could be identified as a separate group. However, in order to avoid unnecessary proliferation of names over unprospective intervals (where stratigraphic control is anyway very limited), this unit should retain its undifferentiated formation status for practical reasons.

### 6.43.8 Synonyms

## 7.0 Acknowledgements

Compiled from a series of Geology notes, well programs, manuals and various texts including;

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