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# Middle Jurassic, Upper Jurassic and Lower Cretaceous of the UK Central and Northern North Sea

Continental Shelf and Margins Programme

Research Report RR/03/001

BRITISH GEOLOGICAL SURVEY

RESEARCH REPORT RR/03/001

# Middle Jurassic, Upper Jurassic and Lower Cretaceous of the UK Central and Northern North Sea



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Glacial till overlying Oxfordian sedimentary rocks at Filey Brigg, North Yorkshire.

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# Foreword

The North Sea Oil Province comprises the Central and Northern North Sea and is one of the world's major oil-producing regions. For the past 30 years this province has been a very important part of Britain's resource base and a major contributor to the Nation's wealth. The private sector's success in vigorously exploring and developing the oil province has been supported and stimulated by the regulatory activities of the Department of Trade and Industry, and by the complementary work of the British Geological Survey (BGS), which has published an extensive range of offshore geological maps and reports. This report summarises much that is known about the tectono-stratigraphic development, palaeogeography and petroleum geology of the Middle Jurassic, Upper Jurassic and Lower Cretaceous rocks within the province. The report text and figures presented here are complemented by three 1:1 000 000 map enclosures that illustrate the distribution and thickness of the Middle Jurassic, Upper Jurassic and Lower Cretaceous lithostratigraphical successions as defined by the BGS on behalf of the United Kingdom Offshore Operators Association.

The Middle Jurassic development of the province was dominated by an episode of transient thermal doming. A subsequent, Late Jurassic, phase of crustal extension developed the Viking Graben, Moray Firth and Central Graben rift systems. During Early Cretaceous times, much of the pre-existing rift topography continued to exert a strong influence on sedimentation, though tectonism and halokinesis were also locally important. Syn-rift organic-rich marine mudstones are the source for virtually all of the region's hydrocarbons and are mature for hydrocarbon generation throughout most of the rift system. Though the Central and Northern North Sea is now considered to be mature for exploration, plays such as the Upper Jurassic syn-rift play and the deep basin-axis high pressure/high temperature gas condensate play are expected to be the focus of much future activity. For example, the recent giant 'Buzzard' discovery in Upper Jurassic sandstones of the Central North Sea may have oil in place ranging from 800 to 1100 million barrels, making it one of the largest discoveries on the United Kingdom Continental Shelf in the last 25 years. The Lower Cretaceous succession has also been a recent exploration target, and significant discoveries have been reported within the Moray Firth Basin.

*David A Falvey*
*Executive Director*
*British Geological Survey*

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# 1 Introduction

Oil and gas production within the United Kingdom (UK) and its offshore-designated area continued to rise through the 1990s and until recently the UK has been net self-sufficient in both oil and gas. To date, about 4000 exploration and appraisal wells have been drilled on the UK Continental Shelf (UKCS). These wells have resulted in more than 285 producing fields and another 300 plus significant discoveries (Munns, 2002). The Central and Northern North Sea area (Figure 1) is now considered to be a mature hydrocarbon province. However, there remains significant potential for increasing the overall reserves through additional, more focussed, exploration, particularly in sparsely drilled basinal areas and by improving recovery from existing fields. Indeed, petroleum production on the UKCS is no longer dominated by a few large fields, but reflects a trend towards the development of small satellite fields that can be brought on stream using existing host platforms and infrastructure (Department of Trade and Industry, 1999).

The exploration and development of the North Sea has provided, and still provides, a vast amount of detailed information regarding the subsurface geology. This report briefly summarises much that is known about the tectono-stratigraphic development, palaeogeography and petroleum geology of the Brent and Fladen, Humber and Cromer Knoll groups (approximately equivalent to the Middle Jurassic, Upper Jurassic and Lower Cretaceous rocks respectively) within the UK Central and Northern North Sea. It includes three 1:1 000 000 map enclosures that, respectively, illustrate the distribution and thickness of the Brent and Fladen groups, the Humber Group and the Cromer Knoll Group (Enclosures 1, 2 and 3). Representative well sections shown on these enclosures illustrate the typical lithofacies and wireline log responses of the successions. The geographical distribution of the lithostratigraphical units on Enclosures 1–3 is based predominantly on information from released well data held at the Department of Trade and Industry Core Store in Edinburgh. Well data up to 2002 (Release 79) were examined in this study and additional information was also extracted from a few regional 2D seismic profiles (Department of Trade and Industry, 2002).

The Middle Jurassic, Upper Jurassic and Lower Cretaceous successions were, in general terms, formed during the pre-rift, syn-rift and post-rift phases of basin development, respectively (Figures 2 and 3) and all three successions include important reservoir rocks. The Upper Jurassic succession also includes the primary source rocks for the Central and Northern North Sea (i.e. units within the Kimmeridge Clay Formation). The geometry of these successions together with lateral facies changes within them reflects a complex interplay between local tectonism and eustatic sea level fluctuations.

A significant proportion of the remaining hydrocarbon potential within the province is believed to lie within the Upper Jurassic and Lower Cretaceous successions. In particular, the Upper Jurassic syn-rift, Mesozoic basin margin and the deep basin axis high pressure/high temperature gas condensate exploration plays are likely to be the focus of future exploration activity (Munns, 2002). The Mesozoic basin margin play was tested by the giant 'Buzzard' discovery in May 2001, which found oil in Upper Jurassic turbidite sandstones near the western margin of the South Halibut Basin (UK Blocks 19/5S, 20/1S, 19/10 and 20/6; Figures 1, 2) (Doré and Robbins, 2003).

## 1.1 STRUCTURAL DEVELOPMENT

Since the end of the Caledonian Orogeny, the Central and Northern North Sea Basin has occupied an intraplate setting. Early Jurassic strata within the North Sea Basin accumulated during a phase of post-rift subsidence following Permo-Triassic extension (e.g. Faerseth, 1996; Ziegler, 1990). In Mid Jurassic times, the Central North Sea area experienced transient thermal doming, erosion and volcanism, possibly associated with a mantle plume (Underhill and Partington, 1993) (Figure 4). The resulting regional unconformity is commonly termed the 'Mid Cimmerian Unconformity' although in the Central North Sea it covers a much wider timespan (Husmo et al., 2003). Stratigraphical relationships indicate that the uplift was centred upon the North Sea rift triple junction (Figure 4). Although the initial formation of a simple trilete rift junction may have been the result of doming and deflation, subsequent extension during the Mid and Late Jurassic led to the development of a series of intra-rift fault sets (Davies et al., 2001). However, the detailed structural evolution of the region has been a topic of many debates. Rattey and Hayward (1993) and Fraser (1993) proposed that rifting was initially most intense at the extremities of the present graben system and as time elapsed it propagated back towards the centre of the domal uplift. Underhill (1991) and Glennie and Underhill, 1998) suggested that the onset of major rifting probably occurred in mid-Oxfordian to early Kimmeridgian times. However, a number of pulses of Late Jurassic extension have been recognised (e.g. Errat et al., 1999; Davies et al., 1999; Davies et al. 2001).

According to Davies et al. (2001), extension may have been initiated on north–south and north-north-east–south-south-west trending faults (in the South Viking Graben) during the Bathonian and Callovian, on north-east–south-west and east–west structures (in the Moray Firth Basin) during the Oxfordian and on north-west–south-east faults (in the Central Graben and Outer Moray Firth Basin) during the Kimmeridgian and Volgian.

Seismic data reveal that the syn-rift (Upper Jurassic) successions commonly thicken dramatically towards syndepositional faults (Figure 5). This general style of sediment thickness variation is in contrast with the pattern which developed during the post-rift 'thermal sag' and sediment loading phase of basin development during Early to Mid Jurassic times, when the basin was more 'saucer-shaped' and the thickest deposits accumulated at its centre.

Rift styles vary substantially between the Northern and the Central North Sea and there were two principal

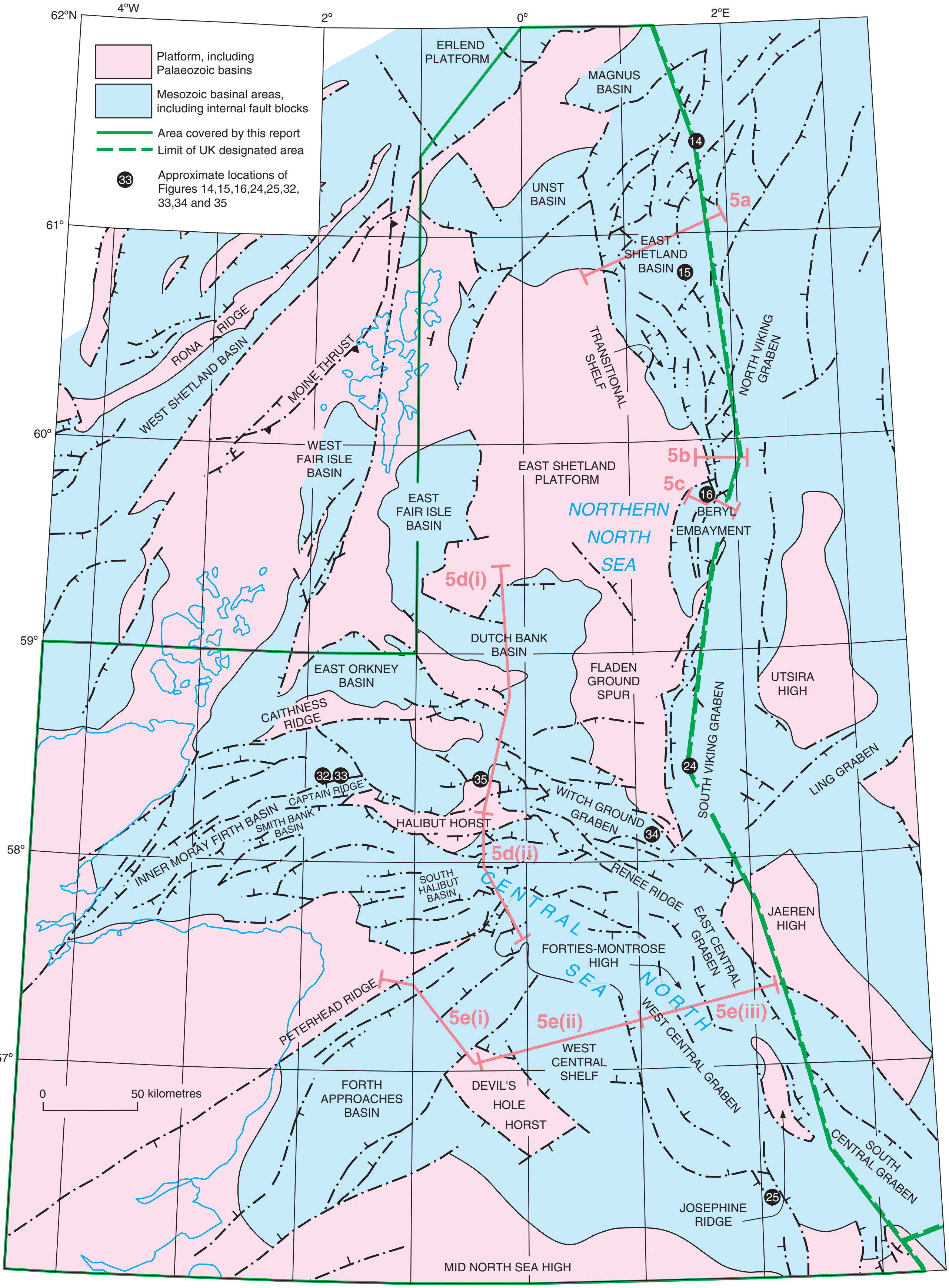


**Figure 1** Structural framework of the Central and Northern North Sea. Approximate locations of cross-sections in Figure 5 as well as Figures 14, 15, 16, 24, 25, 32, 33, 34 and 35 are shown.

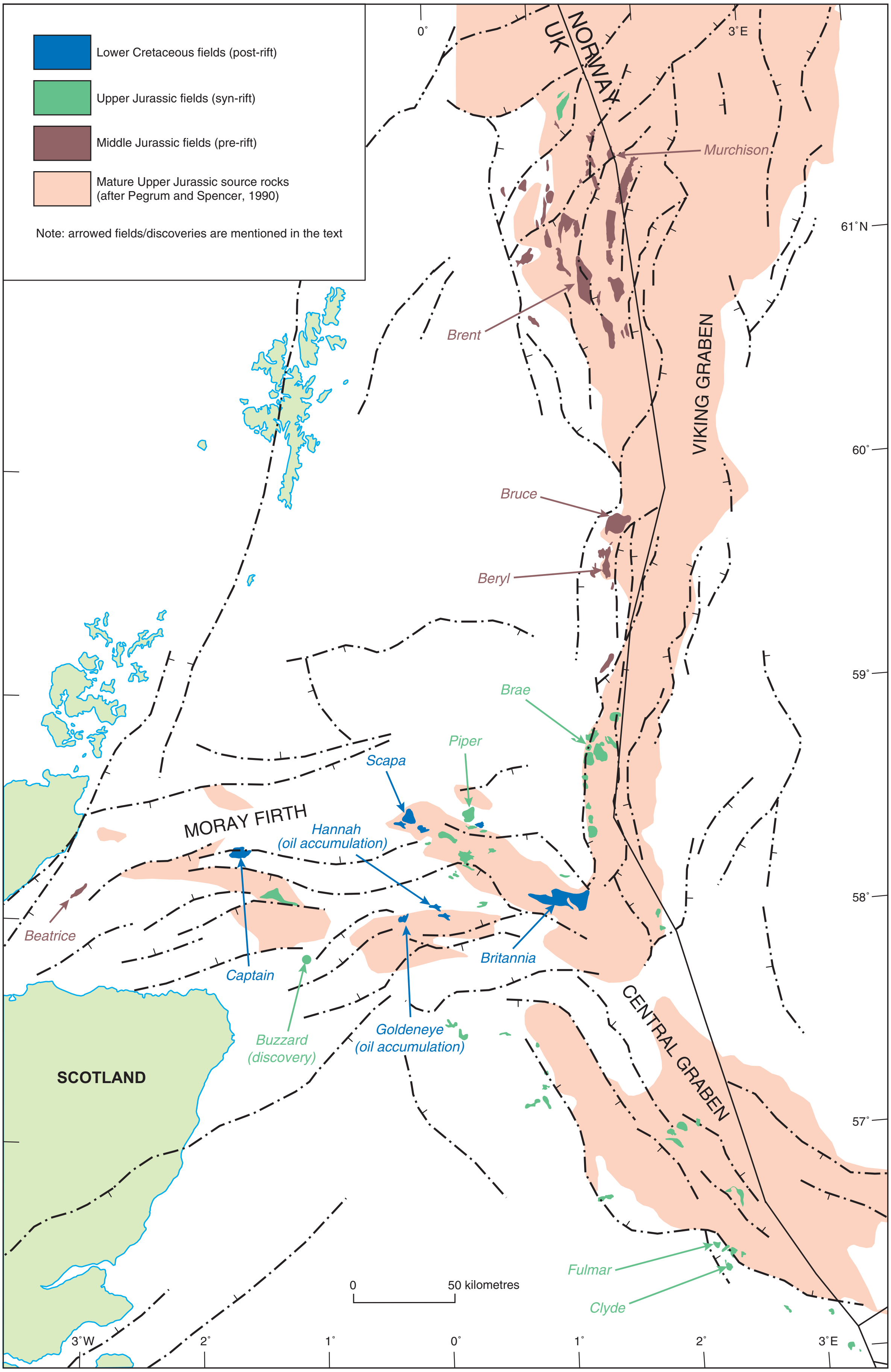


**Figure 2** Location of Central and Northern North Sea hydrocarbon fields in the Middle Jurassic, Upper Jurassic and Lower Cretaceous (after Brooks et al., 2002).

controlling factors. Firstly, differences in the basement composition and tectonic grain between the two regions influenced subsequent structural development. In the Central North Sea, the rifts are more complex and appear to be segmented along both north-east–south-west 'Caledonide' and north-west–south-east 'Trans-European Fault Zone' trends (e.g. Errat et al., 1999; Jones et al., 1999). Secondly, in the Northern North Sea, Upper Permian salt is largely absent, and there is no major detachment between basement and cover rocks. In the East Shetland Basin, for example, deep seismic reflection profiles suggest domino-style rotation of large crustal fault blocks (Figure 5a) (Klemperer and White, 1989). In contrast, the Zechstein evaporites in the Central North Sea provide a major detachment level that essentially separates the basement from the cover succession or 'carapace' (e.g. Hodgson et al., 1992; Smith et al., 1993; Helgeson, 1999).

In the Northern North Sea, uplift of the footwall blocks by extensional faults led in many cases to pronounced erosion and fault-scarp degradation (Underhill et al., 1997; McLeod and Underhill, 1999). Indeed, much of the oil remaining in the Middle Jurassic fields of the East Shetland Basin may lie within such degradation complexes (Underhill, 1999). It should also be noted that many of the major faults probably grew through linkage of originally isolated segments, rather than by simple radial propagation. Pronounced changes in fault strike, displacement minima and transverse hanging-wall highs are commonly inferred to represent palaeosegment boundaries that subsequently became breached and incorporated into an extensive fault zone (e.g. Peacock and Sanderson, 1991; McLeod et al., 2000). A consequence of fault growth by segment linkage is that transfer zones/relay ramps at segment boundaries are transient features (Jackson et al., 2002).

The amount of Late Jurassic extension experienced by the North Sea Basin has been a controversial subject, though beta factors of 1.1–1.2 are supported by backstripping and other structural analyses (e.g. Roberts et al., 1993). Within the graben axes, Late Jurassic beta factors may rise to 1.4–2.0 (Glennie and Underhill, 1998). Similarly, the orientation of Late Jurassic extensional stress and the amount of oblique and strike-slip movement has been a contentious issue. The majority of the evidence presented in support of significant strike-slip movement has been 2D and 3D seismic data over the Central Graben (Bartholomew et al., 1993; Sears et al., 1993; Eggink et al., 1996). However, recent interpretations have tended to emphasise multiple phases of differently orientated dip-slip extension (Underhill, 1999; Davies et al., 2001) rather than oblique-slip.

The degree to which North Sea extensional tectonism continued into Early Cretaceous times has also been the subject of debate. In a recent study of the Northern North Sea, Gabrielsen et al. (2001) commented that the syn- to post-rift transition is unlikely to occur simultaneously throughout the entire basin, due to differences in structural configurations and thermal inhomogeneities associated with variable stretching along and transverse to the basin axis. Over most of the graben system, major rifting is thought to have ended in the late Volgian (Rattey and Hayward, 1993). The rifting might have created a bathymetric relief of up to 2 km, which persisted well into Cretaceous times. However, there appears to be evidence that tectonic uplift and erosion of North Sea fault blocks persisted intermittently into Early Cretaceous times, particularly within parts of the Moray Firth area, and may have influenced the depositional pattern of mass-flow clastics. For example, the Lower Cretaceous Scapa Sandstone Member, which forms an important oil reservoir in the Scapa Field, has been described as a syn-rift deposit (Harker and Chermak, 1992; Harker and Rieuf, 1996). However, Argent et al. (2000) regarded the Lower Cretaceous succession of the Moray Firth Basin as essentially post-rift in character with only local evidence for continued extensional faulting. In contrast, Oakman and Partington (1998) proposed that the transition from the Late Jurassic Humber Group to the Early Cretaceous Cromer Knoll Group represents a change in tectonic style, from mainly transtension in the Jurassic to dominantly transpression in the Early Cretaceous.

| TECTONIC PHASE | AGE |
|---|---|
| Thermal subsidence and pulses of transpression | Cretaceous |
| Second phase of major rifting | Bathonian to Volgian |
| Thermal subsidence and build up and deflation of Central North Sea thermal dome | Toarcian to Bajocian |
| Thermal subsidence | Early Jurassic to Mid - Jurassic |
| Initial phase of major rifting | ?Late Permian and ?Early Triassic |

**Figure 3** Generalised tectonic phases of the Central and Northern North Sea.

Local inversion of Central North Sea depocentres during the Early Cretaceous is commonly considered to be a response to oblique-slip faulting (e.g. Pegrum and Ljones, 1984; Ineson, 1993). Ziegler (1990) mapped many of the Cretaceous inversion axes within the North Sea Basin, most of which trend either west-north-west or east-north-east. Compressional events in early Ryazanian, Valanginian, mid-Hauterivian and mid-Barremian times are thought to reflect north-south compression associated with either Tethyan sea-floor spreading or rifting in the Bay of Biscay (Oakman and Partington, 1998). A compressive pulse in the mid-Aptian was possibly associated with Tethyan closure and Alpine orogenesis. This tectonic event has commonly been referred to as the 'Austrian Orogeny', though the associated unconformity is weakly developed within the Central and Northern North Sea. The transpressional pulses are believed to have triggered the halokinesis of Zechstein salts within the Central Graben, which exerted an additional strong control on patterns of subsidence and sedimentation (Oakman and Partington, 1998; Gatliff et al., 1994).

In contrast to much of the North Sea Basin, the Magnus Basin in the Northern North Sea experienced strong, down to the north-west rifting in Early Cretaceous times, associated with opening of the North Atlantic (Rattey and Hayward, 1993). A thick syn-rift wedge of coarse clastics of mainly Valanginian age is developed on the downthrow side of the so-called 'End-of-the-World-Fault' (Nelson and Lamy, 1987) at the south-eastern boundary of the Magnus Basin.

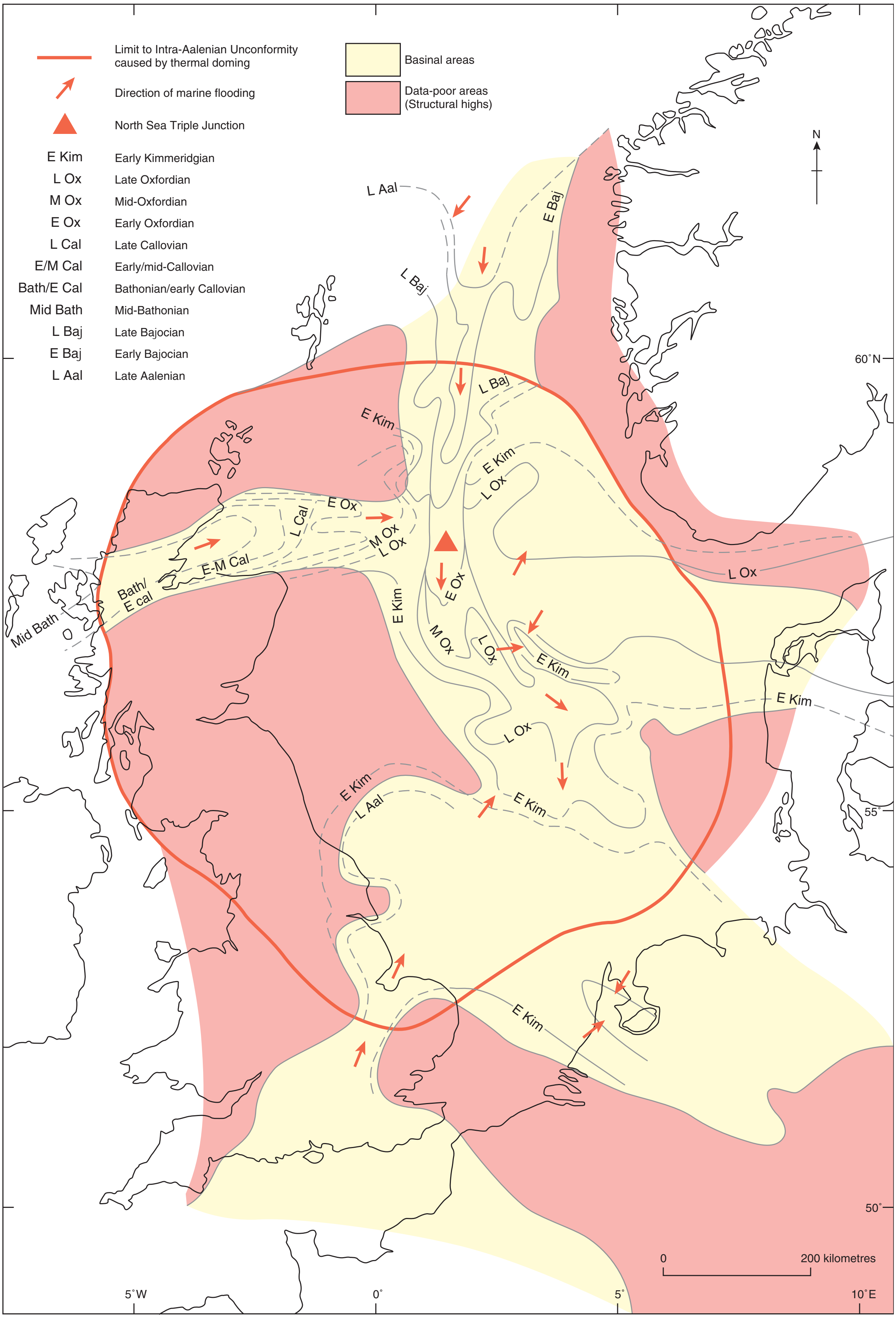


**Figure 4** Approximate extent of the 'Mid-Cimmerian Unconformity' due to transient domal uplift and the pattern of subsequent marine onlap onto the unconformity (after Underhill and Partington, 1993; Underhill, 1998).

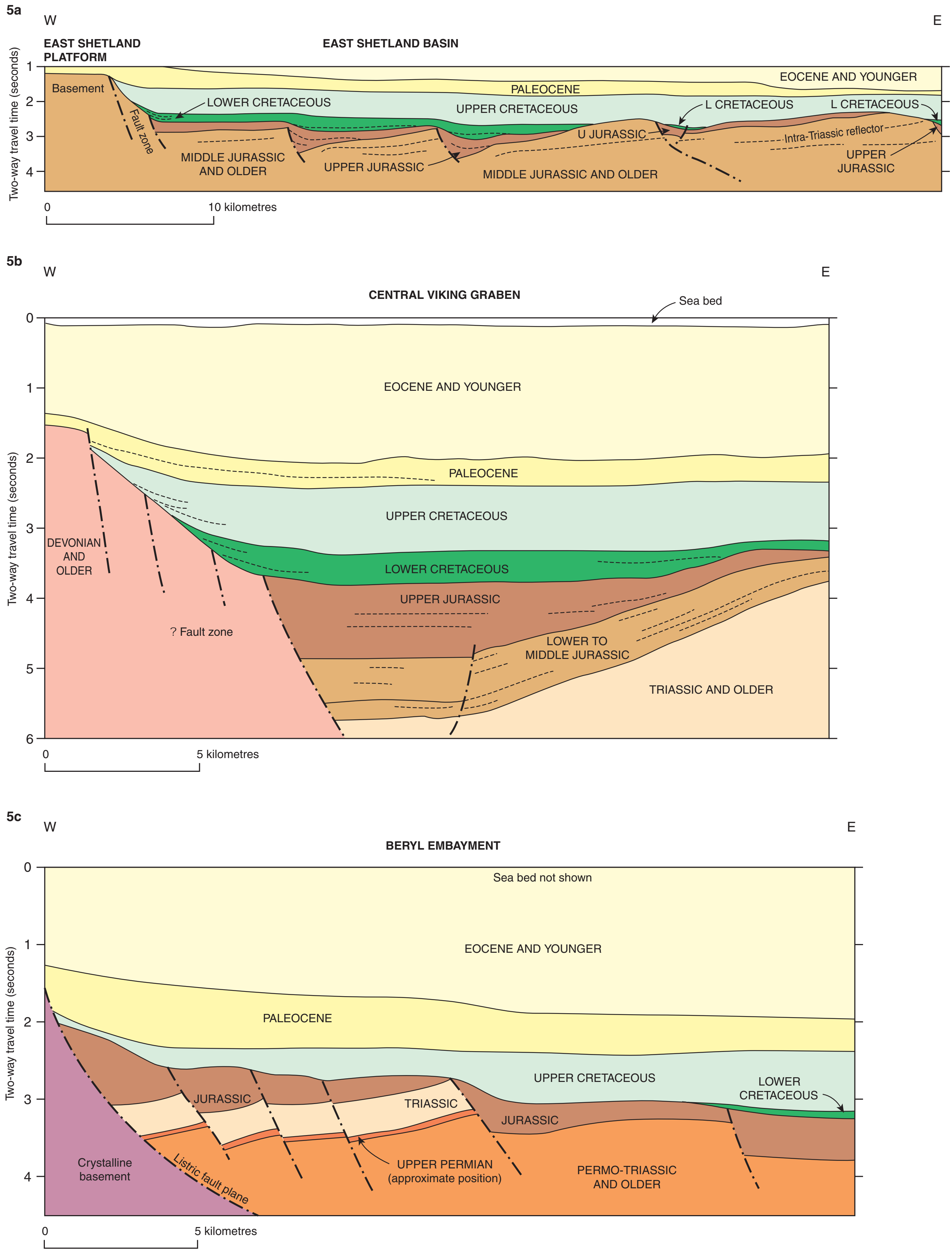


**Figure 5** Generalised cross-sections across the Central and Northern North Sea; locations are given in Figure 1 (after Andrews et al., 1990; Gatliff et al., 1994 and Johnson et al., 1993).

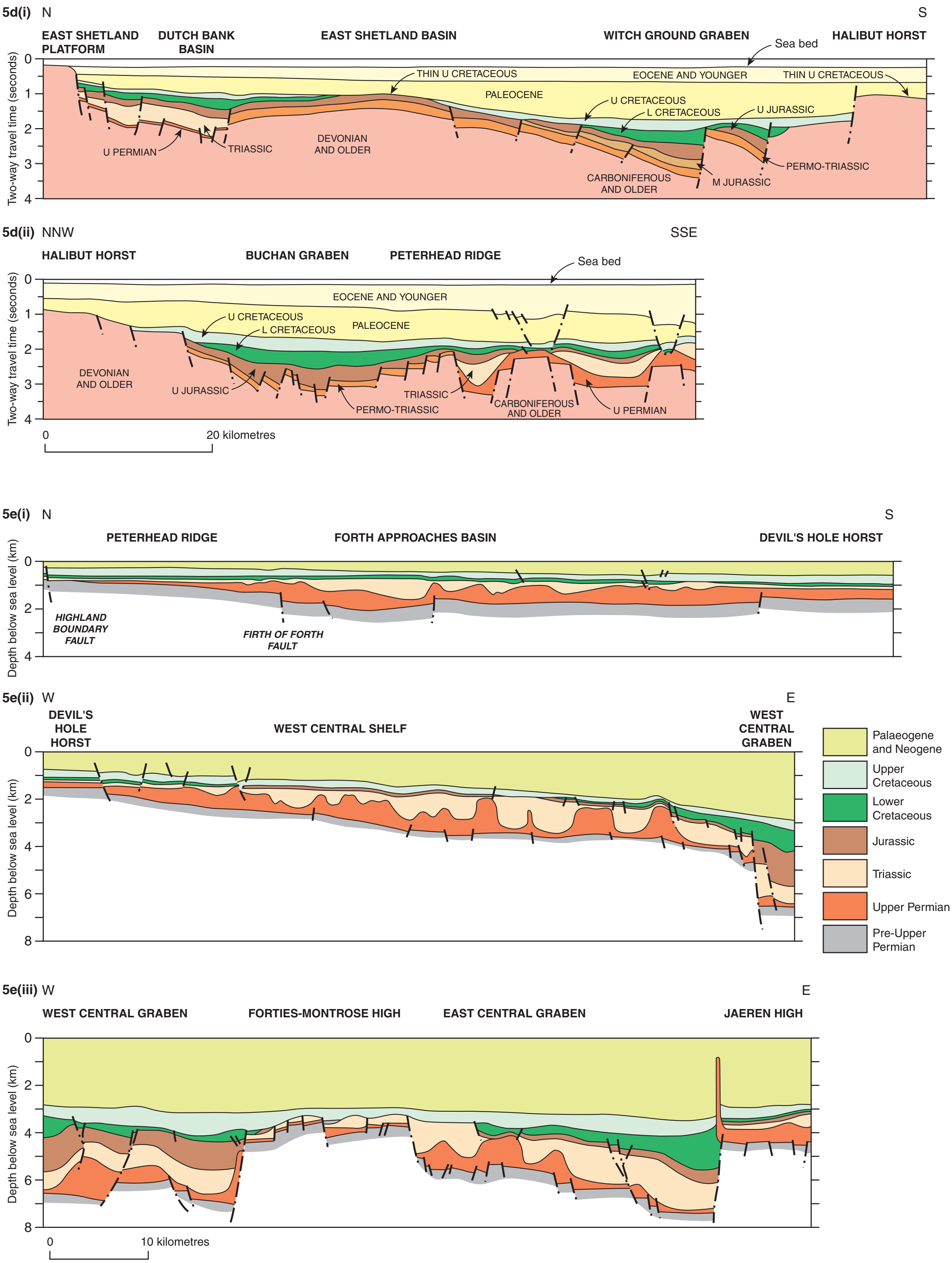


**Figure 5** *Continued.*

## 1.2 STRATIGRAPHIC TEMPLATES

Within the North Sea Basin, a sound understanding of stratigraphy is vital for exploration success, particularly during the current mature phase of exploration, when the remaining lightly tested plays are subtle and at the limit of seismic resolution (Boldy and Fraser, 1999). Early stratigraphic schemes were dominated by lithostratigraphy and a number of contrasting formal national nomenclature schemes for the North Sea Basin have been proposed (e.g. Deegan and Scull, 1977; Vollset and Doré, 1984; Isaksen and Tonstad, 1989; Jensen et al., 1986; Knox and Cordey 1992–94). Over the last decade, sequence stratigraphy techniques have been applied increasingly to improve understanding of the temporal and spatial distribution of reservoir units.

The merits of sequence stratigraphy compared with lithostratigraphy within the North Sea Basin have been debated, and several schools of thought exist. Partington et al. (1993b) advocated the complete abandonment of lithostratigraphy in favour of sequence stratigraphy. In contrast, Price et al. (1993) proposed a lithostratigraphical nomenclature that is based in large part on chronostratigraphy, with formations and members restricted to narrowly defined age ranges. However, Veldkamp et al. (1996) suggested that, in addition to sequence stratigraphy, lithostratigraphical nomenclature with little or no chronostratigraphical connotations (e.g. Richards et al., 1993) is needed for practical reasons, such as communication with non-specialists, particularly during operational decision making, when few biostratigraphical data are available.

Various sequence stratigraphic templates have been proposed and all are calibrated by high-resolution biostratigraphy. However, some difficulties have been encountered regarding inconsistent definition of species due to the vintage of analysis and the degradation of palynomorphs caused by the great depth of burial and high thermal maturity (Jeremiah and Nicholson, 1999).

A key element of sequence stratigraphic schemes for the North Sea Basin has been the recognition of widespread condensed sections of marine mudstone that are interpreted as essentially isochronous maximum flooding surfaces. The maximum flooding surfaces contain a rich and diverse microflora and fauna, and are commonly associated with significant authigenic mineral growth, including glauconite and phosphate, and concentrations of radioactive minerals which often result in prominent high gamma-ray spikes on wireline logs. The flooding surfaces are also important in many oil fields where they commonly form permeability barriers.

An important stratigraphic template for the North Sea Jurassic was proposed by Partington et al. (1993a, b), who named each maximum flooding event by reference to the standard ammonite biozonation scheme. However, recent papers suggest that it may be preferable to define these events by their diagnostic dinocyst extinction event (Underhill, 1998; Veldkamp et al., 1996; Jeremiah and Nicholson, 1999). Within the Jurassic succession, it has commonly proved easier to recognise these key surfaces, rather than sequence boundaries marked by unconformities and their correlative conformities, as favoured by Vail and his co-workers (e.g. van Wagoner et al., 1990). Consequently, the Jurassic sequence stratigraphic scheme of Partington et al. (1993a, b) subdivided the succession into (third-order) genetic sequences in the sense of Galloway (1989). These genetic sequences are grouped together into (second-order) tectono-stratigraphic cycles that were probably controlled by large-scale tectonic processes.

Largely on the basis of data provided by British Petroleum, Oakman and Partington (1998) outlined a prototype sequence stratigraphy for the Lower Cretaceous of the North Sea Basin. This scheme utilises three integral approaches: the unconformity (sequence boundary) seismo-stratigraphy techniques of Vail et al. (1984), the maximum-flood (isochron) techniques, typified in Galloway (1989) and the synchronous plate-wide stress models of Cloetingh (1988). Utilising similar techniques, Jeremiah (2000) described a sequence stratigraphical framework for the Lower Cretaceous of the Moray Firth Basin that is broadly compatible with the scheme of Oakman and Partington (1998). Jeremiah (2000) commented that the concept of 'Vailian' stratigraphy is difficult to apply in the Lower Cretaceous of the Moray Firth Basin, because the facies are dominated by basinal mudstone units and consequently shoreface progradation/retrogradational stacking patterns cannot be followed. He considered the sequences within his scheme to be tectonic sequences with little calibration to eustatic sea-level changes.

Major revisions of genetic sequence stratigraphic templates have been carried out recently for the Upper Jurassic (Fraser et al., 2003) and Lower Cretaceous (Copestake et al., 2003) in The Millennium Atlas (Evans and Graham, 2003).

# 2 Brent and Fladen Groups ('Middle Jurassic')

## 2.1 INTRODUCTION

The Middle Jurassic of the Central and Northern North Sea contains one of the most significant hydrocarbon reservoirs in the North Sea, the Brent Group. Middle Jurassic hydrocarbon fields in the Beryl Embayment and Inner Moray Firth Basin are also significant and, although the play is mature, exploration is still active (Husmo et al., 2003).

## 2.2 LITHOSTRATIGRAPHY

In the scheme of Richards et al. (1993) the Middle Jurassic rocks (Figure 6) are assigned essentially to the Brent and Fladen groups, though, in addition, the lower part of the Humber Group is commonly of Middle Jurassic age. The Brent and Fladen groups are themselves divided into their component formations. Along the coast of the Inner Moray Firth Basin at Brora are exposed the Brora Argillaceous and Brora Arenaceous formations, which are laterally equivalent to the Fladen Group strata within the offshore basin.

The distribution and thickness of the Brent and Fladen groups, together with the well log character of selected formations, are summarised on Enclosure 1.

### 2.2.1 Brent Group

The Brent Group makes up the most important hydrocarbon reservoir sequence within the North Sea Basin. The group is geographically restricted to the East Shetland Basin and comprises, in ascending order, the **B**room, **R**annoch, **E**tive, **N**ess, and **T**arbert formations. These formations comprise a broadly regressive-transgressive wedge of diachronous coastal and shallow marine sediment and reflect the outbuilding and retreat of a major wave-dominated delta largely fed from the south (Budding and Inglin, 1981; Johnson and Stewart, 1985).

The **Broom Formation** is of Aalenian age and comprises up to 50 m of marine sandstone and conglomeratic sandstone with mudstone clasts. The formation is interpreted as a fan delta deposit (Graue et al., 1987).

The **Rannoch Formation** is of late Aalenian to early Bajocian age and consists of up to 100 m of upward-coarsening mudstone to fine-grained micaceous sandstone. The formation is interpreted as a marine offshore to middle shoreface deposit that formed under the influence of storms.

The **Etive Formation** is probably of late Aalenian to early Bajocian age and comprises up to 40 m of massive, clean, cross-bedded sandstone which formed in a barrier-bar/delta-front setting that was transected by channels.

The **Ness Formation** is probably of Bajocian age and comprises up to 180 m of interbedded sandstone, siltstone, mudstone and coal seams that formed in a delta-top setting. The Ness Formation is commonly subdivided into three component parts: a lower interbedded unit, the mid-Ness Shale and an upper interbedded unit.

The **Tarbert Formation** is probably of late Bajocian to Bathonian age. It consists of up to 75 m of sandstone with subordinate siltstone, mudstone and coal seams that mainly formed in a transgressive shallow marine setting. The Tarbert sandstone units are markedly time-transgressive and reflect a pulsed, southerly directed marine transgression that eventually drowned the Brent Delta. The Tarbert Formation may be separated from the underlying Brent Group formations by an unconformity that reflects the early stages of rifting (Underhill et al., 1997).

### 2.2.2 Fladen Group

The Fladen Group comprises the Pentland, Brora Coal, Beatrice and Hugin formations.

The **Pentland Formation** is Toarcian–mid-Oxfordian in age, but is commonly only assigned to the Bathonian. The formation is distributed over the Beryl Embayment, South Viking Graben, Central Graben, Outer Moray Firth Basin and Unst Basin and consists of up to 1200 m of interbedded sandstone, siltstone, mudstone and coal seams, with locally significant volcanics (tuff, lava and intrusive rocks) within the Rattray and Ron Volcanics members. The lavas comprise undersaturated porphyritic, alkali olivine basalt (Dixon et al., 1981; Fall et al., 1982). The Pentland Formation is interpreted as paralic to delta plain deposits and the products of volcanic centres.

The **Stroma Member** of the Pentland Formation is a problematic sequence of mid-Oxfordian sediments that is assigned to the Fladen Group on the basis of lithological characteristics, but is interpreted to mark the start of the Late Jurassic transgression.

The Stroma Member is recognised in the Outer Moray Firth Basin and comprises up to 40 m of interbedded sandstone, carbonaceous mudstone and coal seams of mid-Oxfordian age (Richards et al., 1993). It generally rests unconformably on much older Pentland Formation sediments and volcanics (Rattray Volcanics Member) or Permo-Triassic sediments. The member was deposited in paralic, deltaic and lagoonal environments and represents the drowning of a peneplaned surface during the mid-Oxfordian.

The **Brora Coal Formation** is of Bajocian to early Callovian age and is geographically restricted to the Inner Moray Firth Basin. The formation consists of up to 180 m of interbedded mudstone, sandy mudstone, sandstone and coal seams that are interpreted as alluvial flood plain deposits.

The **Beatrice Formation** is of early to mid-Callovian age and is geographically restricted to the Inner Moray Firth Basin. The formation comprises up to 60 m of sandstone interbedded with subordinate mudstone that formed in marine barrier bar and offshore bar environments. The precise nature of the westward passage from Beatrice Formation facies to the **Brora Argillaceous Formation** facies (see below) remains uncertain.

The **Hugin Formation** is largely of late Bajocian to Bathonian age, but locally may range up to Callovian/Oxfordian age. The formation is distributed over the Beryl Embayment, South Viking Graben and the Unst Basin and comprises up to 300 m of sandstone, siltstone and mudstone with minor coal seams and conglomerate. It is interpreted as having formed in storm influenced coastal barrier to shoreface/offshore settings.

### 2.2.3 Onshore formations

The **Brora Argillaceous Formation** is of early to late Callovian age and consists of up to 89 m of bituminous mudstone, sandy siltstone and muddy and silty glauconitic sandstone, that are interpreted to have formed in a shallow marine environment (Andrews et al. 1990).

The **Brora Arenaceous Formation** is of late Callovian to early Oxfordian age and comprises more than 56 m of bioturbated, muddy sandstone and yellow, fine-grained sandstone with lenticular conglomerate. These rocks probably represent the deposits of migrating bars on a shallow marine shelf (Andrews et al., 1990).

## 2.3 SEQUENCE STRATIGRAPHY

Sequence stratigraphy studies within the Central and Northern North Sea have divided the Middle Jurassic into nine genetic stratigraphic units (termed J22, J24, etc) based on the recognition of ten maximum flooding surfaces or marine condensed horizons (Figure 7) (Mitchener et al., 1992; Partington et al., 1993a, b). Each genetic stratigraphic unit records an individual progradational pulse. A correlation diagram along the axis of the Viking Graben (Figure 8) illustrates the relationship between Jurassic chronostratigraphy, genetic sequence stratigraphy and lithostratigraphy and the truncation and onlap patterns associated with thermal doming and the 'Mid-Cimmerian Unconformity' (Figure 4).

## 2.4 PALAEOGEOGRAPHY

Two palaeogeographic reconstructions have been proposed for the Middle Jurassic of the Central and Northern North Sea. The more traditional model is that sediment was shed off an eroding volcanic dome in the Central North Sea and that delta systems prograded radially from here along the axes of the proto-Viking Graben, Moray Firth Basin and the Central Graben. However, thickness and grain size trends, heavy mineral analyses, age relations between the sediments and the volcanics, and facies analysis in the Beryl Embayment suggest that an additional source for the Middle Jurassic of the Northern North Sea lay on the adjacent platforms and basin margins (e.g. Morton, 1992).

From late Toarcian to early Aalenian times, large areas of the Central North Sea were affected by transient regional uplift associated with the Central North Sea Dome (Underhill and Partington, 1993; 1994). The rise of the dome centre probably continued until Bathonian to early Callovian times, though deflation of the dome margins may have commenced in the Aalenian to Bajocian. The regional uplift has resulted in a widespread stratigraphic break, known as the 'Mid-Cimmerian Unconformity', which is apparent from the North Viking Graben to the Southern North Sea and from the Moray Firth Basin to the Ringkøbing-Fyn High; the subcrop to this

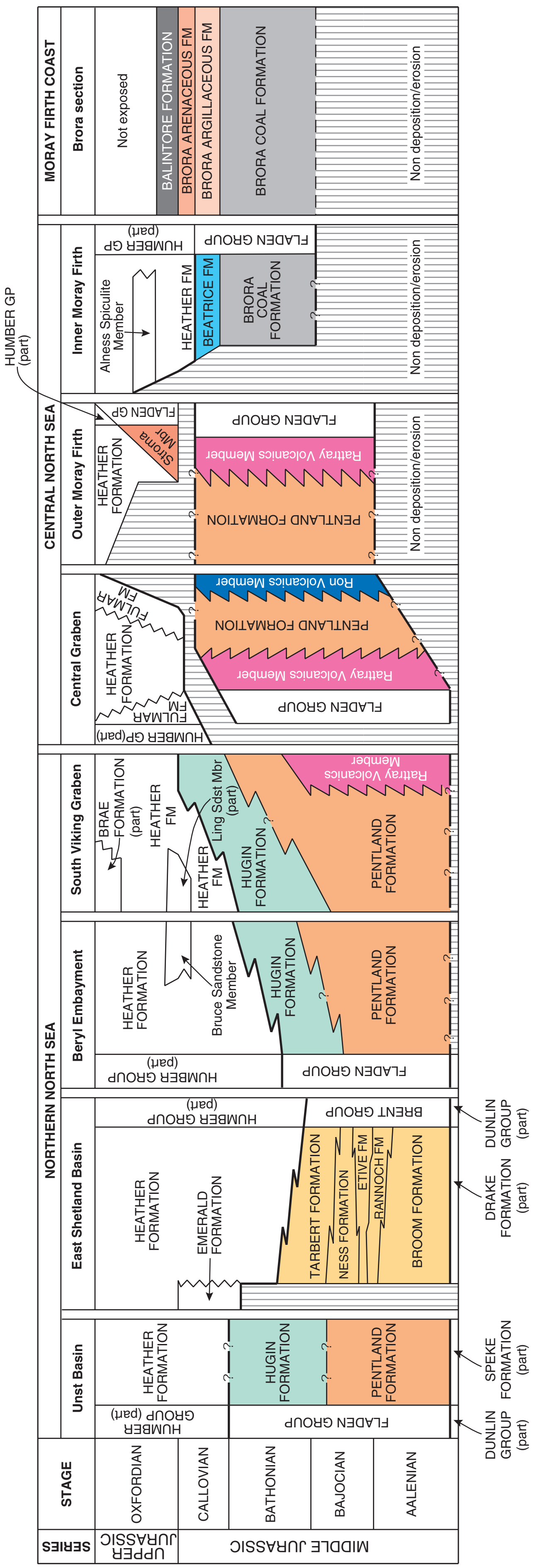


**Figure 6** Brent and Fladen groups (Middle Jurassic) lithostratigraphy (after Richards et al., 1993).

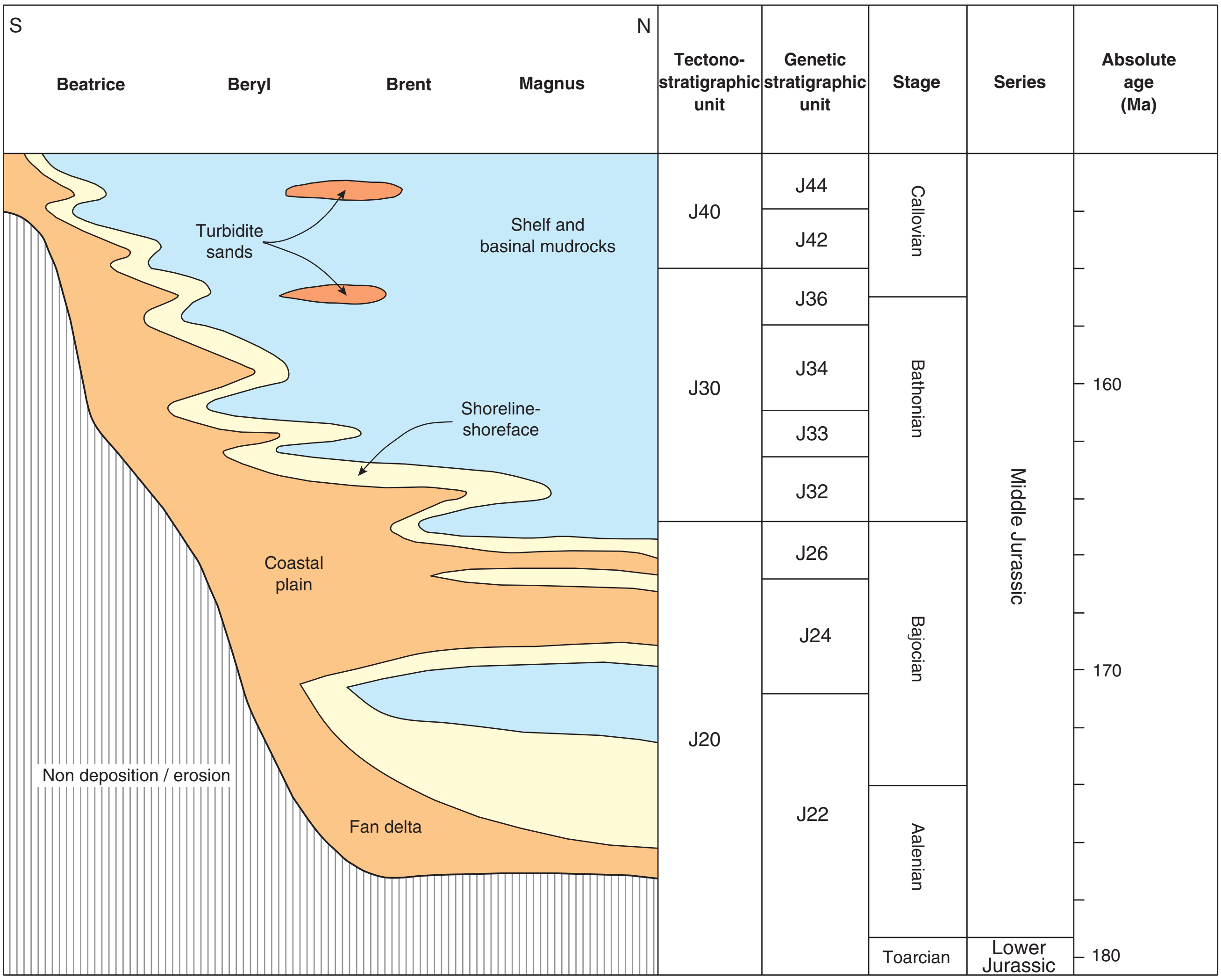


**Figure 7** Generalised Middle Jurassic genetic stratigraphical sequences in the Northern and Central North Sea (after Partington et al., 1993b).

unconformity is broadly circular to elliptical (Figure 4) (Underhill and Partington, 1993, 1994). Estimates of the amount of topographic relief on the dome have varied considerably and range up to 2.5 km (Ziegler and Van Hoorn, 1989). However, a relatively low-lying, though highly variable relief is considered to be a more likely scenario (Underhill, 1998). The pattern of marine onlap onto the 'Mid-Cimmerian Unconformity' highlights the progressive nature of marine transgression down the incipient Viking and Central grabens and across the Moray Firth Basin (Figures 4, 8). Erosion of the exhumed Triassic to Lower Jurassic sedimentary succession led to a major progradation of fluvial-deltaic clastic successions, including those of the Brent Group in the East Shetland Basin. The Middle Jurassic palaeogeographic/palaeofacies development of the Central and Northern North Sea is summarised in Figure 9, which is based on Mitchener et al. (1992).

### 2.4.1 Aalenian

By the end of Early Jurassic times, deposition was restricted to the East Shetland Basin (Figures 1, 8). During the Aalenian, large areas of the Central North Sea experienced domal uplift. Coastal plain sedimentation (lower Pentland Formation) began in the South Viking Graben and Beryl Embayment and further north, in the East Shetland Basin, Broom Formation fan deltas were shedding material off the Shetland Platform. At the end of the Aalenian, Rannoch Formation shelf deposits transgressed rapidly over most of this northern area with a mud-prone shelf (Rannoch mudstone) developing in the extreme north-east.

### 2.4.2 Early Bajocian

During Bajocian times, the sea regressed northwards, taking with it the Rannoch-Etive Formation shoreline and associated shoreface facies belts. By the end of the early Bajocian, a coastal plain (lower Ness Formation) covered most of the East Shetland Basin. Further south, condensed sequences were formed in the Beryl Embayment.

### 2.4.3 Late Bajocian

A major late Bajocian flooding event, marking the base of the mid-Ness Shale, represents the first pulse of a forthcoming transgression. Sedimentation then continued much as in the early Bajocian with fluvial sedimentation (Ness Formation) over much of the East Shetland Basin and deposition of the Pentland Formation resuming in the Beryl Embayment. Non-marine sedimentation of the Pentland Formation may have started in the Outer Moray Firth Basin and Central Graben by this time. It was possibly from mid-Bajocian times that the

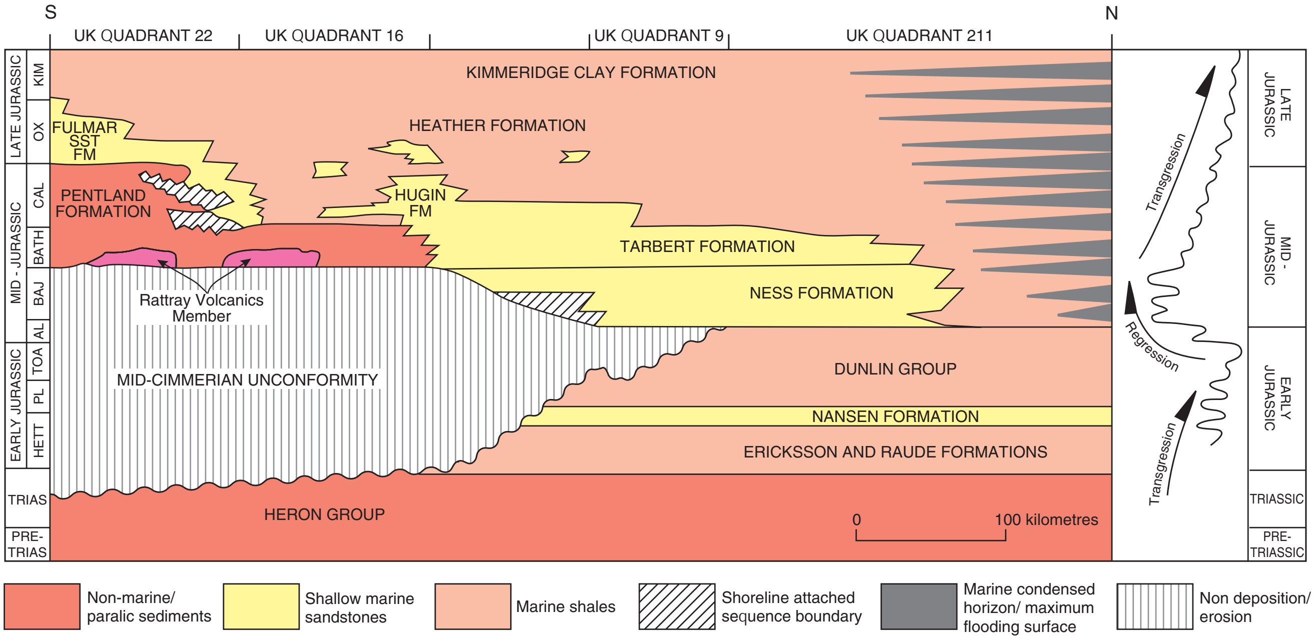


**Figure 8** Generalised correlation of Jurassic chronostratigraphy, genetic sequence stratigraphy and lithostratigraphy along the axis of the Viking Graben (after Underhill and Partington, 1993).

Hugin Formation transgressed south from the Beryl Embayment to the northernmost South Viking Graben and also into the Unst Basin.

### 2.4.4 Bathonian

A transgression brought marine conditions into the East Shetland Basin and Beryl Embayment and sandstone units of the Hugin Formation continued to transgress southwards. Coastal plain deposits (Pentland Formation) extended south into the southern Viking Graben and Central North Sea. In parts of the Outer Moray Firth Basin and Central Graben, volcanic centres were active. Paralic sedimentation (Brora Coal Formation) began in the Inner Moray Firth Basin. By the end of Bathonian times, marine mudstone (Heather Formation, Humber Group) had transgressed into the East Shetland Basin and Beryl Embayment.

### 2.4.5 Mid-Callovian

By earliest Callovian times, marine mudstone deposition (Heather Formation) covered much of the Northern North Sea. The belt of shallow marine sands was restricted to the southern Viking Graben (Hugin Formation), the Inner Moray Firth Basin (Beatrice Formation) and the northern Central Graben (lowermost Fulmar Formation, Humber Group). Non-marine sedimentation (Pentland Formation) continued across much of the Central Graben and Outer Moray Firth Basin. Later, marine mudstone deposition (Heather Formation) spread further south into the southern Viking Graben and Inner Moray Firth Basin. Some turbiditic sands of latest Callovian age were deposited in the southern Beryl Embayment and northern Viking Graben — forerunners of the processes that were going to dominate in the Late Jurassic.

### 2.4.6 Volcanic centres

Smith and Ritchie (1993) used well data, seismic reflection profiles and potential field data to identify four Jurassic volcanic centres in the Central North Sea (Figures 9, 10) that are assigned to the Forties Volcanic Province. Three of these centres (whose volcanic deposits are assigned to the Rattray Volcanics Member) occur at the North Sea rift triple junction (Figure 10). A smaller volcanic centre, whose deposits form the Ron Volcanics Member, exists to the south on the western margin of the West Central Graben. The volcanic centres comprise piles of extrusive, mildly undersaturated, porphyritic alkali basalt (ankaramite) with associated hawaiite and mugearite that reach up to 1500 m in thickness. The lavas were extruded onto land (they are lateritised) and are associated with volcaniclastic sediments on the flanks of the vents. Distally, these strata are interbedded with fluvio-deltaic and paralic sediments.

Dating of the volcanism has been a contentious issue. Radiometric age dates led Smith and Ritchie (1993) to invoke a complex history of igneous intrusion and local uplift spanning Aalenian to Callovian times. However, Underhill (1998) considered it premature to rely on radiometric ages without supporting evidence from volcanic outfall and suggested that the stratigraphical evidence implies a Bathonian to Callovian age (from approximately 160 to 150 Ma) for the volcanism. The timing of Mid Jurassic volcanism relative to Late Jurassic rifting is consistent with a model of active rifting associated with a mantle plume (Houseman and England, 1986), rather than a passive rifting model which requires coeval stretching and volcanism (e.g. McKenzie, 1978).

## 2.5 DEPOSITIONAL ENVIRONMENTS AND RESERVOIRS

Middle Jurassic reservoirs commonly take the form of delta systems that prograded radially up the proto-graben arms from the North Sea rift triple junction, though some deltaic sediments also prograded east from the Shetland Platform to form part of the Brent Delta (Figure 11).

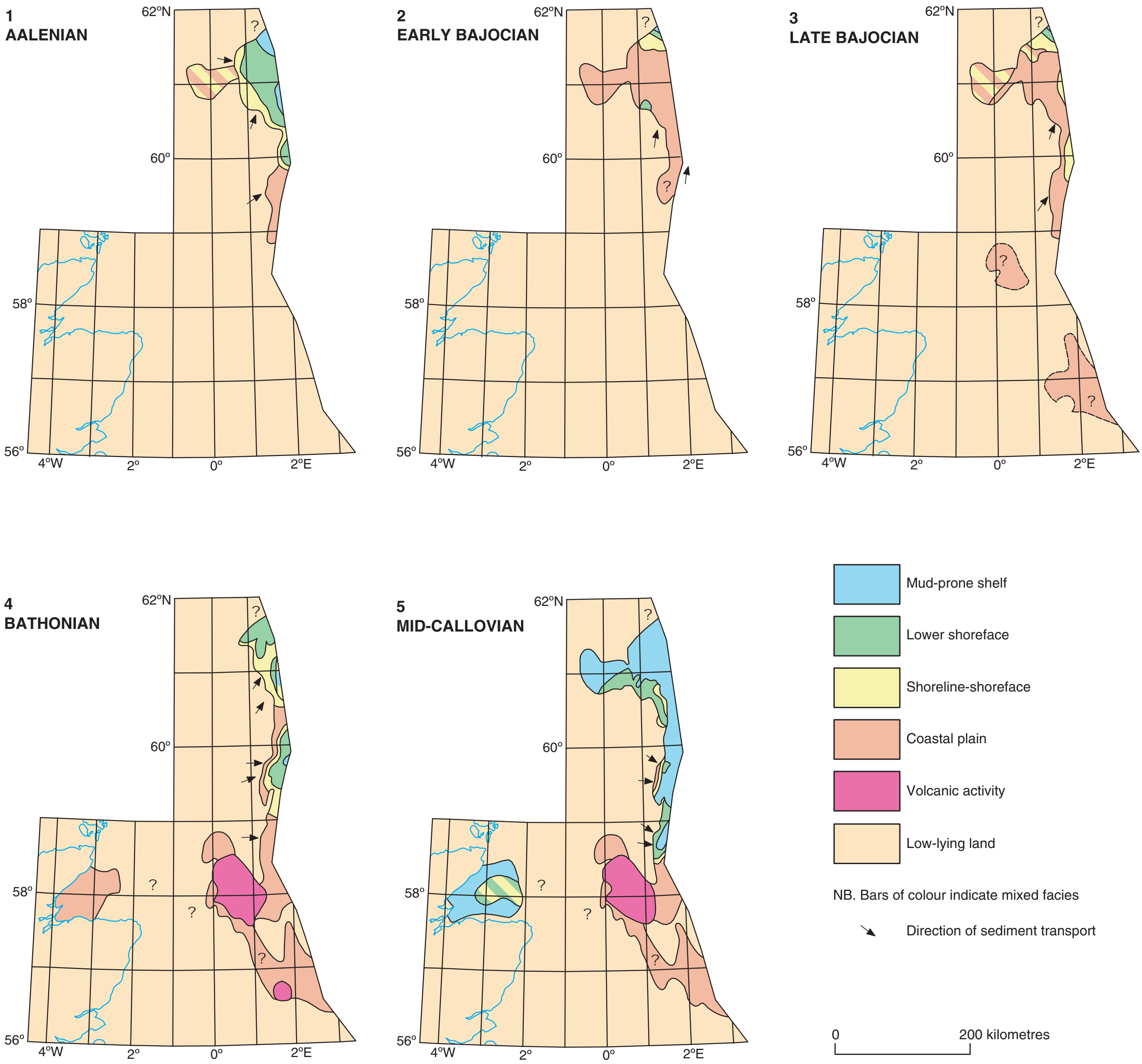


**Figure 9** Mid Jurassic palaeogeography (after Mitchener et al., 1992).

Environmental interpretations for the Brent and Fladen groups are shown in Figure 12.

The Brent Group comprises one of the principal reservoir units within the North Sea. The initial porosity of Brent Group sandstones might have been 35% to 50%, but this was significantly reduced during burial by a combination of compaction and cementation (Figure 13) (Morton et al., 1992). Net reduction in porosity is normally 2.5 to 3.2% for each 330 m of burial, but anomalies are common. For example, over-pressure in the Middle Jurassic of the Viking Graben is probably a major factor in inhibiting porosity reduction due to burial diagenesis. In addition, there is debate as to whether the early emplacement of hydrocarbons into the pores suspended diagenesis. Several studies do not support this theory and suggest that illite continues to grow preferentially below an oil-water contact.

The major pore-filling diagenetic phases within the Brent Group comprise carbonate, kaolinite (vermicular and blocky forms), illite and authigenic quartz; these all have an important effect on reservoir evaluation and performance. Carbonate cements can be detrimental to permeability when forming concretions or cemented horizons. Fibrous illite, the product of vermicular kaolinite diagenesis below 3200 m, can have a negative effect on reservoir properties, especially permeability. Secondary porosity, generated during diagenesis by the dissolution of feldspar and carbonate, is a further complication, but is typically associated with the nearby precipitation of authigenic quartz and kaolinite/illite such that in general the net porosity of a reservoir is not increased, rather redistributed.

The sequence of diagenetic events is often comparable between reservoirs irrespective of the original lithofacies and geographical location. In general, early diagenesis reflects changes in porewater chemistry at shallow depths whilst later the reactions are largely isochemical and controlled by deeper burial and increasing temperature.

In the Outer Moray Firth Basin, paralic sandstone units of the mid-Oxfordian **Stroma Member** (Pentland Formation, Fladen Group) locally form secondary hydrocarbon reservoirs (e.g. parts of the Piper Field).

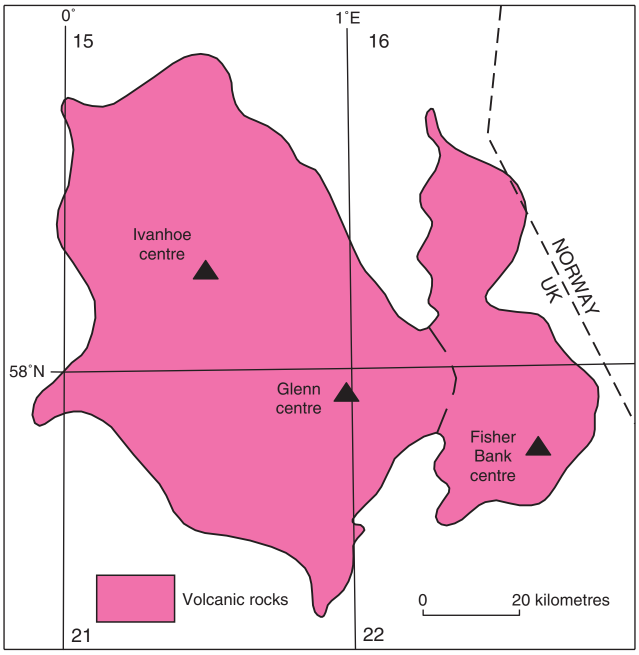


**Figure 10** Simplified map of the Rattray Volcanics Member of the Forties Volcanic Province; numbers refer to UK quadrants (after Smith and Ritchie, 1993).

## 2.6 SOURCE ROCKS

The vast majority of oil contained within Middle Jurassic sediments of the North Sea was sourced from the prolific Upper Jurassic Kimmeridge Clay Formation. The coals and mudstones that locally form a high proportion of the Middle Jurassic succession are a potential source of dry gas and might be thermally mature within the deeper parts of the graben areas.

Hydrocarbons sourced from the Middle Jurassic are not thought to contribute significantly to the oil and gas accumulations in the Northern North Sea. However, oil found in the Beatrice Field in the Inner Moray Firth Basin has a complex origin. In addition to a Devonian component, it appears that the oil-prone, algal-rich mudstones and coals of the Brora Coal Formation have also made a contribution (see Cornford, 1998 and references therein).

## 2.7 TRAPS

Oil and gas fields associated with the pre-rift, Middle Jurassic tilted fault blocks are some of the most productive in the North Sea. However, 'creaming curves' suggest that the exploration play is very mature, with most remaining potential in hanging-wall closures (Johnson and Fisher, 1998; Brooks et al., 2002). Middle Jurassic oil and gas fields occur in three geographical areas (Figure 2): (a) the East Shetland Basin (or 'Brent Province') which relies on the near omnipresence of reservoir quality sandstones in the Brent Group; (b) in the 'Beryl Embayment Province' where the Hugin and Pentland formations form the reservoirs and (c) in the Inner Moray Firth Basin (e.g. Beatrice Field) where Fladen Group and underlying Lower Jurassic sediments act as reservoirs.

### 2.7.1 East Shetland Basin

Oilfields in the East Shetland Basin comprise a variety of tilted fault blocks with two- or three-way dip closures. The

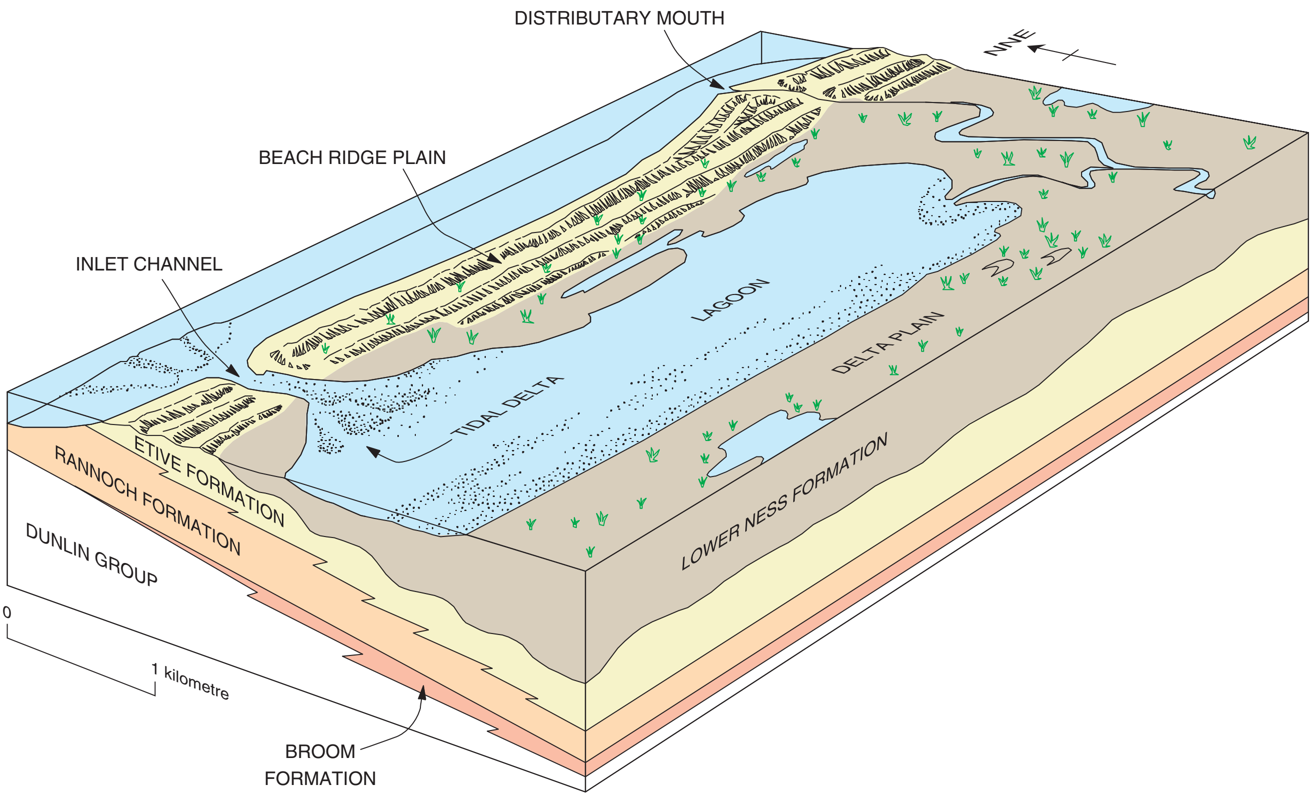


**Figure 11** Depositional model for the Rannoch, Etive and Lower Ness formations (after Budding and Inglin, 1981).

| FLADEN GROUP | | |
|---|---|---|
| FORMATION | | ENVIRONMENT |
| Hugin Formation | Upper | Shallow marine, deepening-upwards, transgressive sequence of basal lags and washovers passing up to shoreface and/or offshore facies with storm influences |
| | Lower | Transgression followed by shallowing-upwards, regressive sequence of mass-flow, up through shoreface, tidal delta, barrier inlet and lagoonal facies |
| Pentland Formation | Paralic succession | Paralic environment with sub-tidal, inter-tidal and salt marsh sub-environments |
| | Lower coal marker | Swamp |
| | Interbedded unit | Shallowing-upwards sequence, with tidal influences and lagoonal or sub- to inter-tidal mud flat environments |

| BRENT GROUP | | |
|---|---|---|
| FORMATION | ENVIRONMENT | PHASE |
| Tarbert Formation | Transgressive sheet sand and shoreface facies | Abandonment phase and southerly retreat of delta (possibly pulsed) |
| Ness Formation | Fluvial-dominated delta top and coastal plain environments. In the north a barrier developed | |
| | Open lagoon | |
| | Marginal marine, back barrier environments. Main facies are back barrier, stagnant swamp and lacustrine. Some marine influence. | Progradation phase of delta with northward progradation of shoreline |
| Etive Formation | Barrier-bar complex with effects of wave/ storm activity dominant. Development of nearshore bar and trough systems with associated rip channels. | |
| Rannoch Formation | Lower to middle shoreface sequence, probably storm dominated | |
| Broom Formation | Locally sourced fan-delta deposition | Reactivation of marginal fault systems (and rift marginal uplift) |

**Figure 12** Depositional setting of the Brent and Fladen groups.

traps vary in structural complexity, dip angle (typically about 5 degrees, rarely more than 10 degrees) and the amount of erosion along their crests. They thus range from pure fault traps where the updip seal is entirely faulted, such as the Murchison Field (Figure 14) to those where stratigraphical truncation of the reservoir below an unconformity forms the updip seal (e.g. Brent, Ninian and Statfjord fields).

In general, the larger the throw of the principal bounding fault, the greater the amount of footwall uplift and the larger the amount of erosion over the crest of the trap. Fault blocks within the East Shetland Basin typically show up to a few hundred metres of erosion from their crests. However, in some cases, the trapping mechanism did not form simply by tilting followed by marine transgression. Rather, the fault scarp, being composed of poorly consolidated sand and shale, collapsed into the deeper water of the adjacent half-graben (Figure 15) (Underhill et al., 1997; McLeod and Underhill, 1999). This process took place by rotation of slide blocks or the complete reworking of sediments.

In some instances, such as in the Don Field, oil is trapped within Middle Jurassic fault hanging wall blocks. The principal faults of the Don Field are sealed by clay smearing across a sand-sand contact, without which the oil would have continued its migration into higher structures.

### 2.7.2 Beryl Embayment

The Beryl and Bruce oilfields are complex, fault-bounded structures. The Beryl Field (UK Block 9/13) is compartmentalised by sealing faults into two main parts: a westward-tilted fault block and a north-north-east-oriented horst. The component parts of the Bruce Field (UK Blocks 9/8 and 9/9) are associated with a major, relatively shallowly dipping fault: a west-dipping, rotated fault block, a graben and a high flanking the Viking Graben (Figure 16).

### 2.7.3 Inner Moray Firth Basin

The Beatrice Field (UK Block 11/30) is a relatively simple north-east-trending, tilted fault block that formed as a result of Upper Jurassic rifting and remained unbreached despite Palaeogene and Neogene transpression along the nearby Great Glen Fault (Thomson and Underhill, 1993; Davies et al., 2001).

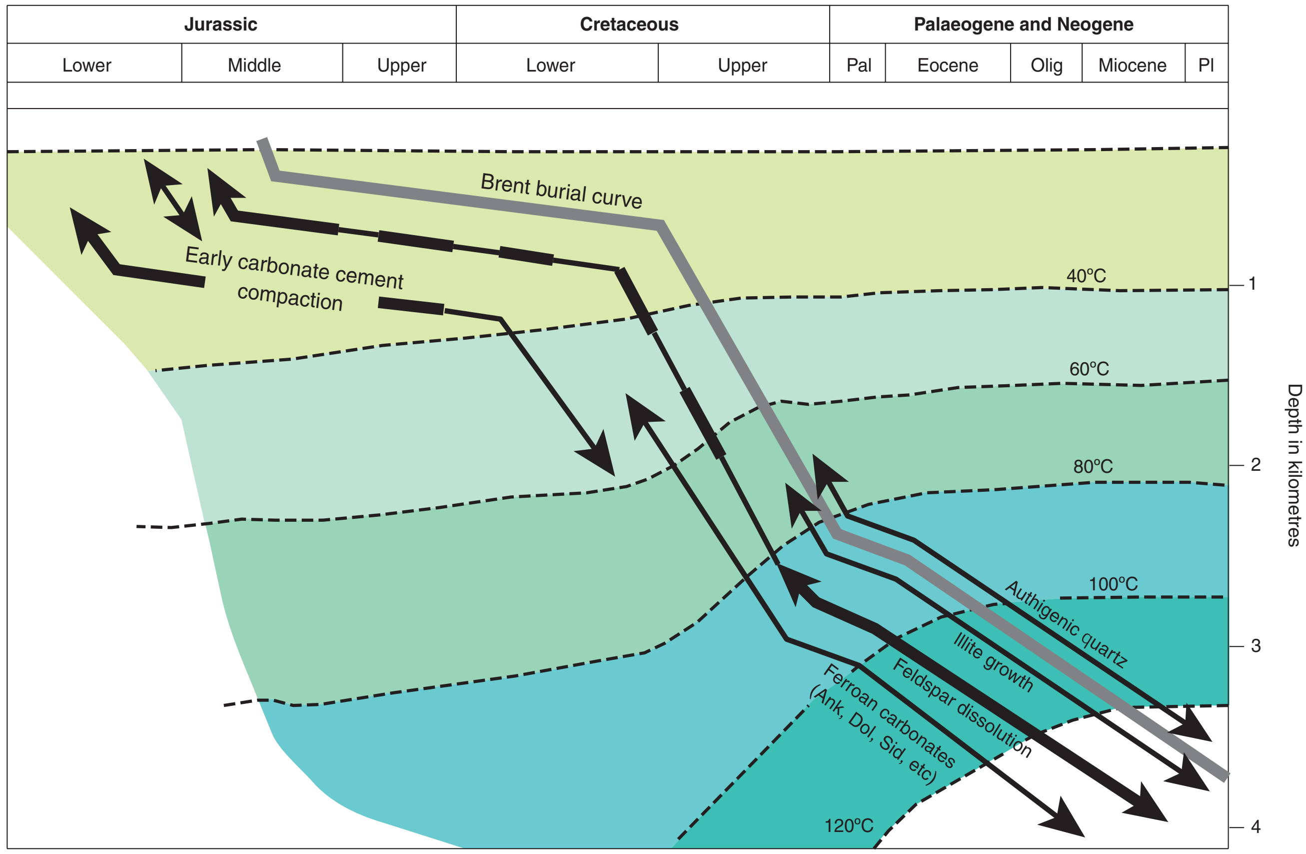


**Figure 13** Summary of diagenetic and burial history of the Brent Group; line thickness indicates relative importance of the diagenetic process (after Giles et al., 1992).

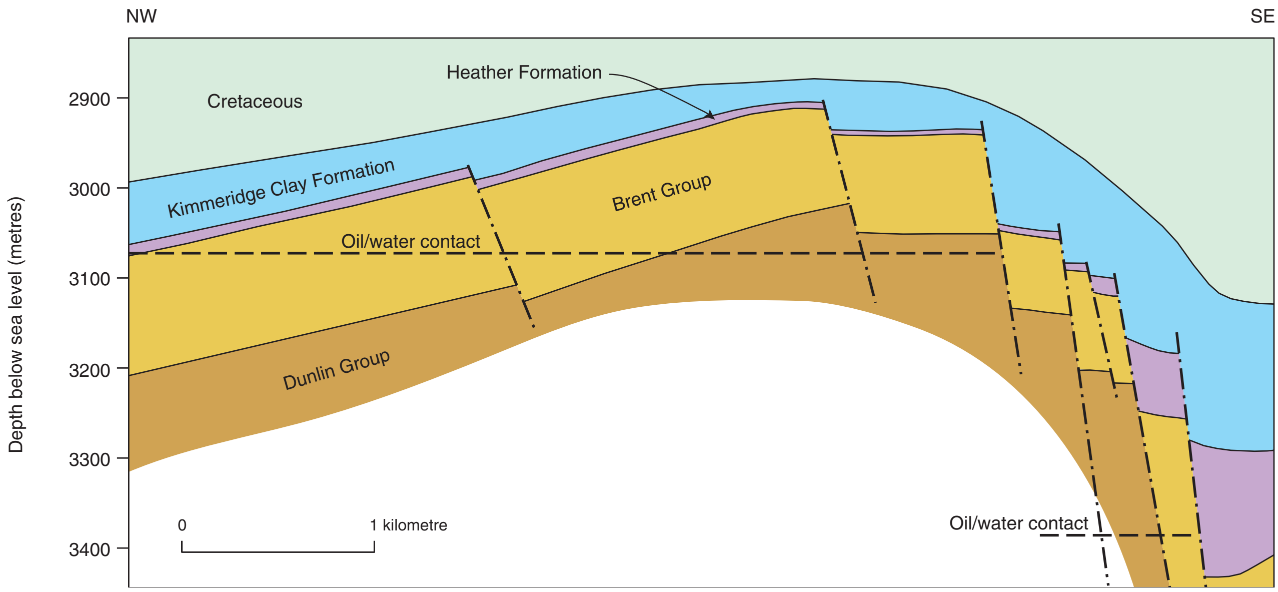


**Figure 14** Structure of the Murchison Oilfield (after Warrender, 1991).

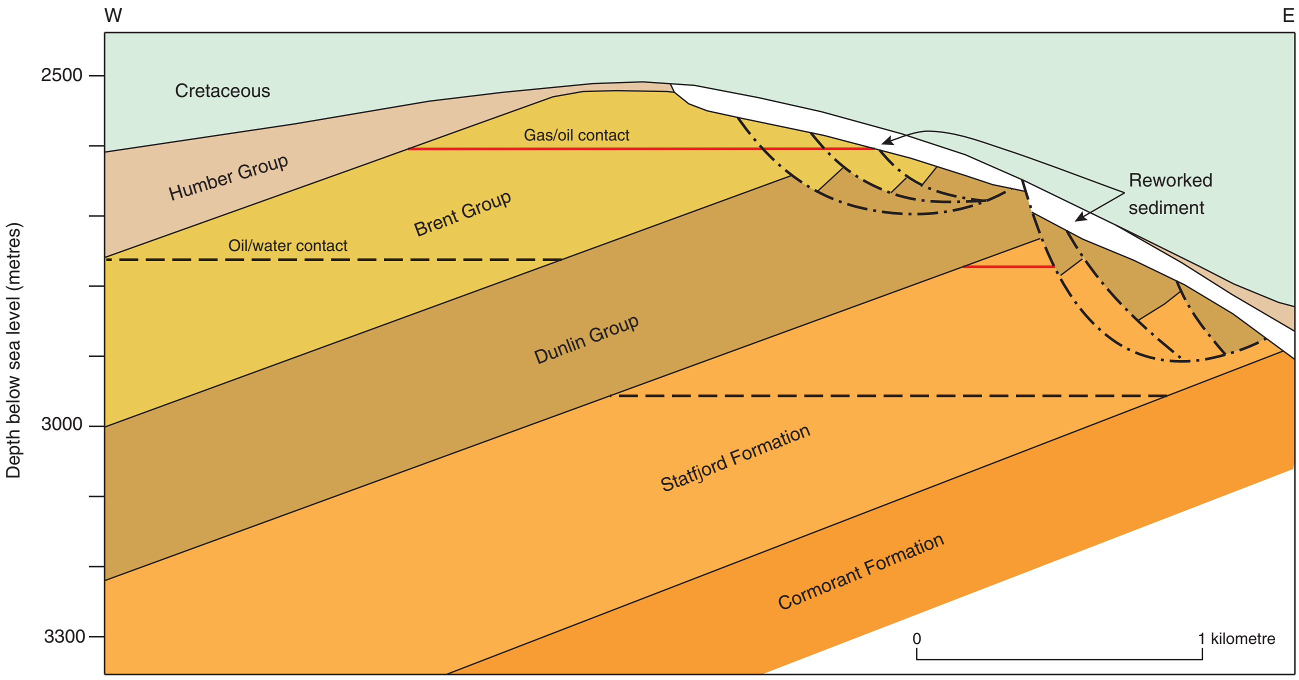


**Figure 15** Structure of the Brent Oilfield (after Struijk and Green, 1991).

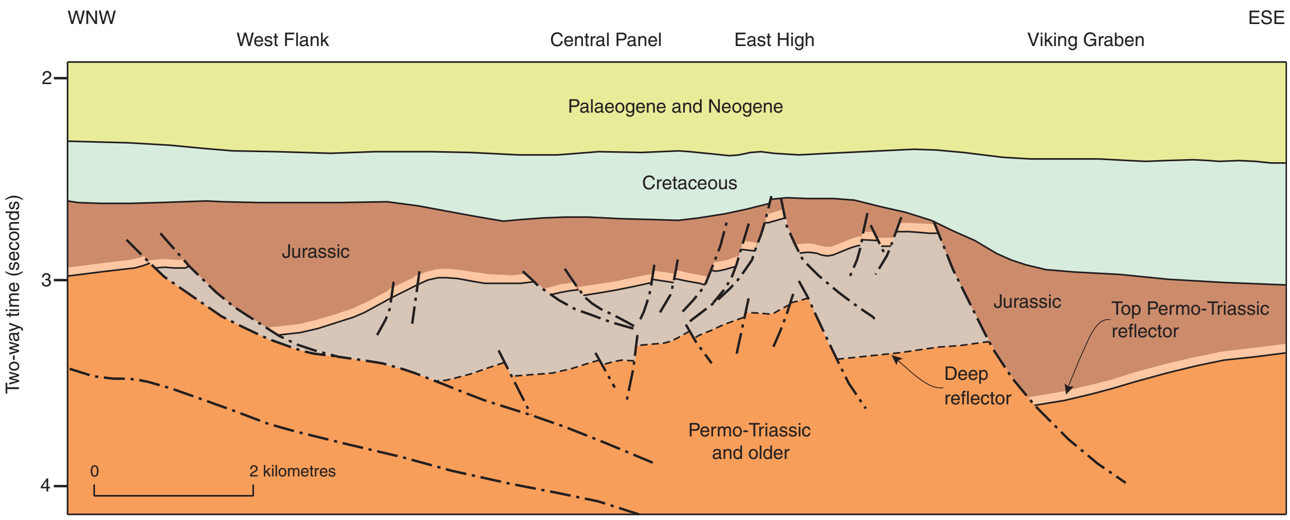


**Figure 16** Structure of the Bruce Oilfield (after Beckly et al., 1993).

# 3 Humber Group ('Upper Jurassic')

## 3.1 INTRODUCTION

The Late Jurassic represents a crucial period during which the most important North Sea source rock, the Kimmeridge Clay, was deposited. During this time sandstones with reservoir potential were also laid down in both shallow and deep water settings and tectonic activity gave rise to structures that formed abundant traps both within the Upper Jurassic and also in older rocks.

## 3.2 LITHOSTRATIGRAPHY

In the UK Central and Northern North Sea, the Humber Group incorporates most of the Upper Jurassic (Figure 17) (Richards et al., 1993), though some Upper Jurassic sediments in the Outer Moray Firth Basin are assigned to the Fladen Group, as discussed in the previous chapter. Two regionally extensive units of marine mudstone are recognised within the Humber Group and are known as the Heather Formation and the Kimmeridge Clay Formation. Localised bodies of mass-flow coarse clastics enclosed within these mudstone formations are typically given member status (e.g. Magnus Sandstone Member); however, the Brae clastics in the South Viking Graben comprise a widespread and thick unit of basinal marine mass-flow deposits that interdigitates with both the Heather and Kimmeridge Clay formations, and are assigned formation status. Within the Central North Sea, the Heather and Kimmeridge Clay formations pass laterally into two major units of shallow marine sandstone known as the Piper and Fulmar formations. The distribution and thickness of the Humber Group, together with the well log character of selected units are summarised on Enclosure 2.

### 3.2.1 Humber Group

The **Heather Formation** is Bathonian to latest Oxfordian in age and is therefore partly of Mid Jurassic age. The formation is distributed widely across the Central and Northern North Sea and consists of up to 700 m of marine mudstone with sporadic thin stringers or concretions of limestone and localised bodies of mass-flow sandstone (e.g. Bruce, Freshney and Ling sandstone members), shallow marine spiculitic sandstone (e.g. Alness Spiculite Member) and paralic mudstone (e.g. Gorse Member). Although it is commonly perceived as representing shelf facies, the Heather Formation also includes mass-flow sandstones of slope or basin association. Bottom waters during deposition of the formation were generally aerobic.

The widespread **Kimmeridge Clay Formation** is Kimmeridgian to late Ryazanian in age. It comprises up to 1400 m of moderately to highly organic-rich, marine mudstone with local bodies of mass-flow sandstone (e.g. Burns, Claymore, Magnus and Ribble sandstone members). The formation was deposited mainly in a basinal setting where bottom waters were anoxic (Miller, 1990).

The **Brae Formation** is mainly Kimmeridgian to mid-Volgian in age, but possibly ranges into the Oxfordian. It is thickly developed along the western, fault-bounded margin of the South Viking Graben. The Brae Formation consists of over 760 m of sandstone, conglomerate, mud-matrix-supported breccia and interbedded mudstone. The formation was deposited by a variety of gravity-flow processes in overlapping, partly channelised, submarine fan systems (Turner et al., 1987; Garland, 1993; Cherry, 1993).

The **Piper Formation** is late Oxfordian to Kimmeridgian in age (Richards et al., 1993) and is widely distributed across the Outer Moray Firth Basin. The Piper Formation consists of up to 300 m of fine- to coarse-grained sandstone with interbedded marine mudstone and accumulated from several progradational and retrogradational phases of a wave-dominated delta (Harker et al., 1993). Two major depositional cycles are recognised, and these equate to the Pibroch and Chanter members. In many wells, the Piper lithofacies are arranged in large-scale upward-coarsening subcycles up to 100 m thick, with overall upward-decreasing gamma-ray profiles.

The **Fulmar Formation** is Callovian to late Ryazanian in age and is widespread in the UK Central North Sea, but displays complex patterns of distribution and thickness that were influenced by penecontemporaneous rifting, halokinesis and salt dissolution. The Fulmar Formation comprises up to 365 m of fine- to medium-grained, generally massive, bioturbated sandstone. The Fulmar Formation commonly includes large-scale upward-coarsening and upward-fining successions and was deposited in shallow marine, low to moderately high-energy, storm-influenced environments.

The **Emerald Formation** is of late Bathonian to early Oxfordian age, but is predominantly Callovian. The formation is geographically restricted to the transitional shelf to the East Shetland Basin and comprises up to 30 m of sandstone and subordinate siltstone, commonly with basal conglomerate. It is interpreted as a transgressive sheet sand that formed in a nearshore to offshore setting.

### 3.2.2 Onshore formations

Upper Jurassic rocks are exposed on the Moray Firth coast and equate to strata within the Humber Group.

The upper part of the **Brora Arenaceous Formation** is early Oxfordian in age. It comprises bioturbated, muddy sandstone and yellow, fine-grained sandstone with lenticular conglomerate. These strata probably represent migrating bars on a shallow marine shelf (Andrews et al., 1990).

The **Balintore Formation** is mid-Oxfordian in age, and conformably overlies the Brora Arenaceous Formation. It comprises up to 10 m of muddy calcareous sandstone in which calcitised spicules are common, glauconitic sandstone and limestone. These rocks are interpreted to have been deposited within inshore marine environments (Lam and Porter, 1977).

The **Kintradwell Boulder Beds** are early Kimmeridgian in age and comprise up to 60 m of thin-bedded sandstone, siltstone, shale and conglomerate deposited in a slightly restricted marine environment (Wignall and Pickering, 1993).

The **Allt na Cuille Formation** is mid-Kimmeridgian in age and up to 122 m in thickness, comprising laminated and massive sandstone and siltstone deposited in a submarine canyon environment (Wignall and Pickering, 1993).

The **Helmsdale Boulder Beds** are mid-Kimmeridgian to mid-Volgian in age and comprise up to 530 m of conglomerate, sedimentary breccia and sandstone. These rocks were probably deposited as submarine gravity flows and screes.

## 3.3 SEQUENCE STRATIGRAPHY

Four tectono-stratigraphic sequences and thirteen genetic stratigraphic sequences have been recognised within the Upper Jurassic by Rattey and Hayward (1993) and Partington et al. (1993a, b) (Figure 18). Harker and Rieuf (1996) applied sequence stratigraphic techniques to subdivide the Humber Group of the Moray Firth Basin into eight genetic units. In a contrasting (Vail-type) approach based on the recognition of unconformities, Donovan et al. (1993) developed a depositional sequence stratigraphic template to understand better the spatial and temporal distribution of Upper Jurassic shallow marine sandstone reservoirs (e.g. Fulmar Formation). These widespread sandstone units display marked physical similarities, but vary widely in age (e.g. Donovan et al., 1993; Price et al., 1993). However, Jeremiah and Nicholson (1999) noted that aspects of the various stratigraphic templates might suffer from incorrect age allocations for a number of their sequence boundaries. Recently, Fraser et al. (2003) have developed the Late Jurassic scheme of Partington et al. (1993b) and applied a subdivision into seven genetic sequences (A to E) based on region-wide maximum flooding surfaces (Figure 18).

## 3.4 PALAEOGEOGRAPHY

The Late Jurassic palaeogeographic/palaeofacies development of the Central and Northern North Sea is summarised in Figure 19. Within the Central and Northern North Sea, repeated rises of relative sea level during the Late Jurassic reflect the interplay of active rifting and eustatic sea level changes. Broadly, the series of marine transgressions progressively drowned basin margins and resulted in the expansion of basinal facies and an associated outward shift of paralic and shallow marine facies belts (Rattey and Hayward, 1993).

### 3.4.1 Early to mid-Oxfordian

In the Central and Northern North Sea, early to mid-Oxfordian subsidence was confined to the developing rifts (Figure 19). The marine transgression initiated in the Mid Jurassic continued and shelf and basinal mudstones (Heather Formation) accumulated in much of the Inner Moray Firth Basin, Viking Graben and East Shetland Basin, and for the first time extended into the East Central Graben (Rattey and Hayward, 1993). The basinal facies usually comprises condensed mudstone sequences, although some gravity-flow sandstones were deposited in the South Viking Graben and Beryl Embayment (e.g. Bruce and Ling Sandstones). Widespread shelf sands accumulated marginal to the Heather mudstone in the Central Graben (Fulmar Formation) and in the Inner Moray Firth Basin (Alness Spiculite Member). In the Outer Moray Firth Basin and

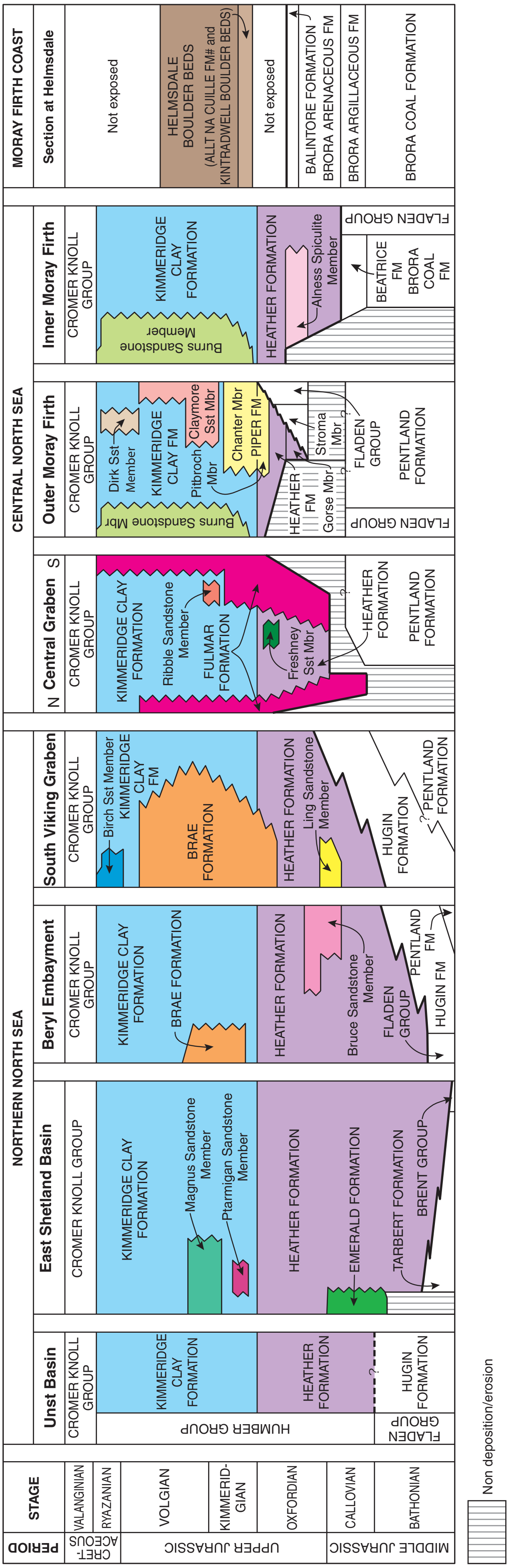


**Figure 17** Humber Group (Upper Jurassic) lithostratigraphy (after Richards et al. 1993; Andrews et al. 1990; Wignall and Pickering, 1993).

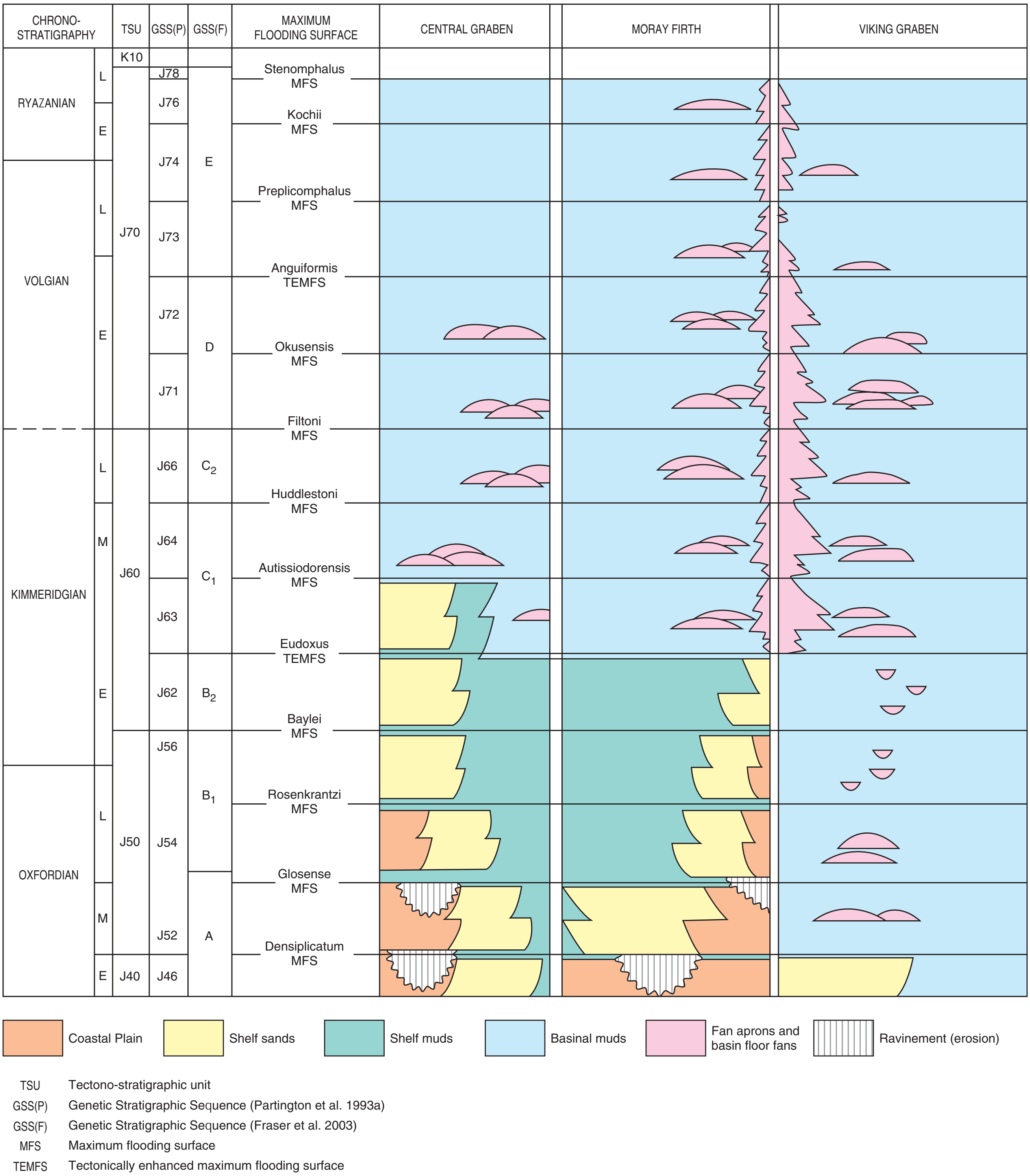


**Figure 18** Genetic stratigraphy template for the Late Jurassic of the UK Central and Northern North Sea (after Partington et al., 1993b and Fraser et al., 2003).

South Halibut Basin, the paralic facies of the Stroma Member (Pentland Formation) commonly overstepped pre-Jurassic strata and mark the start of the Late Jurassic transgression (Richards et al., 1993).

### 3.4.2 Mid-Oxfordian to early Kimmeridgian

There was an increase in the amount of rifting during mid-Oxfordian to early Kimmeridgian times and over much of the graben system subsidence outpaced sediment supply (Figure 19). Consequently, deposition of mudstones of shelf and basinal facies became more widespread (Rattey and Hayward, 1993). Deposition of the Brae Formation gravity-flow clastics may have commenced in the late Oxfordian, or even earlier, in association with the rifting. In the Outer Moray Firth Basin and marginal areas of the Central Graben, however, deposition kept pace with subsidence with the accumulation of expanded, upward-coarsening cycles of wave-dominated delta sands (Piper Formation: Scott Member) and shallow marine sands (Fulmar Formation).

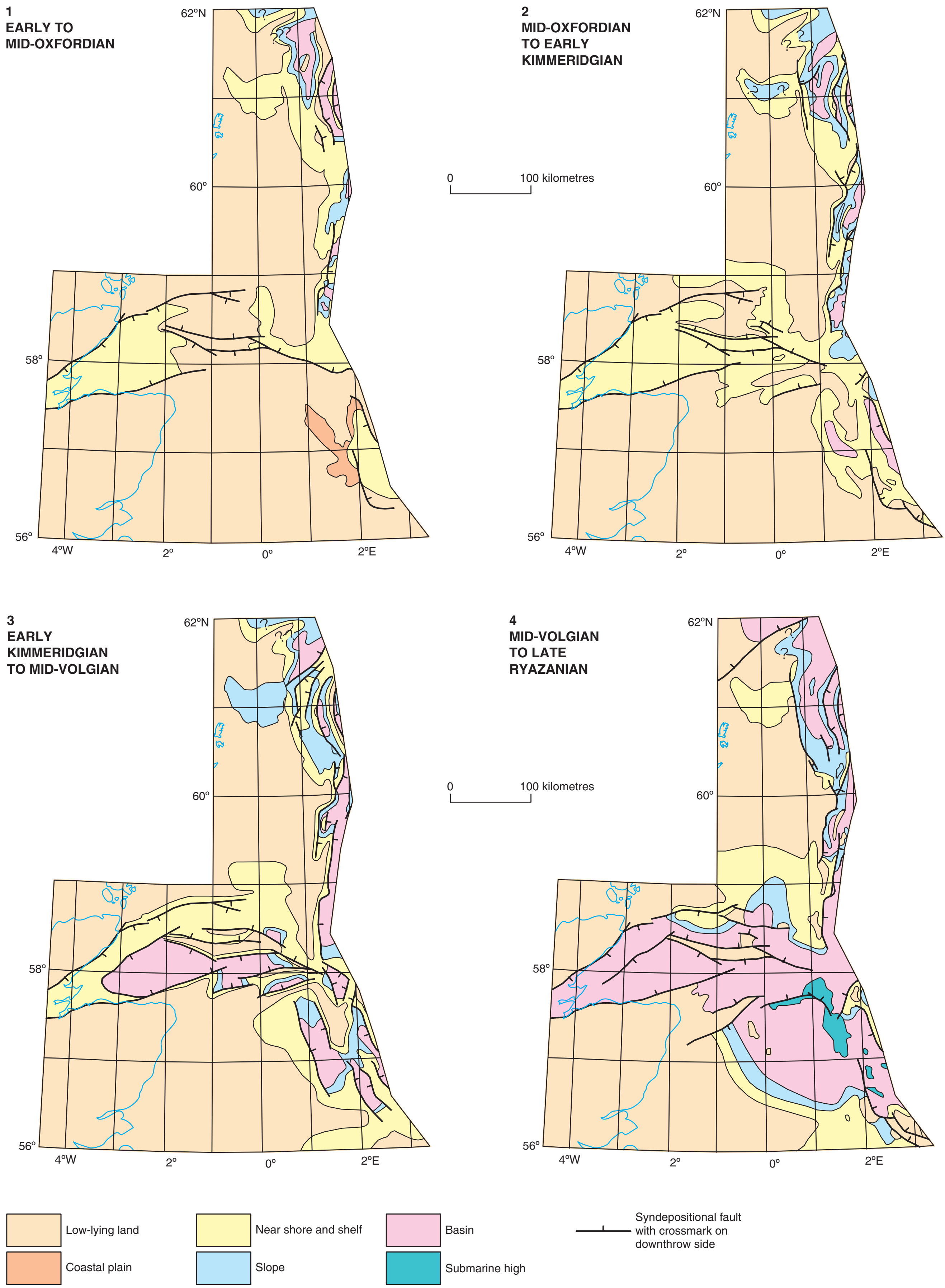


**Figure 19** Upper Jurassic palaeogeography (after Rattey and Hayward, 1993).

### 3.4.3 Early Kimmeridgian to mid-Volgian

During the early Kimmeridgian to mid-Volgian, rifting continued to exert a major control on sedimentation, and prominent wedges of syntectonic clastics accumulated in fault hanging wall basins (Figure 19). Locally, these syn-rift deposits include sand derived from the uplifted and eroded fault footwall blocks. The South Viking Graben formed a deep, narrow, half graben, bounded on the west by an uplifted and subaerially eroded Fladen Ground Spur. This half graben was infilled by thick gravity-flow deposits (Brae Formation) which pass basinward into relatively condensed pelagic mudstones. Transfer faults or relay ramps associated with rift development strongly influenced the position of feeder channels for the Brae clastics (e.g. Cherry, 1993). In the East Shetland Basin and Outer Moray Firth Basin, gravity-flow deposits of the Magnus and Claymore sandstone members, respectively, were deposited during this tectonically active phase (Enclosure 2). In the Central North Sea, rifting was associated with halokinesis and the amount of footwall uplift was commonly insufficient to cause emergence and erosion. Consequently, associated basin floor mass-flow deposits (e.g. Ribble Sandstone Member) appear to be less widespread.

### 3.4.4 Mid-Volgian to late Ryazanian

Active faulting significantly decreased at the beginning of mid-Volgian times and a general deepening led to progressive drowning of fault footwalls (Figure 19). In the East Shetland Basin and Outer Moray Firth Basin, the start of thermally controlled subsidence was marked by cessation of Magnus Sandstone and Claymore Sandstone deposition, respectively. By late Ryazanian times, all but the highest footwalls of faults had been drowned. Although some deep-water sands (the Burns, Birch and Dirk sandstone members) were deposited, this was generally a phase when subsidence exceeded sediment supply and basins were starved of coarse clastic material.

## 3.5 DEPOSITIONAL ENVIRONMENTS AND RESERVOIRS

The interpreted genetic environments of deposition for each formation within the Humber Group of the UK Central and Northern North Sea are tabulated in Figure 20.

In the Moray Firth Basin, Viking Graben and East Shetland Basin, both shallow marine/deltaic and basinal facies contain important Humber Group reservoirs. In contrast, shallow marine strata currently provide the principal reservoirs in the Humber Group of the Central Graben. However, Brooks et al. (2002) noted that recent wells in the Central Graben have extended the play fairway for thick Upper Jurassic syn-rift basin-floor sandstones into that area.

In the Central Graben area, reservoir sandstone units of the Callovian to late Ryazanian **Fulmar Formation** were deposited in shallow marine, low- to moderately high-energy, storm, influenced, nearshore to offshore settings (Figure 21) (Gowland, 1996; Johnson et al., 1986; Donovan et al., 1993; Clark et al., 1993). The Fulmar sands are commonly bioturbated (e.g. Martin and Pollard, 1996), and are locally cross-bedded. Large-scale, upward-coarsening cycles are displayed in some sections and reflect rapid fault- and related halokinetically-controlled subsidence during cycles of shelf progradation (Rattey and Hayward, 1993;

| HUMBER GROUP | |
|---|---|
| Kimmeridge Clay Formation | Moderately deep water, restricted marine environment with local basin floor fans |
| Brae Formation | Apron fringe and basin floor fans |
| Piper Formation | Wave-dominated delta with several progradational and retrogradational phases |
| Fulmar Formation | Offshore shelf with storm influence |
| Emerald Formation | Nearshore to offshore transgressive shelf |
| Heather Formation | Low-energy, open marine shelf with local slope channels and basin floor fans |

**Figure 20** Depositional setting of the Humber Group.

Wakefield et al., 1993). On the western shelf to the Central Graben, reservoir quality within the Fulmar Formation is commonly determined by mainly primary depositional controls, of which the intensity and frequency of physical reworking and the palaeobathymetric setting are the most important (Johnson and Fisher, 1998). For example, rapidly deposited, bioturbated sands have permeabilities an order of magnitude higher than bioturbated sands (Veldkamp et al., 1996). In the Central Graben, a number of factors, such as primary mineralogy (e.g. high feldspar content), burial depth, proximity to fault planes and the timing of hydrocarbon entrapment have influenced diagenesis. Because of the large number of controlling factors, reservoir quality in the graben remains poorly understood (Veldkamp et al., 1996).

The Fulmar Formation forms the principal reservoir in the high pressure/high temperature (HP/HT) Elgin and Franklin fields within the Central Graben. In these deeply buried reservoirs (more than 5 km subsea) there is a significant amount of secondary porosity developed and, together with the extreme overpressure (in excess of 500 bars) and residual stable grain mineralogy, this has resulted in the preservation of high quality reservoirs (Lasocki et al., 1999). The average porosity of the reservoirs is about 16%, but reservoir properties of up to 30% porosity and permeability of over 2 darcies are reported. Early compaction effects were lessened by the early growth of authigenic minerals such as microcrystalline quartz and dolomite. However, the most significant diagenetic event in the burial history of the reservoirs was the development of secondary porosity (up to half the observed porosity) resulting from the dissolution of feldspar, sponge spicules and shell debris. The precise timing of this secondary porosity development is not well constrained. It began before the development of high overpressures and may have continued after the establishment of the 'closed system'. The development of increasingly high overpressure within the reservoir has helped to minimise further compactional effects.

Thicker and better quality reservoir sandstone units of the late Oxfordian to mid-Kimmeridgian **Piper Formation** succeed them. The Piper sands accumulated during two major regressive cycles of a wave-dominated delta system that prograded from the Fladen Ground Spur and the Halibut Horst (Harker et al., 1993). These major cycles correspond to the Pibroch and Chanter members. Both of these members comprise several vertically stacked, large scale upward-coarsening sub-cycles. The Piper Formation generally forms an excellent reservoir, though reservoir quality can be

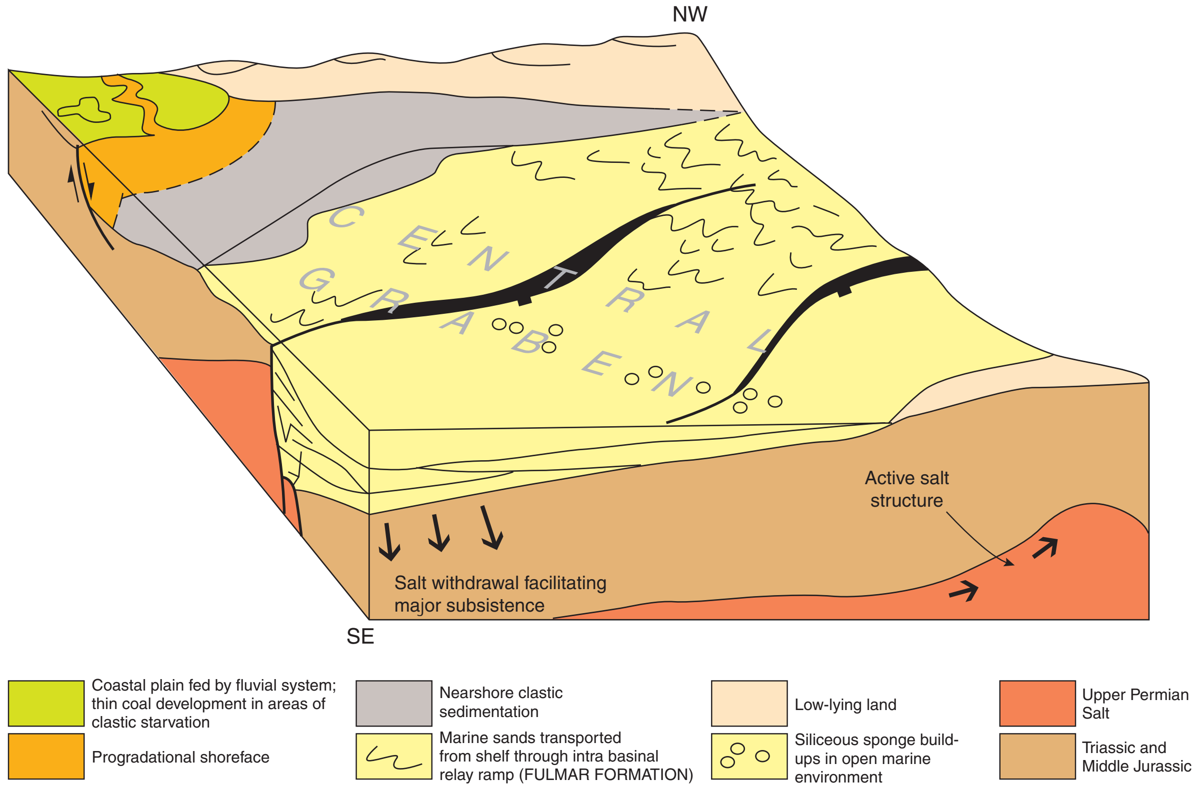


**Figure 21** Depositional model for the Fulmar Formation (after Gowland, 1996).

variable. In the Piper Field, the Piper sands are grain supported and retain porosity values of 20–28% and average permeability values of 4 darcies (Maher, 1981). However, in the Tartan Field (Coward et al., 1991), the formation exhibits markedly different petrophysical properties in each block, with lower porosity in the 'downthrown block' due to cementation and an intense compaction fabric. McCants and Burley (1996) note that in the Lowlander Prospect in UK Licence Block 14/20b, reservoir quality is poor with an average porosity of 9.4% and permeability of 55 millidarcies, because mechanical compaction and diagenetic cementation affect the Piper sandstones. However, total porosities are enhanced by feldspar grain dissolution after quartz overgrowth development.

Drowning of the Piper delta occurred in the mid-Kimmeridgian (Eudoxus Standard Zone) in conjunction with renewed rifting (Partington et al., 1993b). As a result, basinal conditions were established over much of the Moray Firth Basin (Boote and Gustav, 1987). Basinal mudstone development was locally interrupted by deposition of the mid-Kimmeridgian to mid-Volgian **Claymore Sandstone Member**, which now forms an important hydrocarbon reservoir in the Outer Moray Firth Basin (e.g. Claymore Field). The Claymore sands were largely derived from reworking of the Piper Formation on the crests of uplifted fault blocks (O'Driscoll et al., 1990; Boldy and Brealy, 1990; Hallsworth et al., 1996) and were emplaced by a range of gravity-flow processes (Turner et al., 1984). Within the Claymore sandstones of the Claymore Field, porosity averages 20% and permeability lies in the range 10–1300 millidarcies (Harker et al., 1991). There is very little detrital or authigenic clay. A minor amount of degradation of feldspar and mica to kaolinite and mixed-layer clays took place, in addition to relatively early quartz and feldspar overgrowths (Maher and Harker, 1987).

Rattey and Hayward (1993) recognised two main types of Upper Jurassic deep-marine fans in the North Sea Basin: apron-fringe fans and basin-floor fans. The apron-fringe fans are characterised by their small radii (less than 10 km) and thick conglomerate facies, and form much of the **Brae Formation** in the South Viking Graben (Turner et al., 1987). This formation largely comprises thick units of unorganised, sand-matrix conglomerate and mud-matrix breccia with interbedded units of sandstone and mudstone. Oil is commonly held within the matrix of the conglomerates. Proximal conglomerate and breccia occur immediately adjacent to the western faulted margin of the South Viking Graben (Figure 22). Contemporaneous rifting exerted a strong influence on sedimentation and large-scale upward-fining cycles separated by regionally extensive marine condensed horizons reflect rapid changes in relative sea level (Partington et al., 1993b; Garland, 1993). In the Central Brae Field, reservoir porosity averages 11.5%, with average permeability of 100 millidarcies (Turner and Allen, 1991).

Basin-floor fans, such as the Miller Fan system (also included in the Brae Formation) in the South Viking Graben and the Magnus Fan in the East Shetland Basin, are characterised by their relatively large radii (10–15 km), greater basinwards extent, higher proportion of sandstone facies and relatively minor conglomerate component. Within the Miller Field, primary intergranular porosity predominates and average porosity is 16% (Rooksby, 1991). Secondary porosity, after feldspar dissolution, provides a minor contribution to overall porosity.

## 3.6 SOURCE ROCKS

The Kimmeridge Clay Formation is the principal hydrocarbon source rock of the Central and Northern North

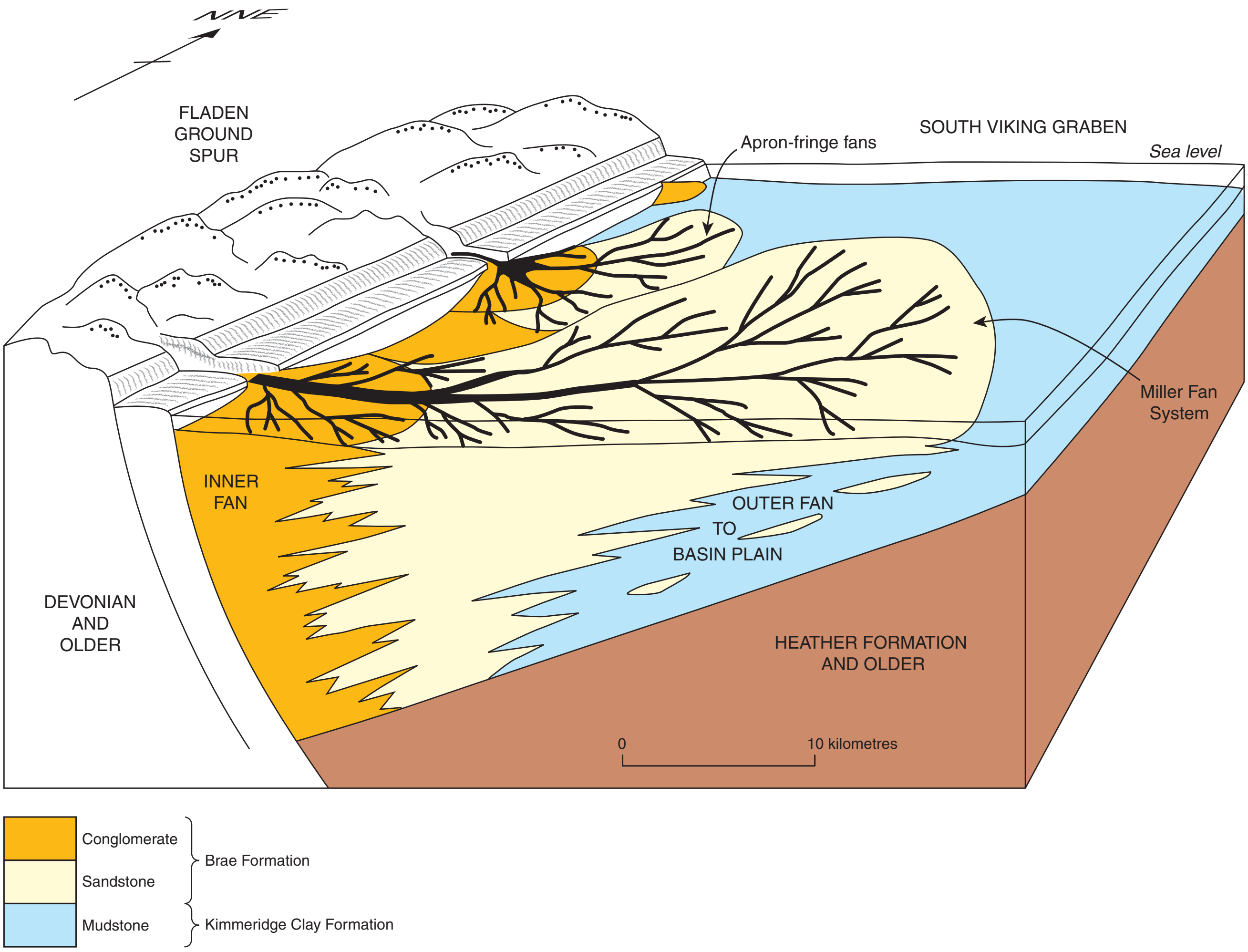


**Figure 22** Schematic block-diagram of the depositional setting of Upper Jurassic sediments in the Brae Oilfield area (after Stoker and Brown, 1986).

Sea and the majority of oil and gas fields in this region were charged from this prolific source (Cornford, 1998). A variably high gamma signature, due to high uranium content, is characteristic of this formation and has led to the term 'hot shale' being applied to uranium-rich units of source rock within the formation. The uranium was probably adsorbed onto the enclosed organic matter during deposition on a stagnant sea floor (Bjorlykke et al., 1975).

There has been much discussion on the overall environmental parameters necessary for source bed development in the Kimmeridge Clay Formation (e.g. Gallois, 1976; Tyson et al., 1979; Irwin, 1979). However, there is general agreement that the organic-rich sediments within the formation were deposited under anoxic conditions, where a lack of bottom feeding organisms and aerobic bacteria resulted in preservation of oil-prone material. Within the graben areas, deposition of the source rock probably occurred below wave base and beneath about 200 m or more of water (Cornford, 1998).

The organic component of the Kimmeridge Clay is derived from both land and marine environments and average values of total organic carbon are generally between 5% and 10% (Barnard and Cooper, 1981). Typical kerogen types are amorphous liptinite of marine planktonic origin (bacterially degraded algal debris) and amorphous vitrinite of terrigenous origin (degraded humic matter). Also present is particulate vitrinite (woody debris) and inertinite (highly oxidised terrigenous plant material). The distribution of the organic matter was influenced by the proximity to palaeocoastlines, the grain size of the sediment and the energy levels at sites of deposition (Fisher and Miles, 1983). In general, inertinite is found in greater proportion closer to palaeocoastlines, with vitrinite to the seaward side and liptinite in the deeper axial parts of the grabens.

Broadly, oil generation began in the Late Cretaceous to Palaeogene, though generation commenced earlier in the deeper parts of the Viking and Central grabens and Outer Moray Firth Basin, and later in the less deeply buried East Shetland Basin (Goff, 1983). The maturity of the Upper Jurassic mainly reflects the amount and timing of Neogene to Recent sedimentation (Figure 23) (Cornford, 1998). The locus of maximum sedimentation migrated south with time, and consequently, source rocks in the Central Graben have experienced oil-generating temperatures for shorter times than equivalents in the north (Cornford, 1998).

Generally, hydrocarbons have migrated up dip from deeply buried source rocks and into adjacent traps. The composition of the kerogen, together with the thermal maturity of the source, are factors in determining the composition of derived hydrocarbons now entrapped in adjacent fields (Fisher and Miles, 1983), though expulsion efficiencies are perhaps the main control on the gross gas/oil ratio of the total expelled product (Cornford, 1998).

### 3.7 TRAPS

Syndepositional rifting exerted a major control on the development of Upper Jurassic traps in the Central and Northern North Sea (Figure 3). In the Central Graben, the associated effects of halokinesis of Upper Permian salt were an additional strong influence on the pattern of Late Jurassic subsidence, deposition and subsequent trap development (Smith et al., 1993). The syn-rift Upper Jurassic exploration play is largely, but not entirely, confined to the syn-rift graben. It owes its success to the widespread occurrence of high-quality sandstone reservoirs, which are juxtaposed against mature source rocks in much of the region. The producing syn-rift reservoirs include both shallow-marine and deep-marine sandstones. The syn-rift producing fields display a wide variety of trapping mechanisms, including tilted fault blocks, four-way dip closures, hanging-wall closures and combined structural-stratigraphic closures (Johnson and Fisher, 1998). A number of Upper Jurassic exploration plays are expected to form the focus of much future exploration activity (Munns, 2002). These plays include the stratigraphic pinch-out of basin floor sandstones such as the recent giant 'Buzzard' discovery in UK Licence Block 20/6 and the deep basin HP/HT play.

#### 3.7.1 Viking Graben

Late Jurassic rifting along the major fault zone that forms the western margin of the South Viking Graben was key to the development of the Brae Formation reservoir, which represents the proximal portion of a tectonically influenced, apron-fringe submarine fan. The submarine fan sediments were derived from a shallow marine shelf on the crest of the uplifted footwall block (and the fault scarp itself) and were channelled into the rapidly subsiding South Viking Graben. In the South Brae Field (UK Block 16/7), the trap was formed by a combination of downfaulting, folding, differential compaction and stratigraphic pinch-out (Figure 24). The maximum height of the oil column within the field is 510 m, though structural closure on the top of the Brae Formation amounts to only 60 m. The main trapping elements are the major fault zone that marks the edge of the Fladen Ground Spur, where the Brae reservoir abuts impermeable Devonian sandstone, and lateral pinch out to the east of the reservoir facies (Roberts, 1991). The overlying Kimmeridge Clay Formation provides a seal.

#### 3.7.2 Central Graben

In the Central Graben, Upper Jurassic reservoirs within producing fields dominantly comprise shallow marine sandstones of the Fulmar Formation. However, some deep-marine sandstone reservoirs are present (e.g. in the recently discovered Jacqui Field) and may be best developed in the relatively unexplored basinal parts of the graben areas.

The Clyde Field, on the western margin of the Central Graben (UK Block 30/17), exemplifies a trap within the shallow-marine Fulmar Formation. It comprises a rotated fault block underlain by a wedge of Upper Permian (Zechstein Group) salt (Figure 25). The lensoid geometry of the Triassic Smith Bank Formation and the Fulmar Formation reflects progressive, syndepositional halokinesis and dissolution. The wedge-shaped geometry of the overlying Kimmeridge Clay Formation is thought to be

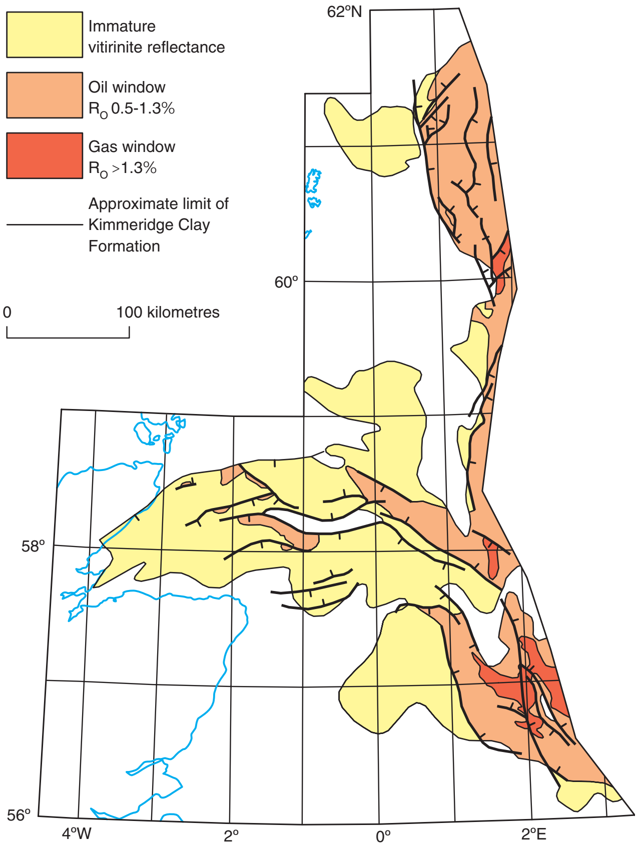


**Figure 23** Approximate thermal maturity at top Kimmeridge Clay Formation (after Cayley, 1987; Field, 1985; Goff, 1983).

related to syndepositional faults that detach in the underlying salt (Smith, 1987). In a contrasting model for structural development of the Clyde Field, Gibbs (1984) postulated post-Fulmar Formation, Late Jurassic gravitational slides with detachments in Zechstein salt.

#### 3.7.3 Moray Firth Basin

Hanging wall-related, slope-apron/basin-floor fan accumulations (Claymore, Galley, Perth and Saltire fields) occur in the Outer Moray Firth Basin. These fields display both stratigraphic and structural trapping elements with the reservoirs in part overlain conformably by Kimmeridge Clay Formation and partly by truncation followed by onlap of Lower Cretaceous shale (Harker et al., 1991; Casey et al., 1993). Similar reservoir/trap systems also extend into the Lower Cretaceous, such as in the Scapa and Claymore fields (McGann et al., 1991; Harker and Chermak, 1992).

In the Outer Moray Firth Basin, hanging wall-related traps commonly contain older, shallow-marine sandstone reservoirs such as the Piper Formation, which is trapped in fault-bounded dip closures with erosional truncation to the south. The Saltire Field, situated in a down-faulted terrace on the northern margin of the Witch Ground Graben, is a good example of downthrown closure in which fault seal is provided by juxtaposition of Upper Jurassic shallow- and deep-water sandstone reservoirs against tight Zechstein carbonate and evaporite and Triassic continental mudstone (Fraser et al., 2003).

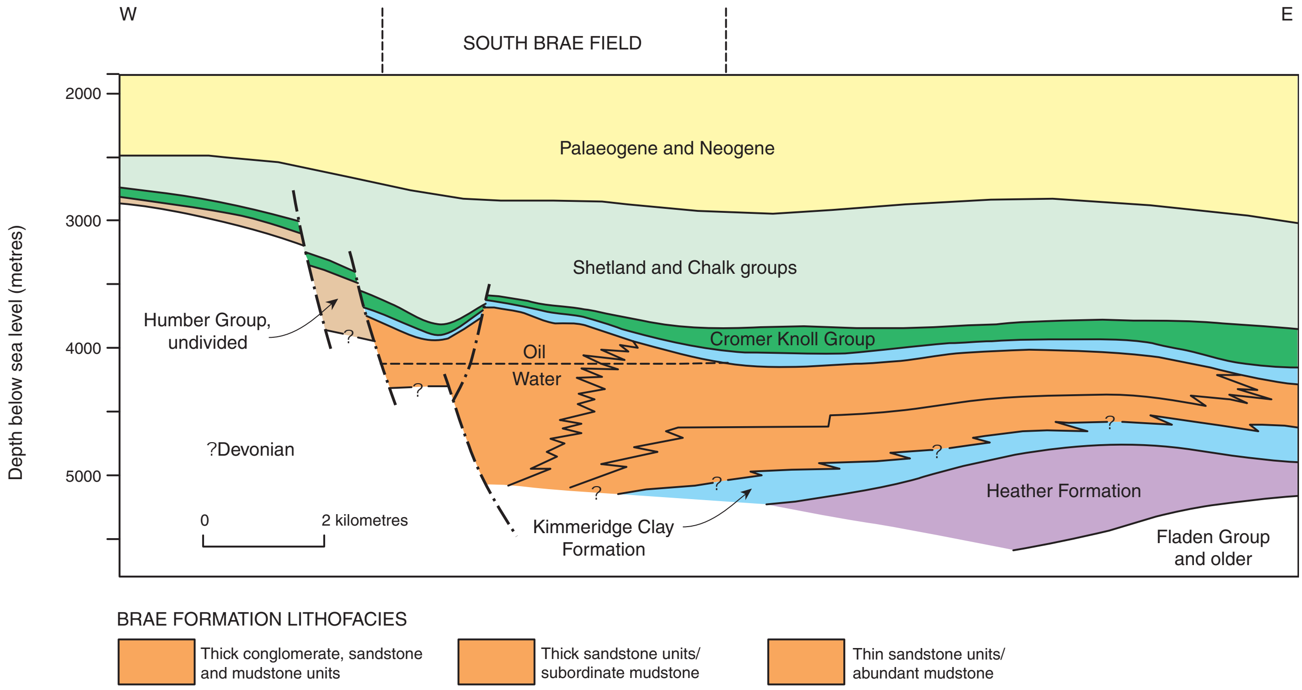


**Figure 24** Structure of the South Brae Field (after Roberts, 1991).

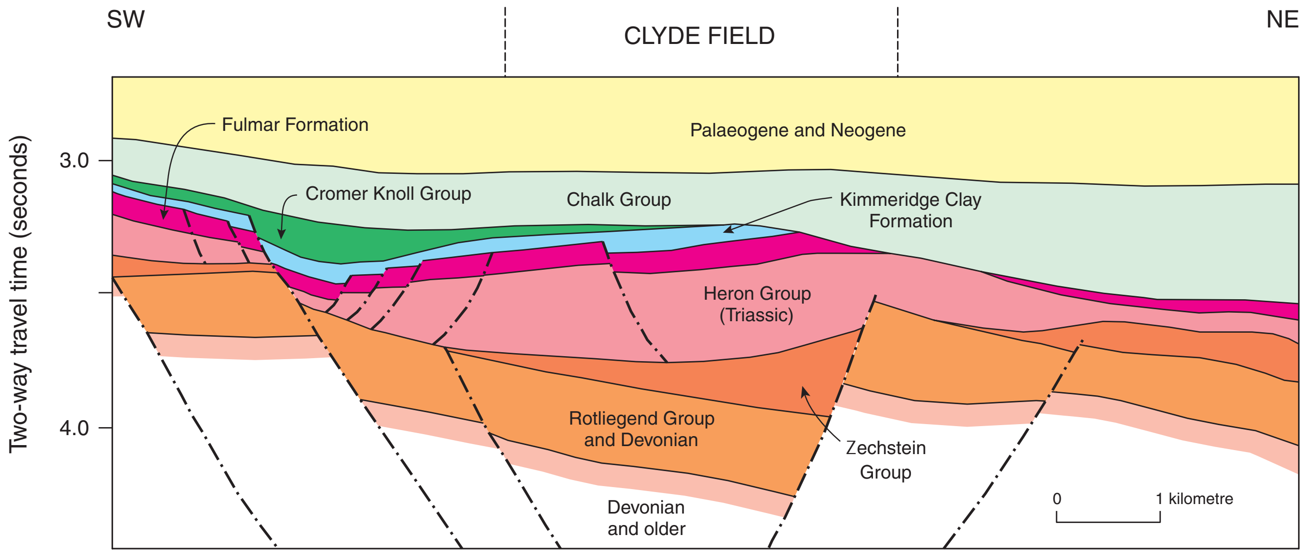


**Figure 25** Structure of the Clyde Field (after Smith, 1987).

# 4 Cromer Knoll Group ('Lower Cretaceous')

## 4.1 INTRODUCTION

Renewed exploration interest and recent hydrocarbon discoveries in a tract lying just to the south of the Halibut Horst, has generated significant new data on the Lower Cretaceous in the Central and Northern North Sea (Copestake et al., 2003). From these data, detailed sequence stratigraphic models have been developed, allowing the deliberate targeting of subtle Lower Cretaceous prospects (Copestake et al. 2003; Garrett et al., 2000).

## 4.2 LITHOSTRATIGRAPHY

The Lower Cretaceous within the UK Northern and Central North Sea is practically synonymous with the **Cromer Knoll Group**. Deegan and Scull (1977) proposed the first formal lithostratigraphic nomenclature for the Lower Cretaceous of the UK and Norwegian sectors of the Central and Northern North Sea. Subsequently, however, many informal terms were introduced, some of which have been applied in a number of different senses. A revision of the formal and informal nomenclature was proposed by Johnson and Lott (1993), who rejected application of the widely used term Sola Formation within the UK sector, due to possible confusion resulting from a differing, formal application of the term within the Danish Sector. In its place, Johnson and Lott (1993) erected the term Carrack Formation (Figure 26). Good summaries of the various Lower Cretaceous stratigraphic schemes are provided by Oakman and Partington (1998) and Copestake et al. (2003) (Figure 27).

Over most of the UK Northern North Sea, the Cromer Knoll Group remains undivided. Within the UK Central North Sea and South Viking Graben, however, five lithostratigraphic formations have been formally defined and proposed as a standard nomenclature (Figure 26) (Johnson and Lott, 1993). Three of these formations comprise regionally extensive units of marine mudstone/chalky mudstone with associated units of argillaceous chalky limestone and localised basin-floor sandstone. In ascending order, they are known as the Valhall, Carrack and Rødby formations. In addition two geographically restricted, sandstone-dominated formations within the Cromer Knoll Group of the Moray Firth Basin are distinguished: the Britannia Sandstone Formation and the Wick Sandstone Formation. These formations consist largely of a range of gravity-flow coarse clastic sediments and pass laterally into the more argillaceous strata of the Valhall and Carrack formations.

The distribution, thickness and well log character of the Cromer Knoll Group are summarised on Enclosure 3.

### 4.2.1 Cromer Knoll Group

The **Valhall Formation** is of late Ryazanian to early/late Aptian age and is widely distributed across the UK Central North Sea and the South Viking Graben. It reaches over 800 m in thickness within local depocentres and consists of interbedded calcareous mudstone, chalky mudstone and argillaceous chalky limestone with localised, sometimes thick, mass-flow sandstone and conglomerate. The thicker, more widespread sandstone bodies, together with smaller bodies that produce significant volumes of hydrocarbons, are given member status within the Valhall Formation (e.g. **Scapa Sandstone Member** and **Sloop Sandstone Member**).

Fine-grained strata of the Valhall Formation are divided into seven, regionally extensive, informal units (V1–V7) on the basis of subtle lithological variation and wireline log signatures (Figure 26). The Valhall Formation was deposited in a predominantly aerobic marine environment, although anoxic bottom-water conditions were widely established in the mid-Barremian and early Aptian when laminated, organic-rich mudstones of the Munk Marl (intra-unit V3) and Fischschiefer (unit V5) were deposited. A thin, green, non-calcareous layer within the Munk Marl has been interpreted as a volcanic ash (Jensen and Buchardt, 1987). The Fischschiefer (V5) correlates with Global Anoxic Event 1a (Arthur et al., 1990).

The **Carrack Formation** is of late Aptian to early/mid-Albian age and is widely distributed across the UK Central North Sea and South Viking Graben. The formation is commonly up to about 100 m thick in basinal areas, though it exceeds 150 m in local depocentres. It consists of medium to dark grey to black, essentially non-calcareous mudstone with thin bentonites and local sandstone. In general, a low interval velocity relative to both the underlying Valhall Formation and the overlying Rødby Formation characterises the formation. Bodies of mass-flow sandstone, such as the **Skiff Sandstone Member,** are enclosed within the Carrack Formation in the South Viking Graben. Individual sandstone units within the Skiff Sandstone Member commonly display upward-fining wireline log profiles. The Carrack Formation mudstones contain a fauna dominated by agglutinating foraminifera and are thought to mark a phase of basin restriction, with bottom-water oxygen depletion.

The **Rødby Formation** is of mid- to late Albian age and is widely distributed across the Central North Sea and South Viking Graben. The formation is commonly up to 100 m thick, but exceeds 150 m in local depocentres. It consists of mainly pale to dark grey, but commonly red-brown, calcareous mudstone and chalky mudstone with sporadic thin limestones. The formation commonly is divisible into three informal units (R1–R3) on the basis of wireline log responses and subtle lithological variation. The faunal content of much of the Rødby Formation suggests it accumulated in a well-oxygenated marine environment.

The **Britannia Sandstone Formation** is mid-Barremian to late Aptian in age and is confined to the south-east of the Outer Moray Firth Basin. The formation locally reaches over 250 m in thickness and comprises mass-flow sandstone with interbedded mudstone. The sandstones are pale grey or tan coloured and mainly fine- to medium-, but locally coarse-grained. Although there are no formal members within the Britannia Sandstone Formation, an informal subdivision into '**Lower Britannia Sandstone'** and **'Upper Britannia Sandstone'** is recognised from the character of the interbedded mudstone. In the lower unit, the calcareous mudstones display lithologies typical of the Valhall

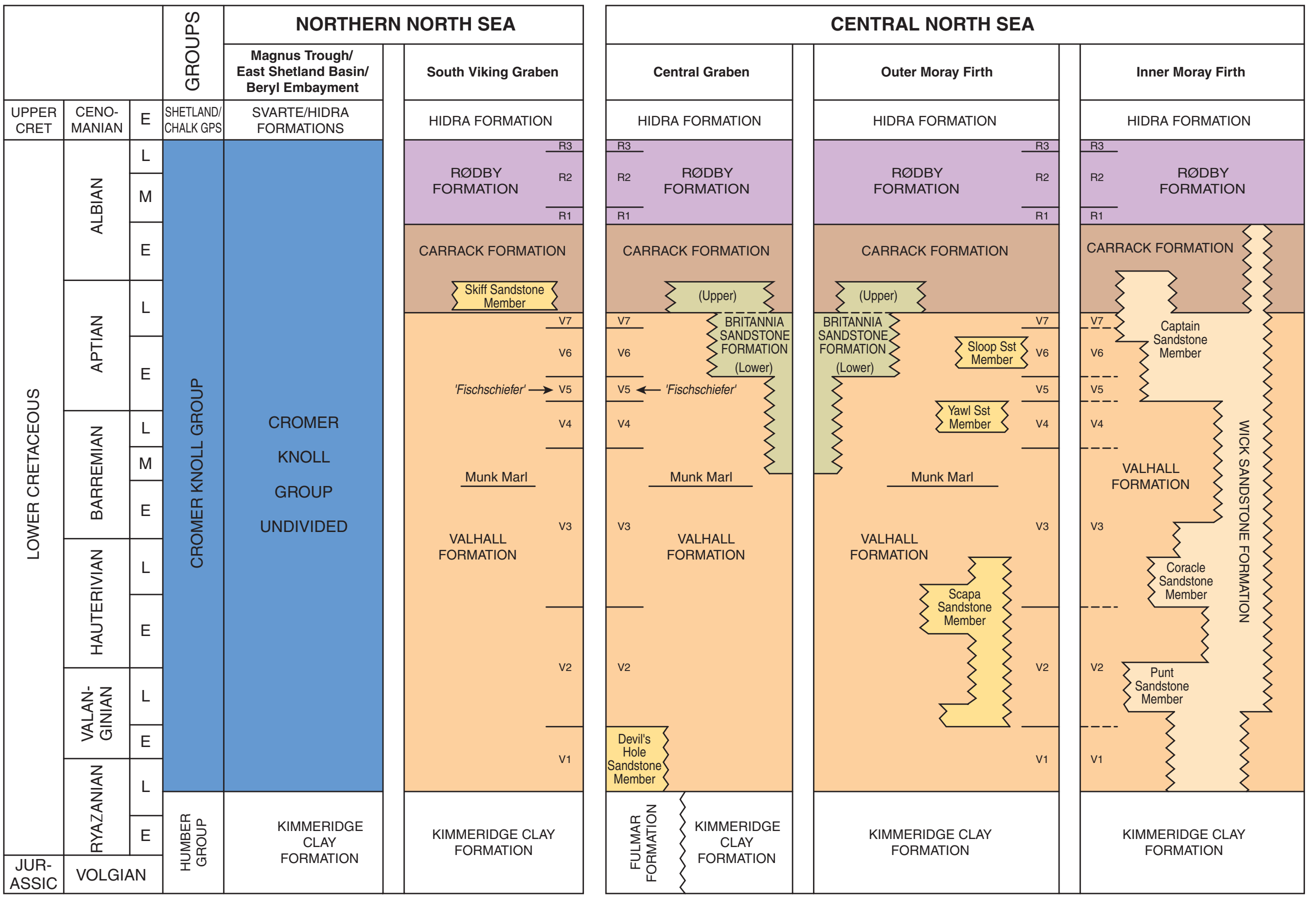


**Figure 26** Cromer Knoll Group (Lower Cretaceous) lithostratigraphy (after Johnson and Lott, 1993).

Formation, whereas in the upper unit they comprise dark grey, fissile mudstone typical of the Carrack Formation.

The **Wick Sandstone Formation** is late Ryazanian to early/mid-Albian in age and is distributed across the northern, central and eastern Inner Moray Firth Basin and into the South Halibut Basin. The formation comprises sandstone with interbedded siltstone and mudstone and locally reaches over 1400 m in thickness on the downthrow side of major (?mainly Late Jurassic) faults. The sandstones are very fine- to coarse-grained and pebbly, poorly sorted, locally argillaceous, and the grains dominantly consist of clear to translucent quartz. The interbedded mudstone units are typical of those within the Valhall and Carrack formations. On wireline logs, the Wick Sandstone Formation displays both 'blocky' and 'serrated' signatures, reflecting massive sandstone units and thinly interbedded sandstones and mudstones respectively. The virtual absence of core material from the Lower Cretaceous succession of the Inner Moray Firth Basin has led to debate about its genetic interpretation. Ziegler (1990) and Oakman and Partington (1998) postulated that shelf sandstone might be present locally, but Jeremiah (2000) considered that all the preserved Lower Cretaceous sediments within the Moray Firth Basin were deposited within a deep marine setting. In the south and east of the Inner Moray Firth Basin, the Wick Sandstone Formation can be divided into the **Punt**, **Coracle** and **Captain Sandstone** members.

### 4.2.2 Undivided Cromer Knoll Group

Within the Beryl Embayment, North Viking Graben, East Shetland Basin and Magnus Basin north of approximately 59°25'N, the Cromer Knoll Group is not formally subdivided (Enclosure 3). An informal subdivision (units 'a' to 'e', in ascending order) is commonly possible on the basis of subtle lithological variation and wireline log signatures. Unit 'a' consists of relatively calcareous beds at the base of the succession and probably correlates with Valhall unit 1 (V1). Broad lateral equivalents of units V2 and V3 are also apparent in the Northern North Sea and correspond to units of relatively less calcareous and more calcareous mudstone, respectively ('b' and 'c'). In northern sections, a prominent high gamma-ray spike provides a useful marker within the Aptian, but the relationship of northerly Aptian and Albian strata (i.e. units 'd' and 'e') to the Carrack and Rødby formations awaits clarification through detailed biostratigraphical studies.

The Cromer Knoll Group reaches over 1400 m on the downthrow side of the major growth fault forming the southern boundary of the Magnus Basin. In this depocentre, thick, unnamed late Valanginian to early Hauterivian mass-flow sandstones and interbedded mudstones are present within the lower Cromer Knoll Group.

## 4.3 SEQUENCE STRATIGRAPHY

Largely on the basis of data made available by British Petroleum, Oakman and Partington (1998) outlined a provisional sequence stratigraphy for the Cretaceous of the Central and Northern North Sea (Figure 27). In constructing the stratigraphic template, Oakman and Partington (1998) assumed that tectonic events occurred synchronously across the North Sea Basin and that major

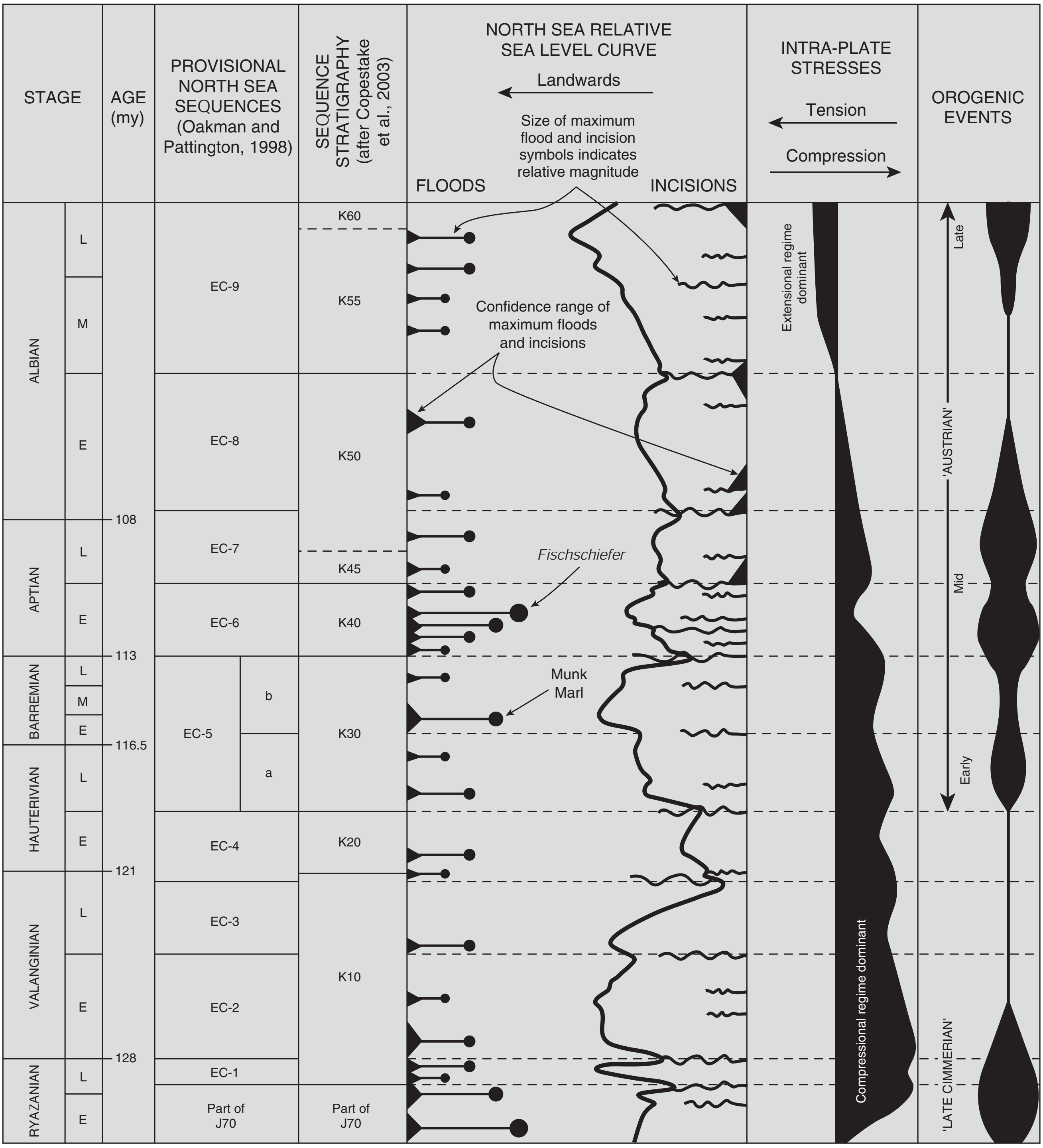


**Figure 27** Generalised Early Cretaceous sequence stratigraphy (after Oakman and Partington, 1998; Copestake et al., 2003).

anoxic events such as the Munk Marl and the Fischschiefer approximate to isochrons and also mark the peaks of marine floods. They recognised nine 'Vail-type' sequences bounded by incision events within the Lower Cretaceous succession. The chronostratigraphic distribution of these sequences within part of the UK Central Graben is illustrated in Figure 28. Subsequently, Oakman (1999) referred to 12 Early Cretaceous sequences defined by the larger incision surfaces with boundaries placed at intra-late Ryazanian, top Ryazanian, top early Valanginian, uppermost late Valanginian, top early Hauterivian, intra early Barremian, topmost Barremian/basal Aptian, intra early Aptian, top early Aptian, topmost Aptian/basal Albian, top early Albian, top mid-Albian and top Albian. In contrast to Oakman and Partington (1998), Oakman (1999) interpreted the Fischschiefer to mark a transgressive systems tract and placed the true maximum flooding horizon within the overlying unit (Ewaldi Marl or Valhall Formation unit V6; Figure 26).

Using a similar approach, Jeremiah (2000) described the results of a detailed biostratigraphical, sequence stratigraphical and seismo-stratigraphical study of the Lower Cretaceous of the Moray Firth. He recognised thirteen unconformity-bounded sequences within the Cromer Knoll Group. The unconformity surfaces bounding many of these sequences and the maximum flooding surfaces within them differ in detail

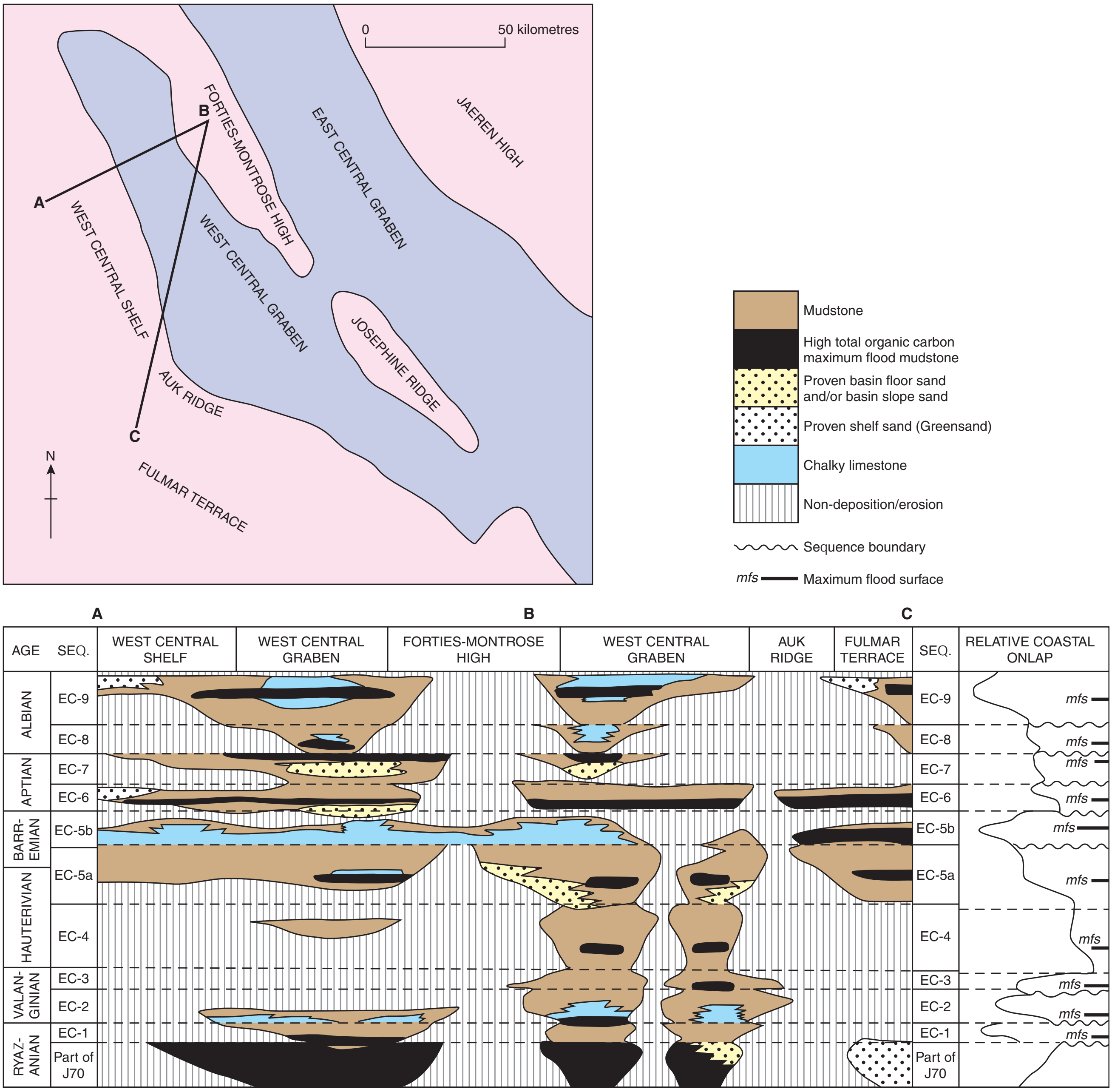


**Figure 28** Chronostratigraphic distribution of Early Cretaceous sequences, UK Central Graben (after Oakman and Partington, 1998).

from those recognised by Oakman and Partington (1998) and some are correlated with the lithostratigraphical boundaries recognised by Johnson and Lott (1993). Jeremiah (2000) regarded these sequences as tectonically controlled with little calibration to eustatic sea level changes.

Copestake et al. (2003) present a sequence stratigraphic scheme including eight sequences (K10–K55) based on log response, lithology and biostratigraphy that they have applied across the UK, Norwegian and Danish sectors (Figure 27).

## 4.4 PALAEOGEOGRAPHY

The generalised Early Cretaceous palaeogeographical/palaeofacies development of the Central and Northern North Sea is summarised in Figure 29. During the Early Cretaceous, the North Sea Basin lay about ten degrees south of its present position, at the southern fringe of the Boreal Ocean and within the Laurasian continent (Zeigler, 1990). The Early Cretaceous was a time of overall eustatic sea level rise, with marked pulses interpreted in the Barremian and in the mid- to late Aptian (e.g. Rawson and Riley, 1982; Oakman and Partington, 1998).

The extent of emergence of highs in the North Sea area during the Early Cretaceous is difficult to assess (Hancock and Rawson, 1992). Though many Jurassic tilt blocks remained uplifted in Early Cretaceous times, they may not have been subjected to significant subaerial erosion. Indeed, although seismic data commonly suggest strong marine onlap of the Cromer Knoll Group onto pre-existing structural highs, in many places condensed sections are found considerable distances beyond the apparent Lower Cretaceous seismic pinch-out (Rattey and Hayward, 1993). However, the Fladen Ground Spur and Halibut Horst may have remained emergent

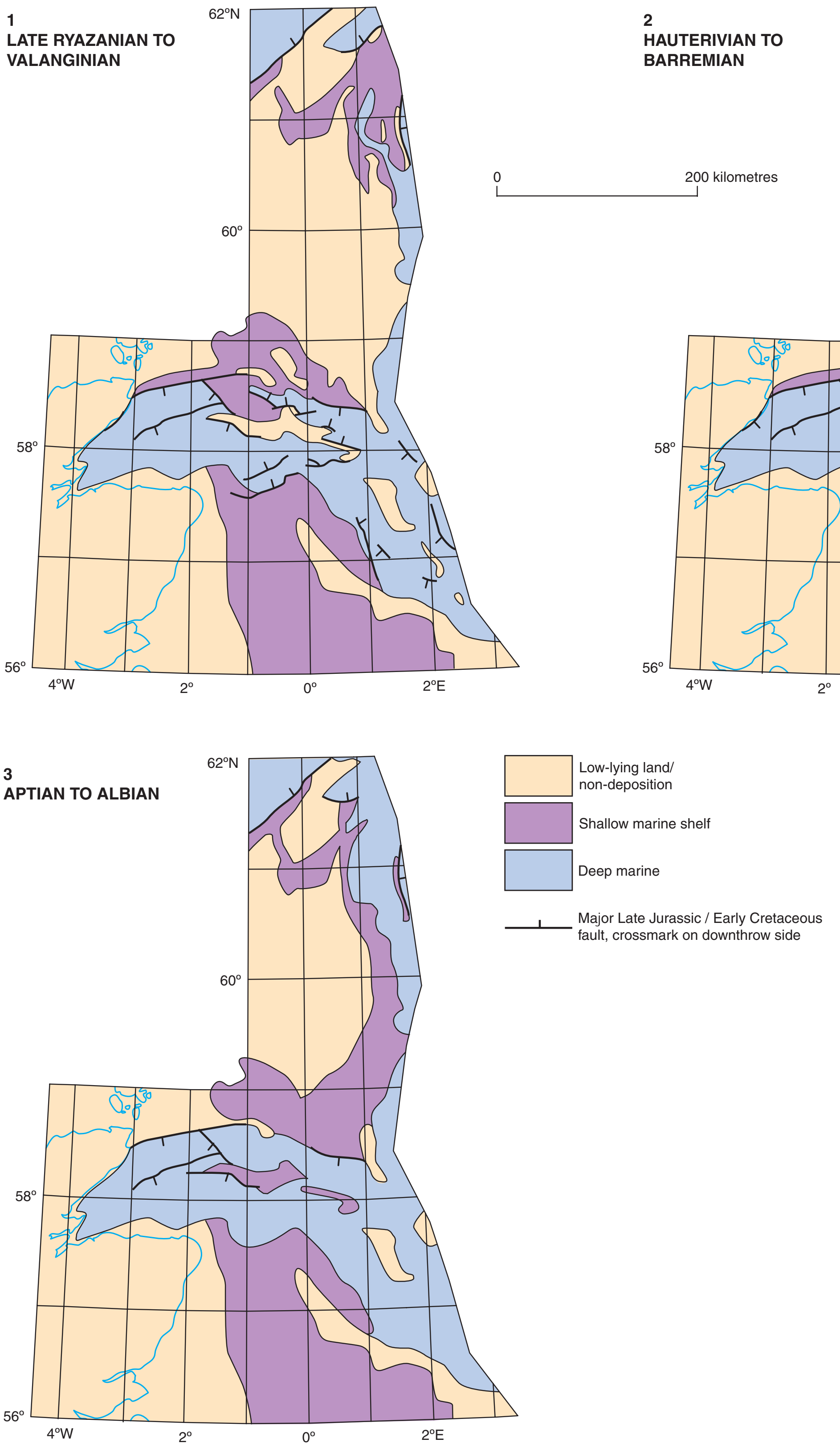


**Figure 29** Early Cretaceous palaeogeography.

throughout much of Early Cretaceous times, when they were periodically important sources of sand (Boote and Gustav, 1987; Crittenden et al., 1997, 1998).

North Sea depositional settings during the Early Cretaceous have been broadly characterised using assemblages of foraminifera, and two main biofacies have been identified (King et al., 1989). A 'shelf' biofacies is widespread over platform areas, whereas a deeper-water 'outer sublittoral-upper bathyal' biofacies is developed in the Central Graben, Moray Firth Basin, Viking Graben, East Shetland Basin and Magnus Basin. In addition a 'restricted basin' biofacies is widespread at several levels from the Hauterivian to the mid-Albian, and a 'carbonate biofacies' occurs in clastic-starved settings developed over intrabasinal highs at several levels in the Valanginian, Hauterivian and Barremian. The 'restricted basin' biofacies is developed in both shelf and deeper water 'flysch-type' environments. The 'carbonate facies' is presumed to have developed in mid- to outer-shelf environments (King et al., 1989).

### 4.4.1 Late Ryazanian to Valanginian

Initially, the late Ryazanian palaeogeography probably changed little from that established in the Late Jurassic (Figure 29). Basin modelling suggests that significant rift basin bathymetry, established in the Late Jurassic, persisted into Early Cretaceous times (Rattey and Hayward, 1993). Some sub-basins are bounded on one side by a major fault (e.g. the Witch Ground Graben, immediately north of the Renée Ridge), others, especially in the Central Graben, are synclines resulting from halokinesis of Zechstein salt, with no distinct half-graben geometry. Within the Witch Ground Graben, the Valhall unit V1 displays only a small lateral variation in the thickness and this, together with its wide distribution, suggests relatively little syndepositional differential subsidence there during late Ryazanian to mid-Valanginian times (O'Driscoll et al., 1990). However, adjacent to relict and new highs, a new generation of deep-marine sandstone was developed locally. Mass-flow sand units within the Inner Moray Firth Basin were probably derived from shallow-shelf greensand facies developed over the footwall blocks of the Wick Fault and Halibut Horst.

Differential subsidence increased significantly in mid-Valanginian times, and Valhall Formation unit V2 commonly shows marked lateral thickness variation. Jurassic basinal areas may have been modified by transpressive downwarping or were partially inverted (Oakman and Partington, 1998). Within the generally underfilled basinal areas, thick successions of slope and basin-floor mudstone and chalky mudstone are widespread. Over some palaeohighs in the Witch Ground Graben, unit V1 is absent, and this has been interpreted as evidence for a significant early Valanginian unconformity (O'Driscoll et al., 1990). Thick, mass-flow conglomerate and sandstone units (Scapa Sandstone Member) of mid-Valanginian to mid-/late Hauterivian age, accumulated in a half-graben-like depocentre on the downthrown side of the Halibut Shelf (Riley et al., 1992; Harker and Chermak, 1992). Similarly, mass-flow sandstone (Wick Sandstone Formation, Punt Sandstone Member) accumulated within the Inner Moray Firth Basin.

Within the Magnus Basin, thick units of late Valanginian to early Hauterivian sandstone and associated mudstone were deposited in a developing half-graben associated with North Atlantic rifting.

### 4.4.2 Hauterivian to Barremian

Tectonism reduced during Hauterivian times, though a minor phase of tectonic inversion and submarine erosion occurred within the Central Graben in the Danish sector (Vejbaek, 1986; Ineson, 1993; Kühnau and Michelson, 1994). The dominant control upon sedimentation during this time appears to have been eustatic sea level rise (Figure 29) (Oakman and Partington, 1998). In mid-Hauterivian to mid-/late Barremian times, the relative proportion of pelagic carbonate to siliciclastic mud sedimentation increased, resulting in the widespread deposition of argillaceous chalky limestone (unit V3 and in the North Viking Graben Cromer Knoll 'unit c', Enclosure 3, well 3/25a-4). This lithological change is thought to reflect the onset of a transgressive phase (Crittenden et al., 1991; Ineson, 1993; Kühnau and Michelson, 1994), though a change to a drier climate may also have reduced the input to the basin of fine siliciclastics (Jensen and Buchart, 1987; Ruffell and Batten 1990). In early/mid-Barremian times a phase of bottom-water anoxia produced the thin, but widespread Munk Marl. Coarse clastic sedimentation appears to have been confined mainly to the Inner Moray Firth Basin, South Halibut Basin (Wick Sandstone Formation, Coracle Sandstone Member) and Central Graben (Lower Britannia Sandstone).

### 4.4.3 Aptian to Albian

Tectonism at the start of the Aptian rejuvenated many of the pre-existing structural highs and these acted as source areas for coarse clastic sediment, even though global sea level continued to rise (Figure 29). In particular, the footwall block of the Wick Fault, the Halibut Horst and the Fladen Ground Spur were important source areas for clastic sediment. The thin, but widespread dark mudstones of the Fischschiefer (unit V5) mark an early Aptian phase of bottom-water anoxia. The Aptian section overlying the Fischschiefer includes a distinctive late Aptian unit of 'chestnut-brown' calcareous mudstone (unit V7) with abundant red-stained planktonic foraminifera, which probably marks a phase of widespread sediment starvation and sea-floor oxygenation (Lott et al., 1985; Guy, 1992; King et al., 1989).

Further tectonism during late Aptian times contributed to a major change in sedimentation that marks the onset of a phase of bottom-water oxygen-depletion within a basin with restricted access to open marine currents (King et al., 1989). Thick, but aerially restricted bodies of gravity-flow sandstones were deposited in the Central North Sea and South Viking Graben during this time (e.g. Upper Britannia Sandstone). These sandstones, together with associated thin bentonites, reflect a phase of regional tectonic instability accompanied by localised uplift, erosion and volcanic activity. Speculatively, sandstone equivalent to the Britannia Sandstone Formation might also be developed and form potential traps for hydrocarbons within the deeper parts of the Central Graben (Enclosure 3), where relatively little deep drilling has taken place.

Within the Inner Moray Firth Basin, gravity-flow sandstones continued to be deposited until final drowning of the source areas by the mid-Albian transgression. Red or pink stained mid-Albian chalky mudstones contain rich and varied planktonic foraminiferal faunas and mark the widespread transgression. A subsequent phase of more restricted water circulation (Rødby Formation unit R2) was followed in latest Albian times by a return to the red stained transgressive facies.

## 4.5 DEPOSITIONAL ENVIRONMENTS AND RESERVOIRS

The interpreted genetic environments of deposition for each formation within the Cromer Knoll Group of the UK Central and Northern North Sea are tabulated in Figure 30.

Argent et al. (2000) proposed a depositional model to account for the distribution and architecture of the Punt Sandstone Member of the Wick Sandstone Formation in the Inner Moray Firth Basin, and also suggested that this model may be applicable to other Lower Cretaceous massive deep-water sands in the Moray Firth Basin. They examined core from well 12/26–2, which is the only core to be taken to date within the Lower Cretaceous of the Inner Moray Firth Basin, and found that the Punt Sandstone comprises massive and generally structureless sandstone, with the exception of dish structures that indicate pervasive dewatering. However, the sands are partially consolidated and these sedimentary structures are poorly preserved. The sands within this core are very fine to coarse-grained and poorly sorted and have an erosive basal contact with the underlying mudstone unit. They are quartzose, with clear translucent grains, minor amounts of glauconite, carbonaceous debris and mica. Thin carbonate-cemented zones in these sands form high-sonic spikes on wireline logs. The underlying mudstone is pale to dark grey, micromicaceous, variably calcareous, fissile and bioturbated. Implicit to their depositional model is the presence of pre-existing basin topography, which provided an underlying control to sand deposition within the available accommodation space. They suggested that several mechanisms could have acted together to develop the subtle, uneven basin floor topography in the Lower Cretaceous Inner Moray Firth Basin:

- underfilled Jurassic fault-controlled lows
- differential compaction of a filled Jurassic graben
- local, active Lower Cretaceous extensional faulting

Argent et al. (2000) envisaged that sand progressively filled depressions in the basin floor, beginning with those most proximal to the sediment input points in the Inner Moray Firth Basin to the west. Once this basin was filled, a feeding channel propagated by incision across the filled basin and interbasin high, allowing sediment to be transported eastwards into a neighbouring basin. This model is comparable to the 'fill and spill' process for massive sand deposition illustrated by Weimer et al. (1998) in the Gulf of Mexico, where the basin floor is characterised by numerous ovoid 'mini-basins' caused by salt withdrawal. The linked architectural elements principally consist of 'ponded' sheets and back-filled, linear, incised channels (Figure 31).

### 4.5.1 Wick Sandstone Formation

Mass-flow sandstones of the Captain Sandstone Member form the reservoir for heavy oil in the Captain Field (UK Block 13/22a) that overlies the western tip of the Captain Ridge (the western extension of the Halibut Horst, Figure 32). The reservoir can be informally divided into the upper and lower Captain sandstones, separated by a unit of tuffaceous mudstone known as the mid-Captain Shale (Rose, 1999). The Captain sandstones were sourced from shallow marine greensand that was originally deposited to the north of the Wick Fault. The lower Captain Sandstone is best

| CROMER KNOLL GROUP | |
|---|---|
| Rødby Formation | Deep water, open marine environment |
| Carrack Formation | Deep water, restricted marine |
| Britannia Sandstone Formation | Basin floor fans |
| Wick Sandstone Formation | Apron fringe and basin floor fans |
| Valhall Formation | Deep water, open marine with sporadic anoxia |

**Figure 30** Depositional setting of the Cromer Knoll Group.

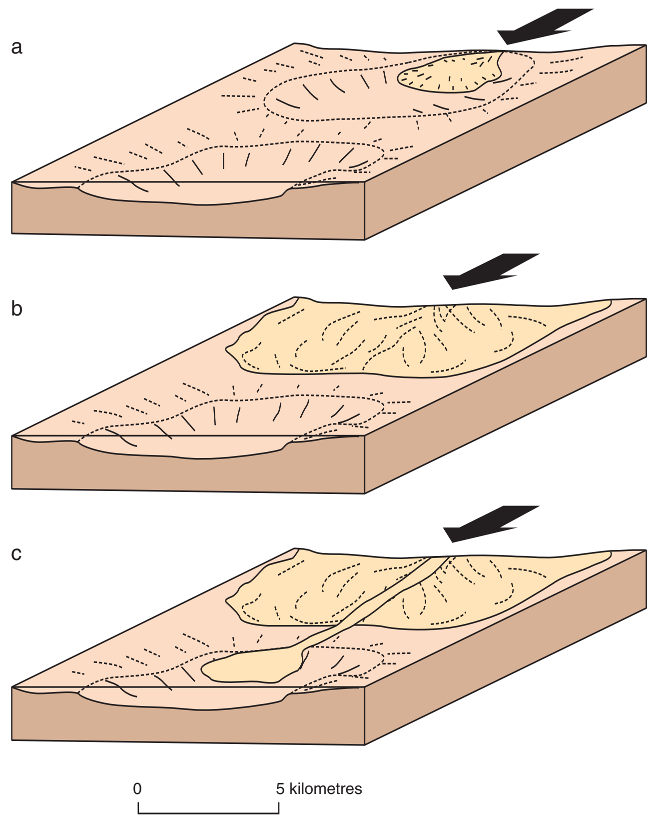


**Figure 31** 'Fill and Spill' model for sand emplacement, in which a channel sand feeds (a) then fills (b) a basin, leading to bypass by the feeder channel (c) and filling of a second basin (after Argent et al., 2000).

developed in a north-north-west-trending sand fairway interpreted as a backfilled submarine canyon that cuts across the Captain Ridge (Figure 32). The upper Captain Sandstone is developed as a continuous sheet that systematically thins and pinches out to the south-south-east. On wireline logs, the sandstones display a blocky character, and form amalgamated sets that can be over 30 m thick. Core evidence indicates that the sandstones are predominantly massive suspension fall-out sediments. Rare bedding, parallel laminations and dewatering structures, including vertical pipes and sporadic dish structures are described from the cores. Evidence for traction current deposition is uncommon, but sporadic mudstone clasts are concentrated into imbricated horizons and there are a few occurrences of graded beds with parallel laminated horizons overlain by cross-bedded units (Rose, 1999).

### 4.5.2 Britannia Sandstone Formation

The Britannia Sandstone Formation forms the reservoir for gas condensate within the Britannia Field, which is the largest producing hydrocarbon accumulation in Lower Cretaceous sediments of the North Sea. The formation comprises mainly fine- to medium-, but locally coarse-grained gravity-flow sandstone and associated mudstone. Both the bioclastic debris and the abundant carbonaceous material within the sandstone units suggest derivation from a high-energy, shallow marine shelf, which may have been located on the Fladen Ground Spur. The Lower Britannia Sandstone is associated with an open marine hemipelagic mudstone similar to that of the Valhall Formation, whereas the Upper Britannia Sandstone is associated with

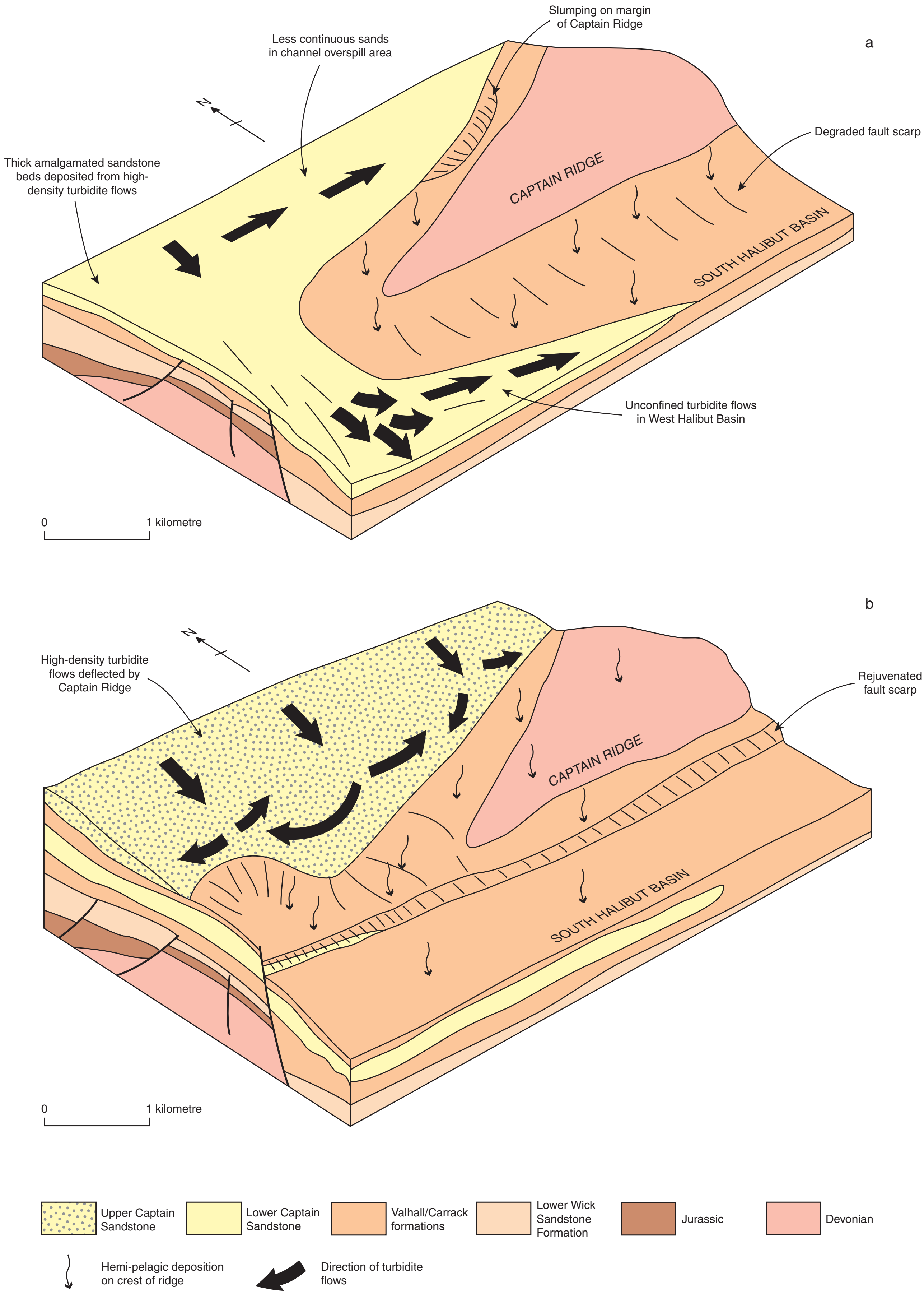


**Figure 32** Captain Sandstone depositional model for (a) the lower Captain Sandstone and (b) the upper Captain Sandstone (after Rose, 1999).

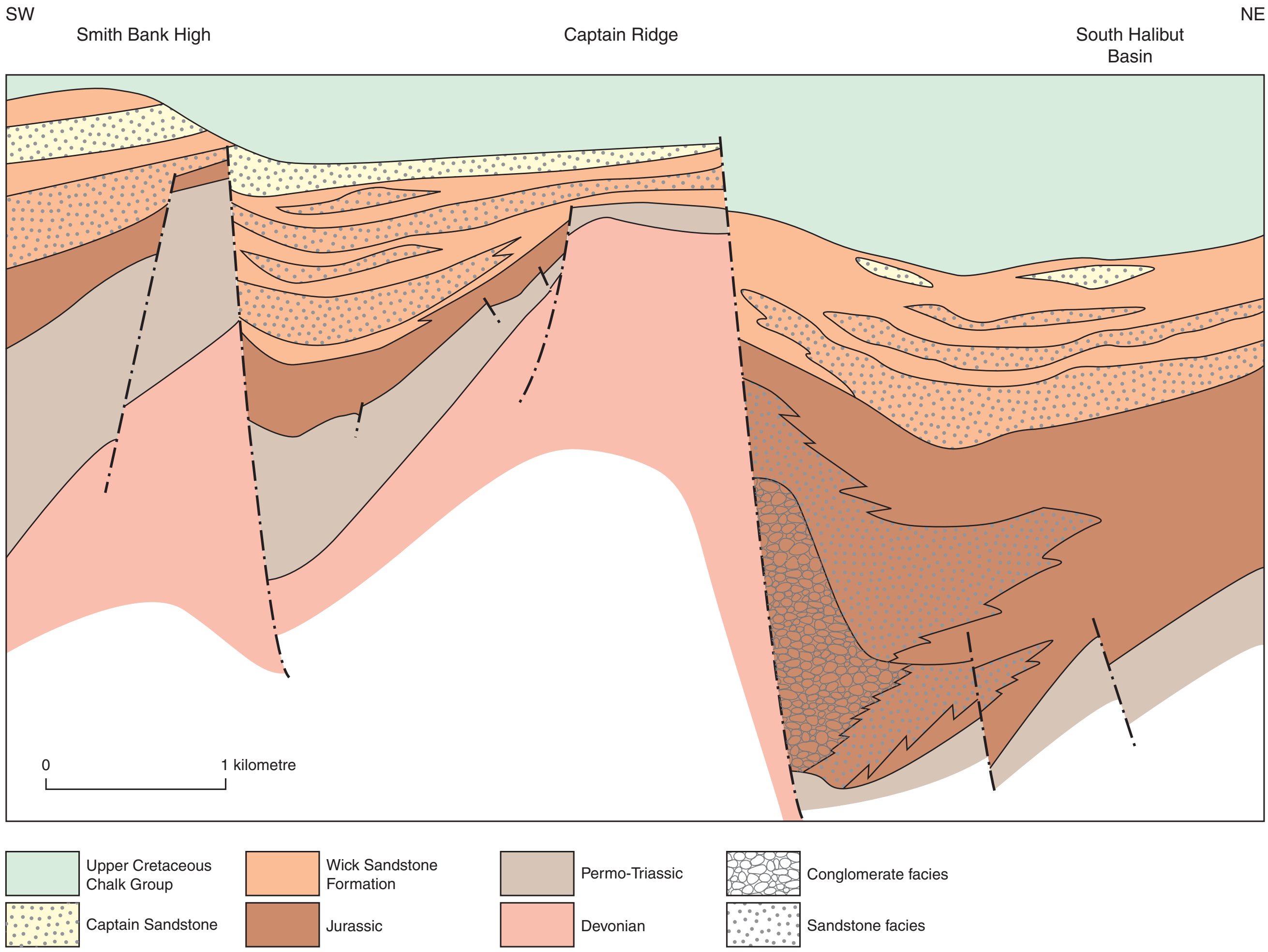


**Figure 33** Schematic structure of the Captain Field (after Rose, 1999).

disaerobic mudstones characteristic of the Carrack Formation. In the western part of the field (UK Blocks 15/29a and 15/30), the lower Britannia Sandstone forms the main reservoir. Clean, high-density turbidite sandstone units are well developed in the lower Britannia Sandstone. These turbidites are massive or show dish structures, commonly with near vertical water escape pipes and sandstone dykes towards the top of the beds. The upper Britannia Sandstone is dominated by units of argillaceous, laminated sandstone with dewatering structures, interpreted as the deposits of muddy slurry flows (Guy, 1992; Jones et al., 1999), together with thick-bedded and vertically stacked units of massive, relatively mud-free sandstone with dewatering structures. These facies are interbedded with upward-fining and upward-coarsening sandstone and conglomeratic sandy mudstone.

### 4.5.3 Scapa Sandstone Member

The Scapa Sandstone Member forms an important oil reservoir in the Scapa Field and in nearby fields. The Scapa Sandstone Member in the Scapa Field was derived from Jurassic, Permian and Carboniferous sources eroded from the Halibut Shelf, possibly during a phase of localised tectonism (Harker and Chermak, 1992; Oakman and Partington, 1998). Conglomeratic facies fringe the fault scarp to the north of the Halibut Shelf and pass laterally into reservoir sandstone that accumulated in more distal areas. The reservoir sandstone units comprise a range of gravity-flow deposits and are interbedded with calcareous and chalky mudstone typical of the Valhall Formation. The sandstone units are fine- to medium-grained and mainly massive to poorly laminated. Core evidence indicates that both non-graded and upward-fining sandstone is present. Clasts of micrite and mudstone, together with comminuted carbonaceous debris and broken shelly material are common. The widespread occurrence of structures associated with sediment traction suggests that bottom currents reworked the sands. The associated conglomerate facies are matrix-supported and poorly sorted. Matrix composition varies from sandy mudstone to coarse sandstone or conglomerate. Slump structures and deformed clasts are common in the conglomerate facies. Biostratigraphic studies indicate that the locus of sand deposition across the Scapa Field shifted through time (Riley et al., 1992), possibly in response to continued tectonism.

## 4.6 TRAPS

A number of important hydrocarbon-producing fields and recent discoveries occur in the Lower Cretaceous deep-water sandstones of the Moray Firth and South Halibut basins (Figure 3) (Garrett et al., 2000). Law et al. (2000) summarised many of the trapping mechanisms associated with this exploration 'play fairway' in the Inner Moray Firth and South Halibut basins. They recognised four-way

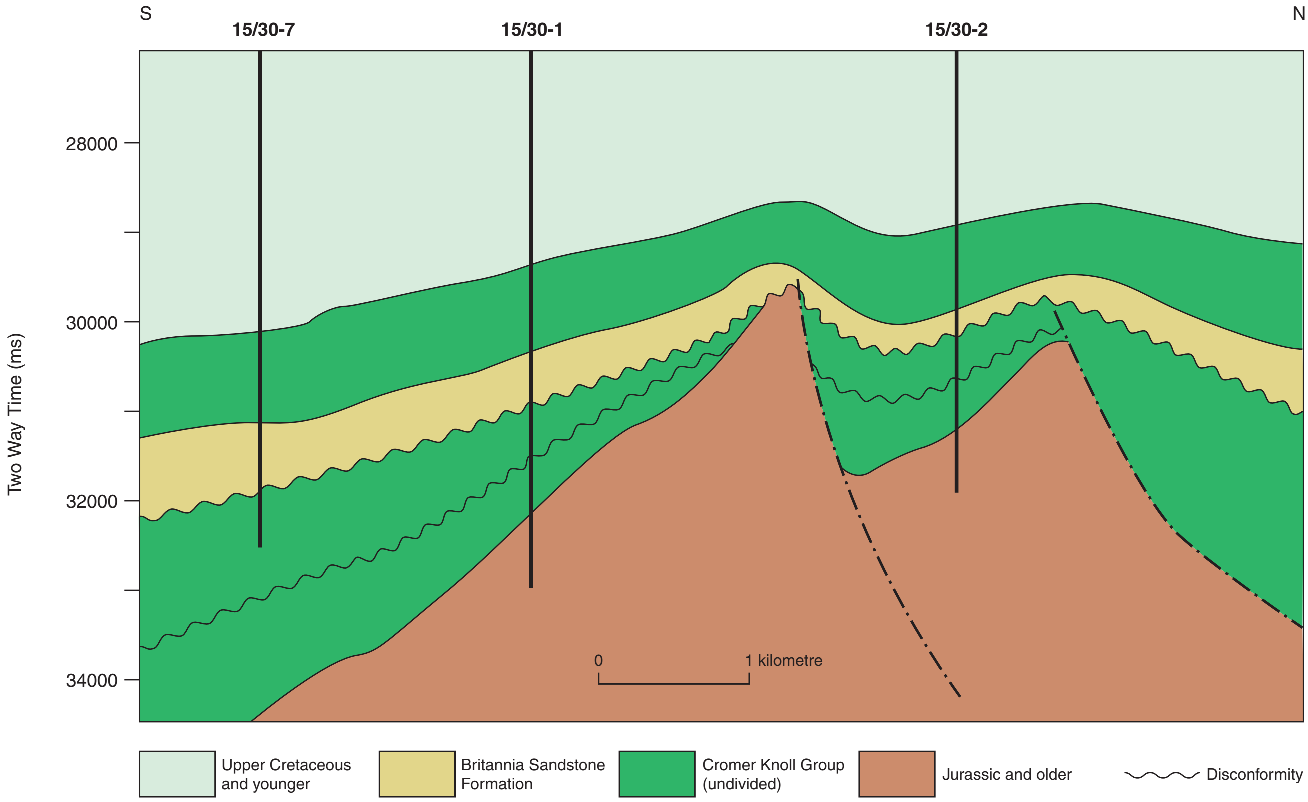


**Figure 34** Structure of the Britannia Field (after Copestake et al., 2003).

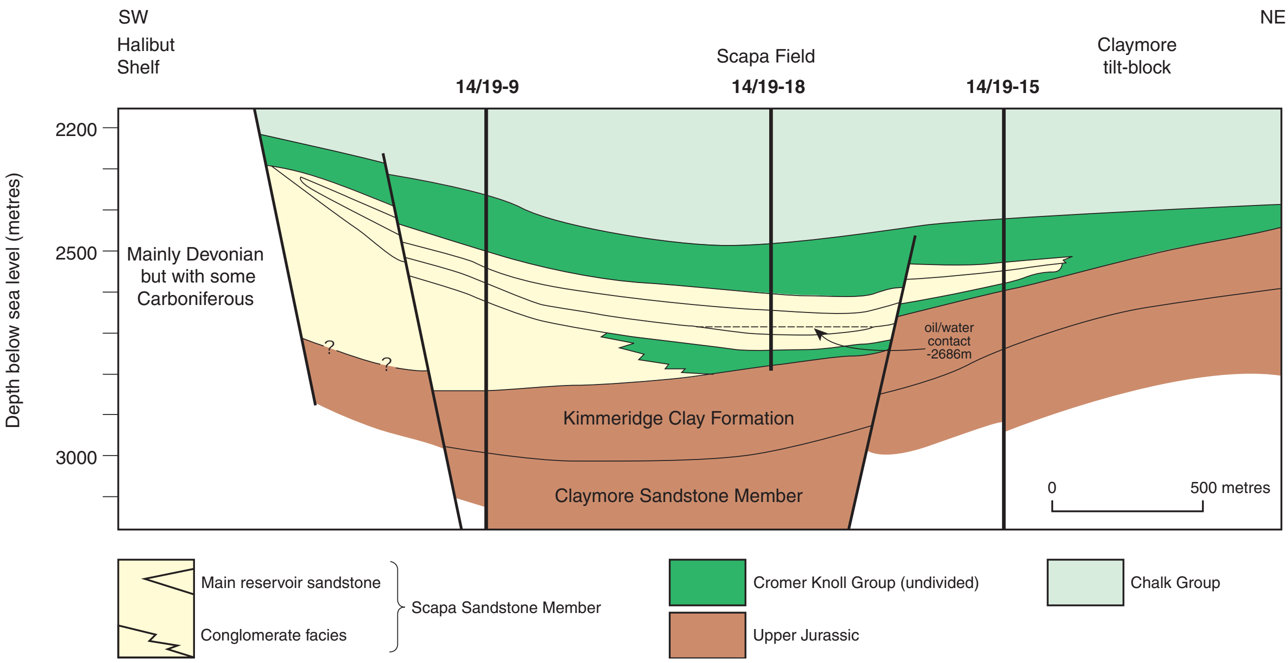


**Figure 35** Structure of the Scapa Field (after McGann et al., 1991).

dip closure traps (e.g. the 'Hannay' oil accumulation) and combination traps involving structural closure and stratigraphic pinch-out of the reservoir (e.g. the 'Goldeneye' oil accumulation). Law et al. (2000) commented that almost all the successful traps they reviewed have two key elements. First, structural closure to the west, counter to the regional dip from west to east, and second either structural closure or sand pinch-out to the north or east, countering the rotation of dip approaching the Halibut Horst (e.g. 'Goldeneye', Captain). Structural closure is provided either by inversion of pre-existing structures or by drape over them.

The abundance of fields marginal to the Halibut Horst may be a function of the exploration activity in the area. Outside this area, many Lower Cretaceous depocentres within the UK Central and Northern North Sea have not yet been tested by drilling and may still yield discoveries. The Agat Field in Norwegian Waters, comprising Aptian to Albian mass-flow sands on the margin of the North Viking Graben, indicates that conditions for Lower Cretaceous reservoir charging do exist in the Northern North Sea (Copestake et al., 2003), but until further exploration takes place it remains uncertain whether significant additional reserves will be found.

### 4.6.1 Captain Field

The Captain Field lies in UK Block 13/22a on the eastern margin of the Inner Moray Firth Basin. The trap overlies the Captain Ridge at the western end of the Halibut Horst, and is estimated by the field operators to contain up to 1.5 billion barrels of oil in place within the Captain Sandstone Member. The trap combines elements of dip closure and stratigraphic pinch out of the reservoir sandstones (Figure 33). The dip closure to the north, west and south is caused by drape over the west-plunging Captain Ridge. Closure to the east is controlled by stratigraphic pinch out of the reservoir. The oil is of high viscosity and is biodegraded (Rose, 1999). There are two main reservoirs, known informally as the upper and lower Captain sandstones (Figure 32), separated by the mid-Captain Shale. The 'sandstones' are largely unconsolidated and lie at relatively shallow depths of about 900 m below sea bed.

### 4.6.2 Britannia Field

The Britannia Field lies in UK Blocks 15/30 and 16/26 in the Outer Moray Firth Basin and contains 4.3 trillion cubic feet of gas in place and condensate reserves of 150 million barrels. The field includes the discoveries that were formerly known as Kilda and Lapworth. The hydrocarbons are contained in the Britannia Sandstone Formation and the trapping mechanism incorporates a combination of stratigraphic pinch out of the reservoir over the Fladen Ground Spur to the north and structural closure (Figure 34) (Jones et al., 1999). Mudstone units of the Cromer Knoll Group provide the seal.

### 4.6.3 Scapa Field

The Scapa Field in UK Block 14/19 of the Outer Moray Firth Basin is a combined structural and stratigraphic trap (Figure 35) (McGann et al., 1991; Harker and Chermak, 1992). Oil is contained in the Scapa Sandstone Member, which forms a wedge-shaped body that abuts the faulted northern margin of the Halibut Shelf and thins northwards onto the Claymore tilt-block. Deposition of these coarse clastic sediments may have been accompanied by active oblique slip tectonism along a pre-existing Jurassic half graben. The tectonism, together with subsequent differential compaction, has resulted in the present day structure of the field; a fault bounded south-east-plunging syncline with relatively little internal faulting. The field is terminated to the south-west by a combination of major 'down-to-the-north' faults and a facies change from reservoir sandstone to tightly cemented conglomerate.

Closure to the north-east is controlled by onlap onto the dip slope of the Claymore tilt-block and by lateral passage from reservoir sandstones to mudstones and chalky mudstones. The south-eastern limit of the field is determined by the dip of the plunging syncline. The structure is not filled to spill point. To the north-west of the Scapa Field, trapping probably results from a combination of dip and fault closure and stratigraphic pinch-out of the reservoir sandstone (McGann et al., 1991).

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# Enclosure 3
# 'Lower Cretaceous' (Cromer Knoll Group) of the UK Central and Northern North Sea

1:1 000 000

BGS Report RR/03/01: Middle Jurassic, Upper Jurassic and Lower Cretaceous of the UK Central and Northern North Sea

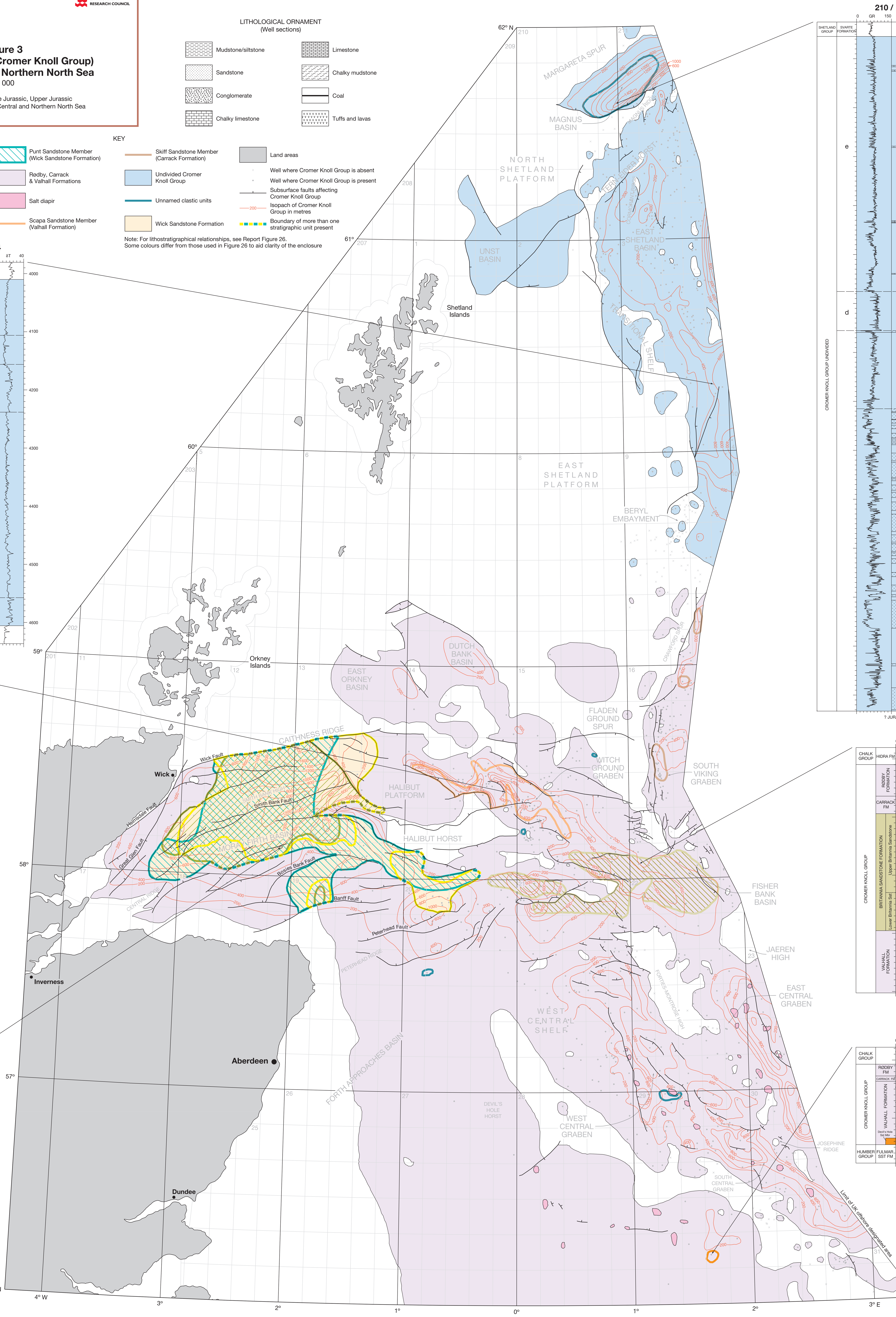
LITHOLOGICAL ORNAMENT
(Well sections)

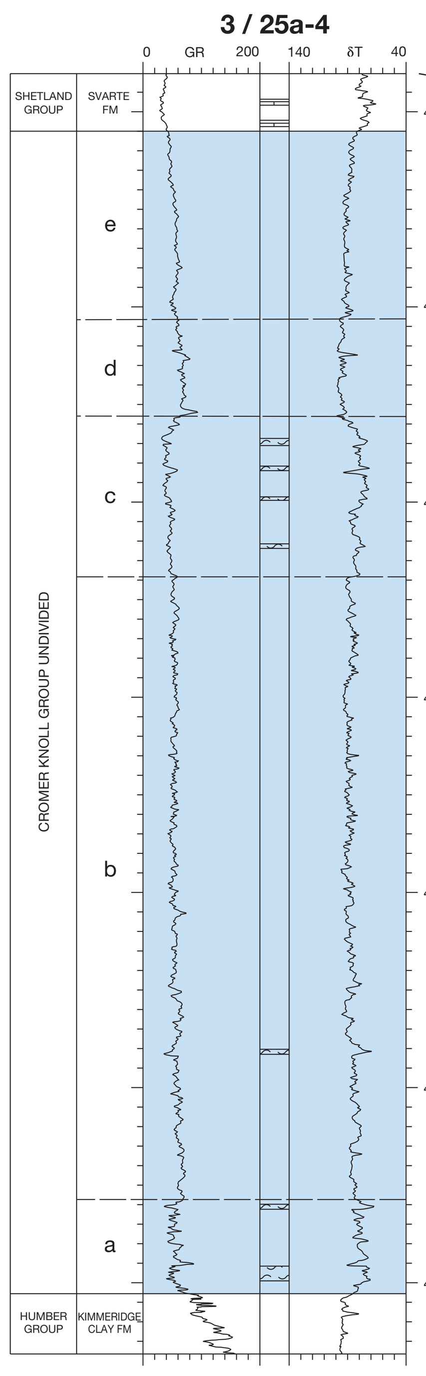
- Mudstone/siltstone
- Limestone
- Sandstone
- Chalky mudstone
- Conglomerate
- Coal
- Chalky limestone
- Tuffs and lavas

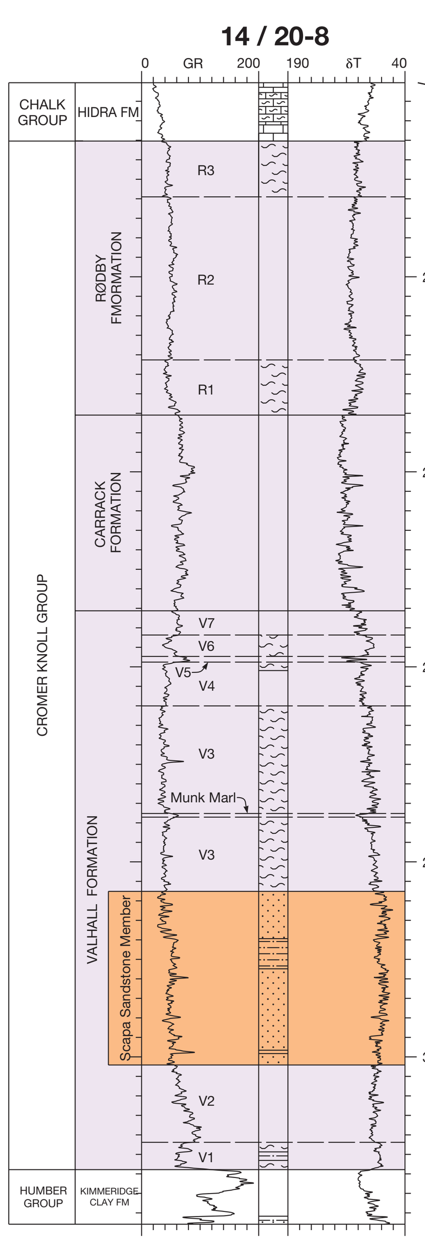
KEY

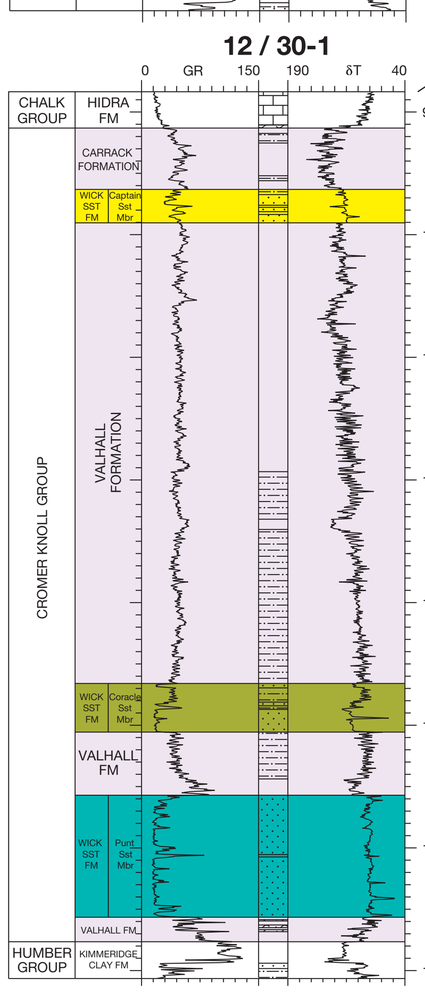
- Britannia Sandstone Formation
- Captain Sandstone Member (Wick Sandstone Formation)
- Coracle Sandstone Member (Wick Sandstone Formation)
- Devil's Hole Sandstone Member (Valhall Formation)
- Punt Sandstone Member (Wick Sandstone Formation)
- Redby, Carrack & Valhall Formations
- Salt diapir
- Scapa Sandstone Member (Valhall Formation)
- Skiff Sandstone Member (Carrack Formation)
- Undivided Cromer Knoll Group
- Unnamed clastic units
- Wick Sandstone Formation
- Land areas
- Well where Cromer Knoll Group is absent
- Well where Cromer Knoll Group is present
- Subsurface faults affecting Cromer Knoll Group
- Isopach of Cromer Knoll Group in metres
- Boundary of more than one stratigraphic unit present

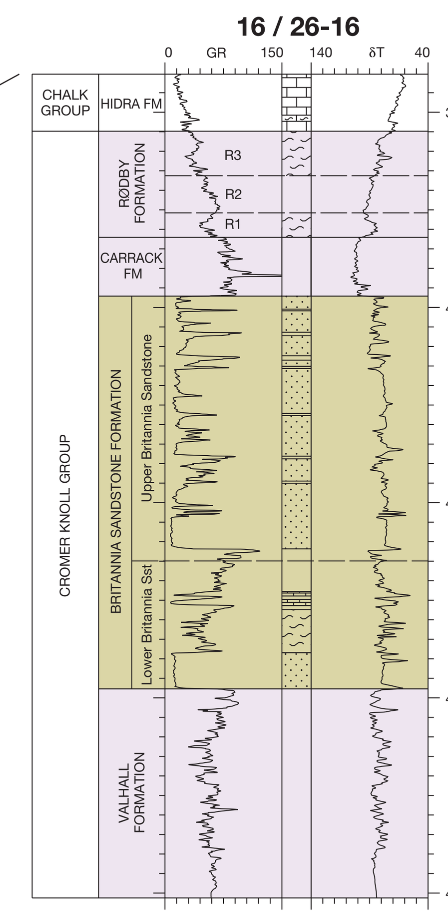
Note: For lithostratigraphical relationships, see Report Figure 26.
Some colours differ from those used in Figure 26 to aid clarity of the enclosure

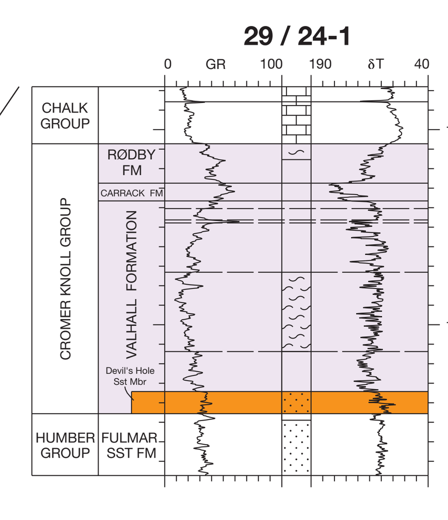


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# Enclosure 1
## 'Middle Jurassic' (Fladen/Brent group) of the UK Central and Northern North Sea
1:1 000 000

BGS Report RR/03/01: Middle Jurassic, Upper Jurassic and Lower Cretaceous of the UK Central and Northern North Sea

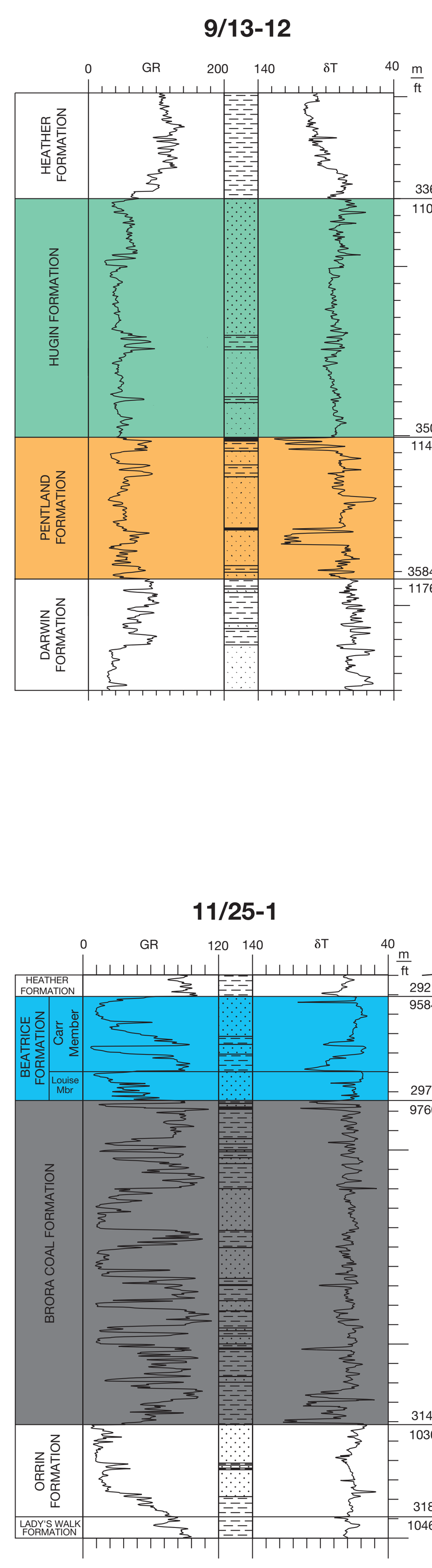
### KEY

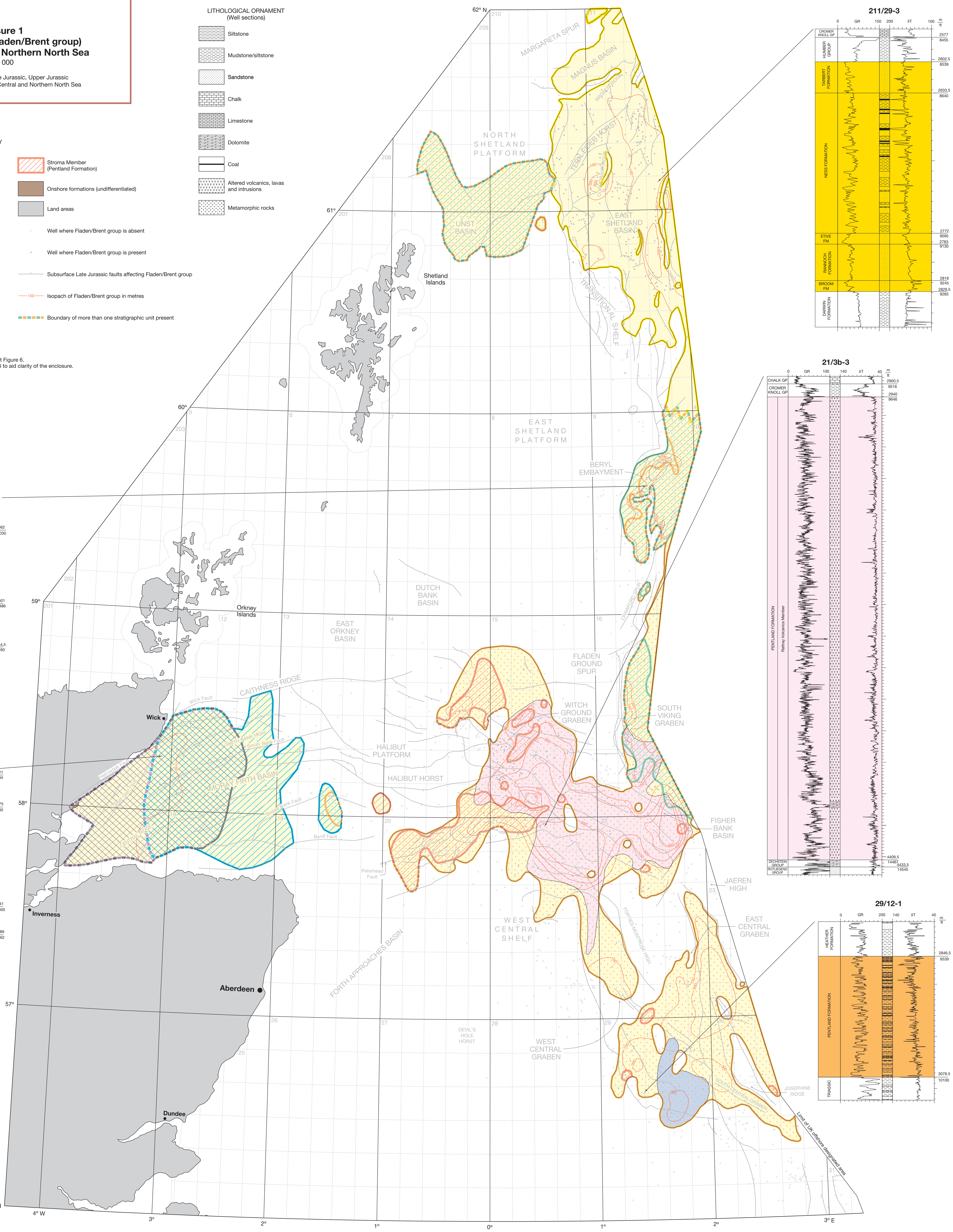
- Beatrice Formation
- Brent Group
- Brora Coal Formation
- Callovian strata of Heather or Beatrice Formation facies
- Fladen/Brent group
- Hugin Formation
- Pentland Formation
- Rattray Volcanics Member (Pentland Formation)
- Ron Volcanics Member (Pentland Formation)
- Stroma Member (Pentland Formation)
- Onshore formations (undifferentiated)
- Land areas
- Well where Fladen/Brent group is absent
- Well where Fladen/Brent group is present
- Subsurface Late Jurassic faults affecting Fladen/Brent group
- Isopach of Fladen/Brent group in metres
- Boundary of more than one stratigraphic unit present

Note: For lithostratigraphical relationships, see Report Figure 6.
Some colours differ from those used in Figure 6 to aid clarity of the enclosure.

### LITHOLOGICAL ORNAMENT (Well sections)

- Siltstone
- Mudstone/siltstone
- Sandstone
- Chalk
- Limestone
- Dolomite
- Coal
- Altered volcanics, lavas and intrusions
- Metamorphic rocks

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# Enclosure 2
# 'Upper Jurassic' (Humber Group) of the UK Central and Northern North Sea

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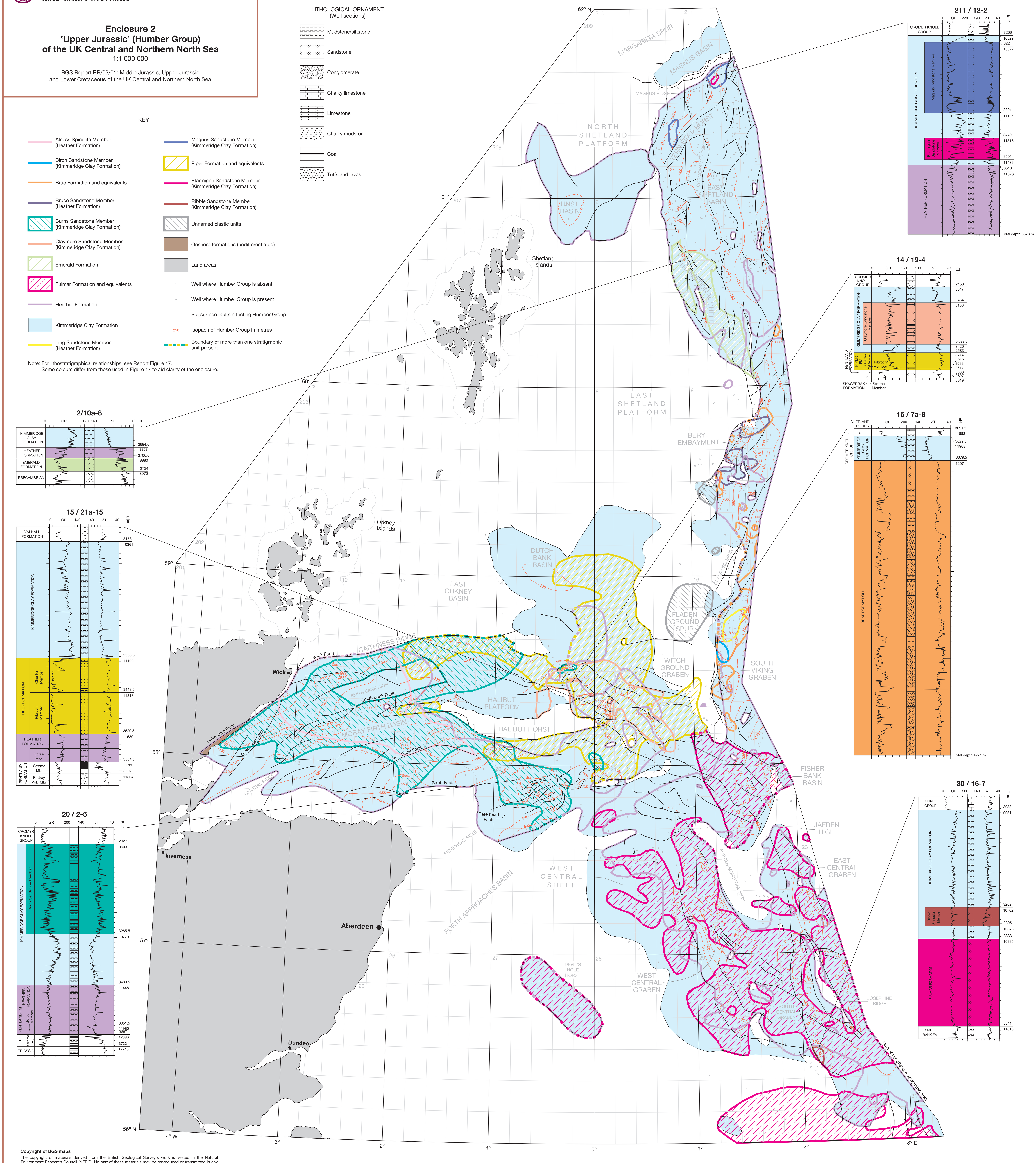
BGS Report RR/03/01: Middle Jurassic, Upper Jurassic and Lower Cretaceous of the UK Central and Northern North Sea



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