Principal tectonic events in the evolution of the northwest European Atlantic margin

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Abstract: The Atlantic margin of the Norwegian, Faeroese, British and Irish sectors encompasses numerous basins which vary in character, but are related in terms of their evolution as part of a single passive margin. Lineament analysis of the margin shows a predominance of NE–SW, N–S and NW–SE trends, mainly reflecting Mesozoic–Cenozoic extensional faulting. Some major Precambrian and Caledonian structures, principally steeply-dipping shears, were opportunistically reactivated according to the prevalent stress pattern. The extensional history of the margin spanned a *c.* 350 Ma interval between the close of the Caledonian orogeny and early Eocene break-up. Episodes of Permo-Triassic, (mainly late) Jurassic, Early Cretaceous, 'middle' Cretaceous and latest Cretaceous–Early Eocene age can be distinguished from one another in space and time. The anomalous length of the total period of extension prior to continental separation is partly explained by step-wise lateral offsets of the crustal thinning axes towards the line of eventual break-up. The picture is, however, complicated by some changes in extensional style and direction. These include mosaic-like fragmentation of Pangea in the Permo-Triassic, the imposition of more systematic E–W extension by Jurassic times, and the change to NW–SE extension focused on the present margin in the Early Cretaceous (probably Hauterivian). The resulting structural configuration reflects the overprinting of a complex network of Jurassic and older basins by a continuous NE–SW chain of deep Cretaceous–Cenozoic basins. An extensional pulse of latest Cretaceous to earliest Eocene age (best observed in the Norwegian Sea) with extensive basaltic volcanism led to continental break-up at approximately 53 Ma.

The margin was structurally modified by some important events postdating the Early Eocene. On break-up, the background stress field changed from extension to mild SE-directed compression, and widespread inversion structures formed in the thick Cretaceous–Cenozoic depocentres. The inversions can best be explained by ridge-push from the adjacent spreading centres, but could also be linked to Tethyan closure events and changes in the North Atlantic spreading vector. Post-break-up extension of the North Atlantic passive margins has been reported in the western Barents Sea, Jan Mayen and East Greenland and (for the first time here) in the northern Vøring Basin. We propose that these areas were linked by a single extensional pulse induced by the change to a more ESE-directed relative plate motion in the Oligocene–Miocene.

Major uplift and exhumation of peripheral landmasses and inboard basins took place at intervals throughout the Cenozoic. Initial uplift can be attributed to pre-break-up rifting and post-break-up compression, but the most significant event took place in the Plio-Pleistocene and was intimately associated with glacial erosion and isostatic adjustment through repeated glaciations and interglacials. The regional scale of this event and its significance for exploration is widely under-estimated.

The Atlantic margin of northwest Europe is currently the subject of intense exploration activity by the petroleum industry. Deep water acreage under evaluation spans four national sectors (Norwegian, British, Faeroese and Irish). The superficial similarity of many of the exploration plays and the repeated structural geometries make it advantageous to take a regional view in identifying significant tectonic phases and their implications for prospectivity. A more detailed account of exploration concepts (frontier reservoirs, source rocks, charging regimes and trapping styles) is given by Doré *et al.* (1997*a*), while Spencer *et al.* (1999) provide a systematic, basin-by-basin description of the petroleum system on the margin.

The area covered in this paper is the part of the Atlantic passive margin bounded to the west and northwest by oceanic crust of Cenozoic age. It extends for approximately 3000 km from the western part of the Barents Sea to the termination of the Rockall Trough and Porcupine Basin against oceanic crust of Cretaceous age. The overall geological configuration of the margin is illustrated by a tectonic elements map (Fig. 1) and by a series of geoseismic cross-sections (Fig. 2). These diagrams, which will be referred to throughout, show that the margin is essentially defined by a series of linked NE–SW trending Cretaceous–Cenozoic depocentres. Before the development of this basin chain and Cenozoic plate separation, the NW European Atlantic margin had no existence as a single geological province, except in a very general sense as a reactivation of the Caledonian fold belt (see following section). The Cretaceous–Cenozoic basins overprint a complex array of older rifts (e.g. Permo-Triassic and Jurassic) which, based on position and trend, show a more indirect relationship with the adjacent oceanic crust.

Overall, the basins shown in Figs 1 and 2 record the most easily observable part of an extensional history lasting from post-orogenic back-sliding and collapse following the Late Caledonian consolidation of Laurasia (*c.* 400 Ma) to Early Eocene break-up (*c.* 53 Ma). The prolonged history of intermittent extension over 350 Ma contrasts dramatically with some other extensional systems – for example, the rifting

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Table 1. List of abbreviations used in the figures for structural, magmatic and sedimentary features

AD	Anton Dohrn Seamount	MA	Modgunn Arch
ADT	Anton Dohrn Transfer	MR	Mohns Ridge
AR	Aegir Ridge	MT	Moine Thrust
B	Brønnøysund Basin	MTFZ	Møre–Trøndelag Fault Zone
BAF	Barra Fan	MVR	Median Volcanic Ridge (Porcupine)
BF	Billefjorden Fault Zone	N	Nordkapp Basin
BJ	Bjørnøya Basin	NCS	North Celtic Sea Basin
BJF	Bjørnøya Fan	ND	Naglfar Dome
BK	Bothnian–Kvaenangen Fault Complex	NOR	Nordland Ridge
BL	Bivrost Lineament	NR	Northern Rockall Trough
BSZ	Bothnian–Senja Shear Zone	NS	Nordfjord–Sogn Detachment
BVR	Barra Volcanic Ridge	O	Orphan Basin
C	Central Graben	OG	Oslo Graben
CF	Caledonian Front	OH	Outer Hebrides Fault Zone
COB	Continent–Ocean Boundary	OL	Ormen Lange Dome
E	Erlend Transfer	P	Porcupine Basin
EC	Erlend Complex	PZ	Protogine Zone
EF	East Faeroes High	R	Rockall Trough
EG	East Greenland Rift	RB	Røst Basin
EJMFZ	East Jan Mayen Fracture Zone	ROB	Rosemary Bank
ET	Erris Trough	S	Sverdrup Basin
F	Froan Basin	SB	Sørvestnaget Basin
FD	Faeroes Dome	SFZ	Senja Fracture Zone
FF	Fles Fault Zone	SH	Sea of the Hebrides Basin
FS	Faeroe-Shetland Basin	SL	Surt Lineament
G	Gjallar Ridge	SR	Senja Ridge
GB	Galicia Bank Basin	SSF	Sula Sgeir Fan
GGF	Great Glen Fault	ST	Slyne Trough
GM	Geikie Margin	T	Tromsø Basin
H	Halten Terrace	TK	Trollfjord-Komagelv Fault Zone
HB	Hammerfest Basin	UB	Unst Basin
HBF	Highland Boundary Fault	V	Vestfjorden Basin
HF	Hornsund Fault Zone	VB	Vøring Basin
HG	Hel Graben	VD	Vema Dome
HH	Helland–Hansen Arch	VF	Variscan Front
HZ	Hardangerfjord Shear Zone	VG	Viking Graben
HT	Hatton Trough	VH	Veslemøy High
IS	Iapetus Suture	VMH	Vøring Marginal High
J	Judd Transfer	VT	Victory Transfer
JB	Jeanne D'Arc Basin	VV	Vestbakken Volcanic Province
JM	Jan Mayen	WJMFZ	West Jan Mayen Fracture Zone
JML	Jan Mayen Lineament	WR	Westray Ridge
KOR	Kolbeinsey Ridge	WSB	West Shetland Basin
KR	Knipovitch Ridge	WSO	West Spitsbergen Orogen
L	Labrador Sea	WT	Westray Transfer
LL	Lofoten Line (informal, Doré *et al.* 1997*b*)	WTR	Wyville–Thompson Ridge
LR	Loppa-Ringvassøy Fault Complex	YR	Ymir Ridge
MB	Møre Basin		

between Africa and Arabia, which developed into seafloor spreading in the Red Sea in approximately 15–20 Ma (Girdler 1991). The long duration of rifting in the NE Atlantic is illustrated by Fig. 3, which shows migration of successive rift axes from Jurassic times onwards, based on crustal profiles, magmatic features and observed age and intensity of faulting. The axes to some extent reflect changing stress directions through time, with the most significant swing in extensional vector being that from E–W to NW–SE in the early Cretaceous (see later sections). Figure 3 also shows the progressive migration of rift axes towards the eventual site of Early Eocene Atlantic opening. This reflects a consistent pattern whereby each rift basin has side-stepped, and only partly reactivated the constituent faults of, the preceding one. One possible explanation for this geometry is that mantle material beneath areas of crustal thinning, given enough time to cool, is stronger than the adjacent continental lithosphere and will thus be avoided by subsequent rifting, as suggested by Steckler & ten Brink (1986). The thermal state of the lithosphere, as affected by the cooling time between successive rifts, is a key factor in determining lithospheric strength (Kusznir & Park 1987) and may explain the longevity of the extensional regime.

Inherited grain and reactivation

The inheritance of basement structural grain is widely considered to be an important factor in the structural development of NW Europe (e.g. Coward 1990; Bartholomew *et al.* 1993; Doré *et al.* 1997*b*). The strong association, albeit mainly circumstantial, between onshore basement structure and offshore basin geometry is illustrated by the lineament map of Fig. 4. At the largest scale, the northwest European Atlantic margin reflects a somewhat oblique re-opening along the Caledonian suture system and fold belt. The oblique opening left large tracts of Laurentian crystalline basement along the margin, including the Scottish Highlands and, by implication, the shallow basement of the Rockall Bank (Figs 1 and 4). On the Barents Sea margin, opening followed a northerly course along

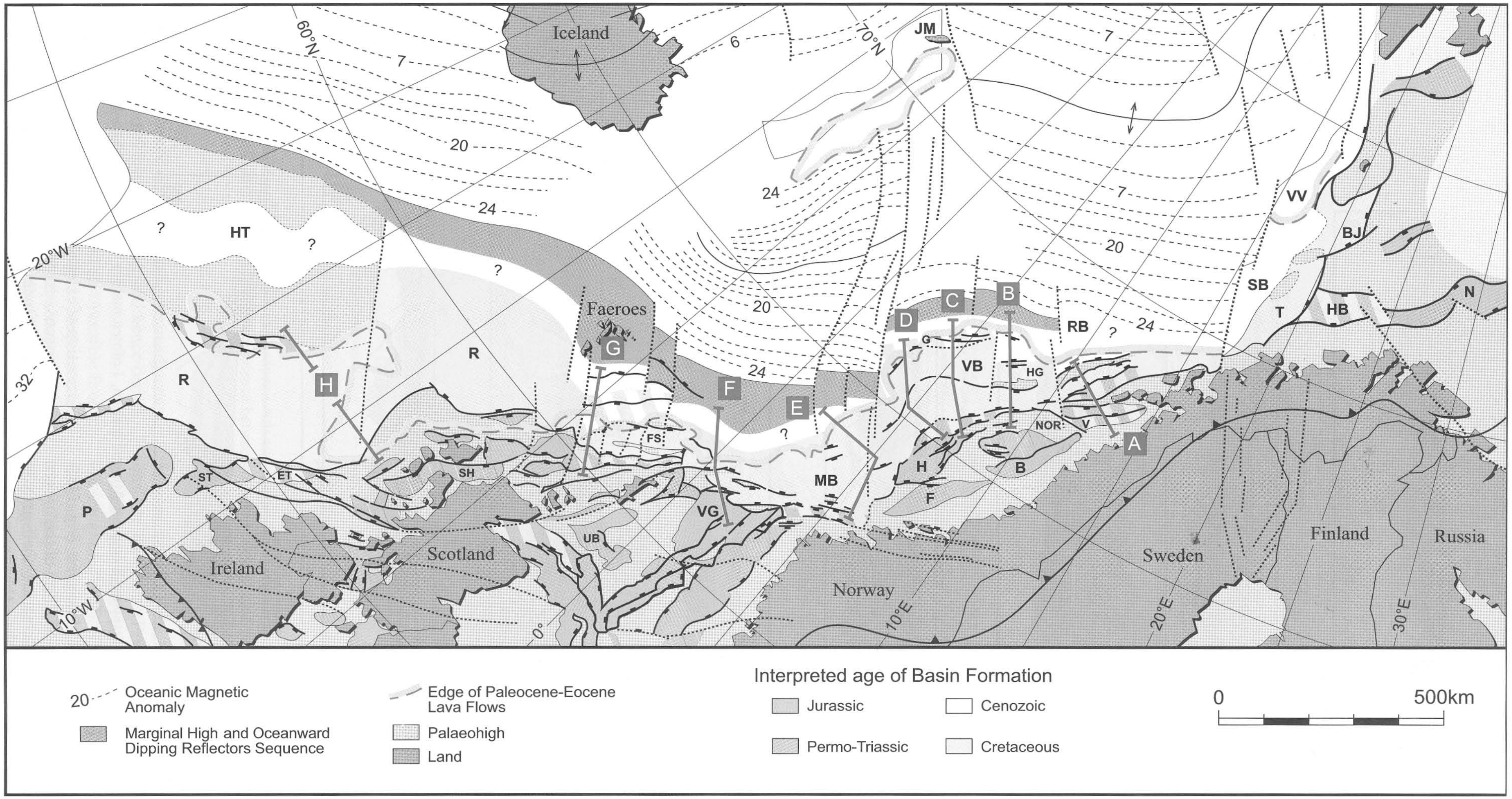

Fig. 1. Tectonic elements map of the northwest European Atlantic margin and adjacent oceanic crust, western Barents Sea to southwestern Rockall Trough. Basins are coloured according to the principal extensional episodes responsible for their formation. Extent of Paleocene–Eocene lava flows, marginal highs and oceanic magnetic anomalies are also indicated. For abbreviations see Table 1.

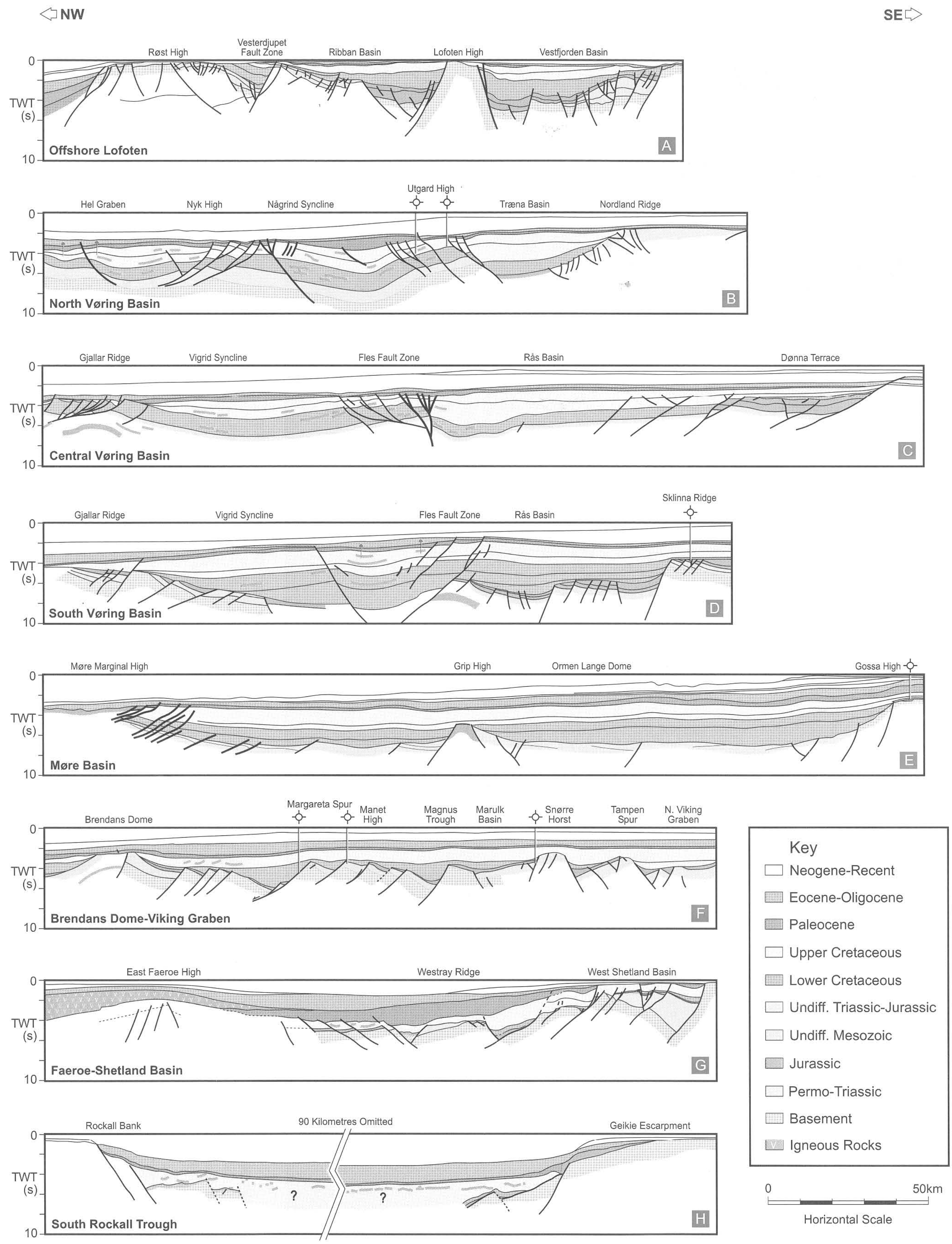

Fig. 2. Geoseismic cross-sections over the northwest European Atlantic margin, Lofoten margin to Rockall Trough. For locations see Fig. 1.

the Svalbardian–Innuitian arm of the Caledonides (e.g. Gudlaugsson *et al.* 1987), while a buried NE–SW arm of the orogen is postulated by some workers to traverse the shelf area to the east (e.g. Johansen *et al.* 1994). This phenomenon, the formation of extensional zones and new oceans along the line of old orogens, is common in the geological record and is a basic constituent of the 'Wilson Cycle'. Its causes are poorly understood, although it has recently been suggested that

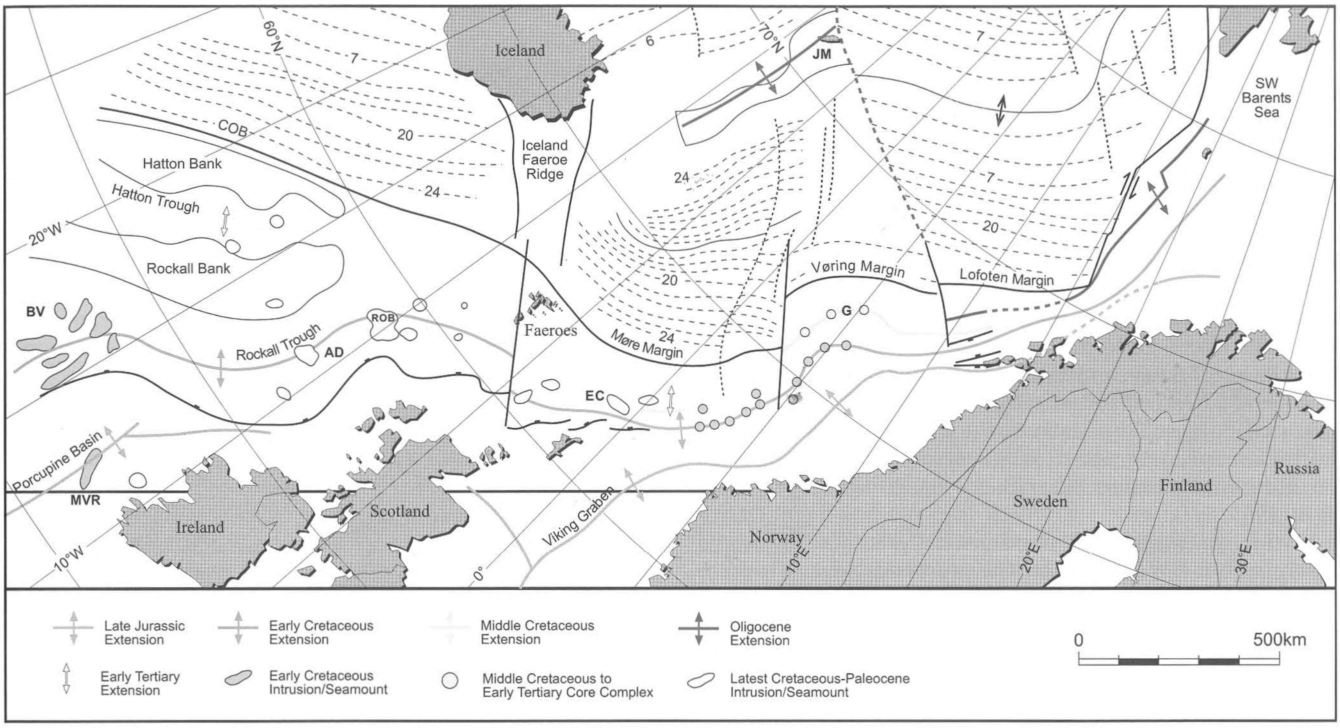

Fig. 3. Interpreted location of rift axes on the northwest European Atlantic margin, late Jurassic to mid-Cenozoic. For abbreviations see Table 1.

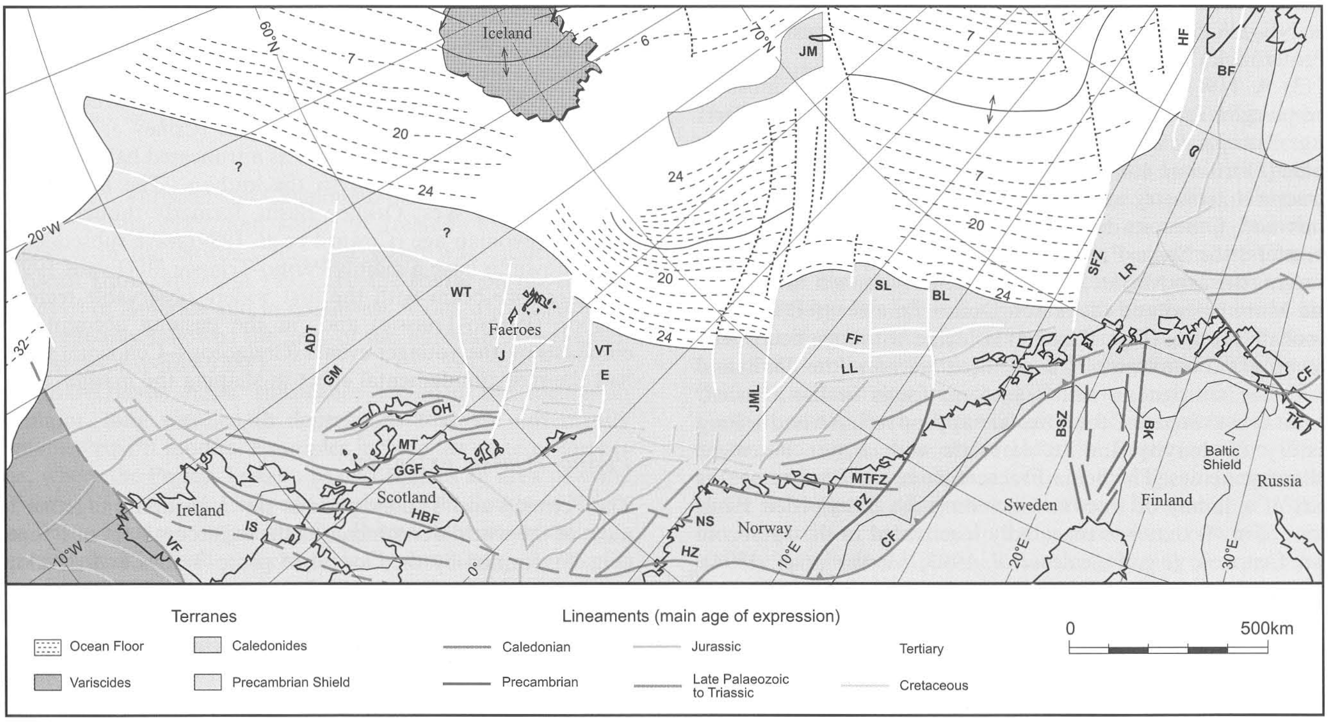

Fig. 4. Basement terranes and lineaments on the northwest European Atlantic margin. The lineaments are coloured according to their main observed age of expression as a means of illustrating possible correspondence between onshore features and those in offshore sedimentary basins. For abbreviations see Table 1.

eclogite-facies roots of collapsed orogens, weaker than adjacent lithosphere, provide preferred sites for rifting and hence ocean formation (Ryan & Dewey 1997).

The lineament pattern in Fig. 4 includes most possible fault trends, but NE–SW, N–S and NW–SE sets predominate. These sets are also strongly represented on adjacent sections of mainland such as Norway (Gabrielsen & Ramberg 1977). Based simply on alignment, there is a strong connection between some of the larger lineaments mapped offshore and onshore basement (Precambrian to Caledonian) features. This evidence has been reviewed in detail by Doré *et al.* (1997*b*) and Olesen *et al.* (1997). The essential points, of relevance to later tectonic development, are as follows:

(1) Major NE–SW steeply-dipping shears of Late Caledonian age, somewhat oblique to the overall trend of the orogen, closely parallel the Cretaceous–Cenozoic basin chain and the

line of eventual Atlantic opening. They include the Highland Boundary Fault, Great Glen Fault System (GGF) and Møre–Trøndelag Fault Zone (MTFZ). The MTFZ shows evidence of reactivation onshore, where dextral movement of Jurassic age probably represents oblique slip associated with E–W extension (Grønlie & Roberts 1989; Doré *et al.* 1997*b*). Offshore, the projection of the MTFZ forms the southeastern boundary of the Møre Basin (Blystad *et al.* 1995) and probably accomodated extension of Cretaceous age orthogonal to the lineament. The GGF in its northerly projection (Walls Boundary Fault) was also reactivated in the Mesozoic (Flinn 1992). Caledonian shears can be traced offshore from the Norwegian mainland into the North Sea, where they intersect and segment Permo-Triassic and Jurassic extensional basins (Færseth *et al.* 1995). West of Britain, these fractures influenced Mesozoic structuring of the Malin Sea (e.g. Fyfe *et al.* 1993) and, farther southwest, appear to create segmentation and offsets in the northern Porcupine Basin and Slyne Trough (e.g. Dancer *et al.* 1999).

(2) Lineaments of N–S trend generally lie inboard of the dominant NE–SW lineaments. The two trends interact to form a repeating rhomboidal geometry (Fig. 4), a pattern which also continues eastwards across the Barents Sea (Gudlaugsson 1994). Many of the N–S lineaments can be attributed directly to extension of Jurassic (and in the North Sea, of Permo-Triassic) age. However, based on onshore lineament trends a basement origin is possible for some elements of the N–S grain. For example, Coward (1990) and Doré *et al.* (1997*b*) have suggested that the N–S lineaments originated in immediate post-Caledonian time, in sinistral strike-slip duplexes between the NE–SW shears, while Færseth *et al.* (1995) suggest an older (Proterozoic) origin.

(3) A NW–SE 'transfer' trend is observed over most of the margin, manifested as lineament terminations and offsets (e.g. Rumph *et al.* 1993) and strongly segmenting the basin chain (Doré *et al.* 1997*b*). The transfers had a marked effect on structural geometry and sedimentation patterns in the Cretaceous and Cenozoic depocentres. The three most prominent transfers, the Senja Fracture Zone (SFZ) on the Barents Sea margin, the Jan Mayen Lineament (JML) between the Vøring and Møre basins and the Anton Dohrn Transfer (ADT) in the Rockall Trough (Figs 1 and 4) coincide with significant left-stepping basin offsets. Two of these features (the JML and SFZ) are contiguous with transform faults in the adjacent ocean crust. Some of the transfers appear to have had a long history of activity and to correlate with major basement inhomogeneities. The Senja Fracture Zone (of Tertiary age) is part of a family of fractures including the Billefjorden Fault Zone (Fig. 4) that was repeatedly reactivated in the Mesozoic and Cenozoic (e.g. Faleide *et al.* 1993; Manby *et al.* 1994). It is continuous with a major Proterozoic disturbance traversing the Baltic Shield, the Bothnian–Senja Shear Zone (BSZ) (Olesen *et al.* 1997). Work in progress by one of us (CF) suggests a connection between other transfer zones in the Vøring Basin (Surt and Bivrost Lineaments; Fig. 4) and Precambrian shears on the Norwegian mainland. Much farther SW, the radiometric and geochemical data suggest that the ADT formed at a major terrane boundary in the Precambrian basement (Dicken 1992; Hitchen *et al.* 1997). A consistency in trend between the transfer zones and NW–SE fracture sets in the Precambrian basement in Scotland (Watson 1984) and Norway (Romer & Bax 1992) indicate, speculatively, a more general inheritance of basement grain.

In general, we conclude that certain Precambrian and Caledonian shears were reactivated because they were conveniently orientated to accommodate Mesozoic and Cenozoic extension. East–west extension (for example, of Jurassic age) may have exploited a pre-existing N–S grain and caused oblique slip on NE–SW shears. Early Cretaceous and later extension was almost normal to the NE-SW shears, which were exploited as basin-bounding fault complexes (e.g. MTFZ). Basement shear zones striking at a low angle to the prevailing extension direction – for example the NW–SE lineaments in the Norwegian Sea and Faeroe–Shetland Basin, and the NE–SW lineaments in the North Sea, Slyne and Porcupine basins – appear to have determined the position of major transfer zones. This mechanism is suggested as a general principle of extensional terrains by Cartwright (1992).

The most probable examples of reactivation on the margin are subvertical shears (MTFZ, GGF, BSZ), an observation consistent with the idea that extension should preferentially reactivate steeply-dipping faults (Sibson 1985). Reactivation of lower angle structures such as Caledonian thrusts is more difficult to observe, but may have occurred where such features acted as lower crustal detachments to Mesozoic extension (Snyder *et al.* 1997). Ultimately, however, the probable complexity of reactivation is illustrated by the Outer Hebrides Fault Zone (Fig. 4) in which thrusting, strike slip, low angle dip-slip and normal faulting occurred successively (Imber *et al.* 1997).

Tectonic events, Permo-Triassic to break-up

Extensional movements began in immediate post-Caledonian (Devonian) times with post orogenic collapse, back-sliding of the nappe pile, and the development of molasse basins in Norway (Séranne & Séguret 1987), East Greenland (Strachan 1994) and northern Britain (Coward *et al.* 1989). These events, and the formation of Carboniferous extensional basins, are important onshore and influenced parts of the Atlantic margin. Generally however, sediment packages associated with these movements are poorly resolved seismically, mainly because of overprint by younger events. The Devonian–Carboniferous Clair Field reservoir west of Shetlands (Coney *et al.* 1993), which is resolved on seismic data as a truncated half-graben, is the only exception known to the authors. The half-graben comprising the West Orkney Basin, formerly thought to be also of Devonian age (Coward *et al.* 1989) have subsequently been shown to have a mainly Permo-Triassic fill (Evans 1997). We therefore begin with the first widely observable tectonic episode (Permo-Triassic) and, in the ensuing account, lay emphasis on the younger events (Cretaceous–Cenozoic) which had the most fundamental effect in shaping the margin.

Permo-Triassic extension

The Permian and Triassic periods saw a grouping together of most of the world's continents as the supercontinent of Pangea (Fig. 5), formed by the closure of proto-Tethys and development of the Variscan fold belt in the Late Carboniferous, and the suturing of West Siberia and Laurasia along the Urals fold belt in the Late Permian–Early Triassic (e.g. Scotese 1987). The supercontinent was uplifted, perhaps resulting from an accumulation of heat under low conductivity continental lithosphere (Nance *et al.* 1988) and interior continental sedimentation was widespread. The supercontinent appears to have been inherently unstable, with the result that assembly and the beginnings of continental break-up were virtually simultaneous. Studies of Permo-Triassic basins record a wide variation in extension vector (e.g. Coward 1995), creating the impression not of systematically directed extension but rather of mosaic-like fragmentation along the fused orogenic belts of the supercontinent (see Ryan & Dewey 1997 and earlier sections). In the region of the future Atlantic margin, Permo-Triassic basins followed the Caledonian fold belt, while to the north they tracked the Innuitian fold belt of Arctic Canada and the Uralides in the eastern Barents Sea (Gudlaugsson 1994). Onshore in Britain, basin development inherited underlying

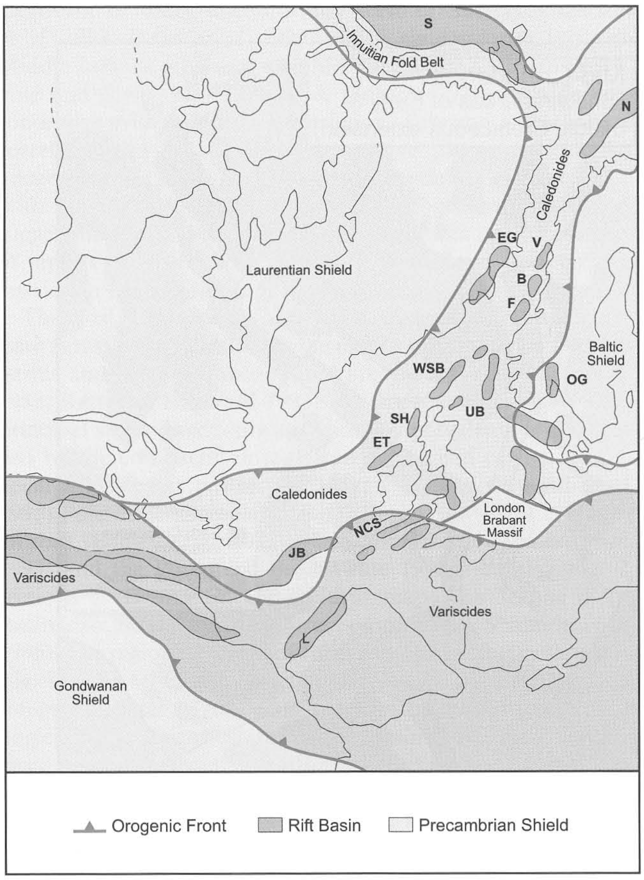

Fig. 5. Pangean orogenic belts and Permo-Triassic basins. For abbreviations see Table 1.

Malvernian, Variscan and Caledonian basement trends (Chadwick & Evans 1985) and south of Ireland, Permo-Triassic extension in the North Celtic Sea Basin was influenced by Variscan grain (Shannon 1991). To the south, on the eastern seaboard of America and in northwest Africa, the extensional basins broadly followed the lines of the Variscan–Alleghanian Orogen (Manspeizer 1988).

Permo-Triassic basin subsidence included the formation of major, long wavelength depressions that are not readily explained by rift models. Examples include the eastern Barents Sea, where the Permo-Triassic basin occupies an area of some 10^6 km^2 (Vågnes *et al.* 1995) and, probably, the Southern North Sea Basin. However, more usually, Permo-Triassic extension is characterized by half-graben, typically containing significant thicknesses of continental sediments. Large portions of the northwest European Atlantic margin are flanked by such basins, generally with a Caledonoid trend and lying inboard of the younger depocentres (Fig. 1). Sediment piles in the basins are up to 8 km thick (e.g. Evans 1997). Offshore mid-Norway, the Froan Basin, Brønnøysund Basin (our informal name) and inner Vestfjorden Basin (Fig. 2, section A) comprise NE-trending half-graben arranged in a left-stepping, *en echelon* pattern. Significant Permo-Triassic thicknesses on the Nordland Ridge (Fig. 2, section B) and Halten Terrace, and evidence of Permo-Triassic faulting in this area, suggests that fragments of Permo-Triassic basins are likely to be present beneath the Cretaceous–Cenozoic basins to the west. Farther southwest in the UK sector, significant Permo-Triassic expansions occur in the Unst Basin, West Shetland Basin (Fig. 2, section G), West Orkney Basin and Sea of the Hebrides–Minch Basin, while Permo-Triassic rifting is recognized as far SW as the Erris Trough in the Irish sector (Chapman *et al.* 1999). Marine influences periodically penetrated the basin network from the northern (Boreal) and southeastern (Tethyan) oceans bordering Pangea, but never succeeded in breaching the supercontinent (Doré 1992).

Permo-Triassic extension is generally poorly dated, but is best constrained onshore in East Greenland where a major phase of normal faulting culminated in the Middle Permian and further block faulting took place in the Early Triassic (Surlyk 1990). In onshore Britain two separate extensional phases of Late Permian and Early Triassic ages have been proposed (Chadwick & Evans 1995). A two-stage extensional history is also suspected in the Northern North Sea (Badley *et al.* 1988; Gabrielsen *et al.* 1990). Similarly, in the North Celtic Sea two phases (Early Permian and Early Triassic) have been suggested (Shannon 1995). Early Permian magmatism associated with the rifting has been described from East Greenland (Surlyk 1990) and from the West Shetland Basin–southwestern Møre margin area (Hitchen *et al.* 1995), while volcaniclastics of probable Late Triassic age from the north Porcupine Basin, Erris Trough and Donegal Basin have been taken by Tate & Dobson (1989) to indicate contemporaneous rifting.

Permo-Triassic extension has had limited direct significance for Atlantic margin petroleum exploration. Moderate quality continental-paralic reservoir sandstones exist in the half-grabens, and are locally an exploration target. Indirectly, Permo-Triassic graben-fills, when uplifted and eroded during subsequent rift phases, provided recycled sands for later and more prospective reservoirs. Salt intervals introduced into the basins during marine incursions – for example the Ladinian–Carnian halites of Haltenbanken – were locally important as detachment zones during Jurassic rifting (Pascoe *et al.* 1999).

Jurassic uplift and extension

The Triassic–Jurassic transition in the North Atlantic region saw a change to rift tectonics associated with incipient ocean-floor spreading in the Tethys to the southeast and in the proto-Central Atlantic to the southwest. Marine flooding of the old Permo-Triassic rift basins took place as rifting breached Pangea (Doré 1992). Seafloor spreading began in the Central Atlantic in the early Middle Jurassic, and precursor extensional faulting has been described in the southern part of the incipient Atlantic margin, offshore Nova Scotia and Newfoundland, in the Lusitania Basin of Portugal and in the North Celtic Sea Basin (see review in Roberts *et al.* this volume). Farther north, Early Jurassic rifting is interpreted to have taken place in the Sea of the Hebrides Basin (Morton 1989) and some extensional fault activity of this age is documented as far northeast as offshore mid-Norway (Blystad *et al.* 1995). In comparison to later Jurassic extension, however, this activity was limited. Central Atlantic spreading was probably decoupled from the future northwest European Atlantic margin along transverse shear zones such as the Azores–Gibraltar Fracture Zone, as shown in Ziegler (1988) (see also Fig. 6).

The general pattern of mild extensional tectonism and thermal subsidence on the NW European Atlantic margin was interrupted in the Middle Jurassic by an interval of severe restriction between north (Barents Sea, East Greenland, Mid-Norway, northernmost North Sea) and south (Southern North Sea, southern UK, southern Europe). In the Central North Sea, this restriction was caused by a latest Toarcian to Bathonian uplift postulated to be a hotspot-related dome (e.g. Underhill & Partington 1993). The nature, magnitude and significance of the North Sea dome remains a matter of debate. However, a restricted or completely closed seaway is necessary to account for the total marine faunal separation between the northern (Boreal) and southern (Tethyan–Atlantic) realms that occurred in the Late Bajocian and Bathonian (Callomon 1984). This faunal provinciality also indicates a lack of marine continuity along what was to become the Atlantic margin. A major

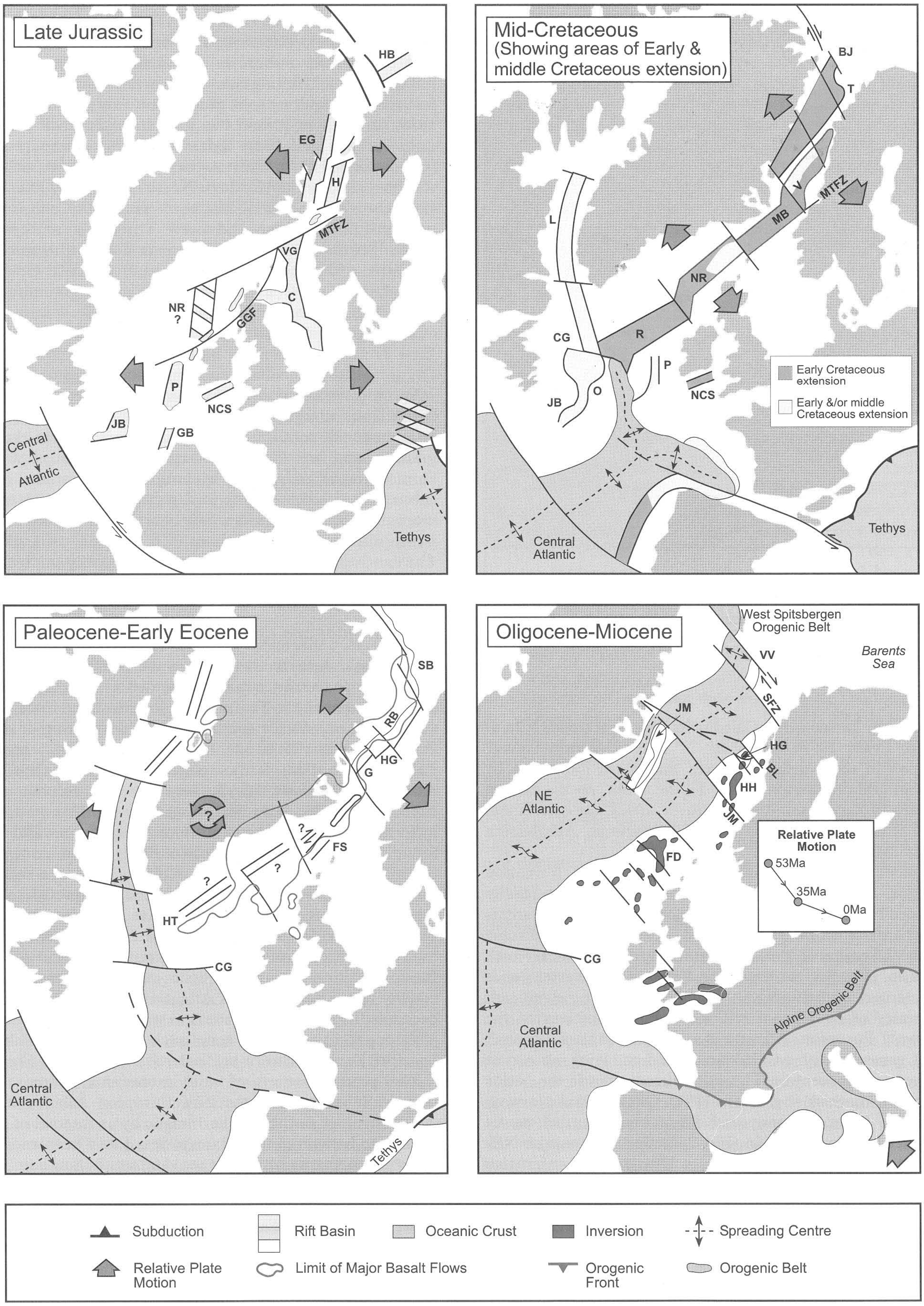

Fig. 6. Plate reconstructions – Late Jurassic, mid-Cretaceous, Paleocene and mid-Cenozoic, indicating relative plate motion, contemporaneous rifts and areas of inversion. For abbreviations see Table 1.

Callovian or older unconformity west of Shetlands (Stoker *et al.* 1993; Dean *et al.* 1999) and a similar latest Early to Middle Jurassic erosional unconformity in the northern Porcupine and Slyne Basins (Tate & Dobson 1989) provide corroborative evidence for this restriction. Tate and Dobson have correlated the Porcupine–Slyne erosive phase with similar unconformities in the Irish Sea and in northern England. Thus, both the faunal evidence and the palaeogeography strongly suggest that the Central North Sea dome was one of a family of uplifts that extended across NW Europe and created restriction in the Middle Jurassic.

The most intense phase of rifting occurred in latest Middle to Late Jurassic times, although the precise timing varied between basins and between intra-basinal provinces (e.g. Badley *et al.* 1988; Rattey & Hayward 1993). An approximately E–W least principal stress direction was regionally prevalent, as exemplified by the consistent close-to-northerly trend of the unequivocal Jurassic rift basins: the Halten Terrace (Blystad *et al.* 1995), the East Greenland Rift (Surlyk 1990), the Viking Graben (Badley *et al.* 1988), the Slyne Trough (Dancer *et al.* 1999) and the Porcupine Basin (Tate 1993) (see also Fig. 2, sections C, D and F). On pre-drift maps, the Jeanne d'Arc Basin also fits this regional stress pattern (e.g. Shannon *et al.* 1995). The regional picture of Jurassic basin geometry shown in Fig. 1 is of a series of parallel or *en echelon* rifts, strongly overstepped by later (Cretaceous–Cenozoic) depocentres. A N–S dogleg in the southwestern Vøring Basin may reflect Jurassic basin geometry underlying the thick Cretaceous–Tertiary section and, based purely on pattern recognition, a 'missing basin' between the North Sea and Porcupine Basin may exist in the N–S segment of the Rockall Trough seaward of the Geikie Escarpment (Fig.1).

The fabric and stress patterns of the Late Jurassic differed strongly from those of the subsequent extension leading to north Atlantic separation, and this observation is a critical element of our model of migrating, rather than repeating, rifts. We suggest that the Late Jurassic rifting in northwest Europe was less influenced by central Atlantic spreading than by the imposition throughout northwest Europe of a stress regime associated with seafloor spreading in Tethys (Ziegler 1988) (Fig. 6). Thus on the Atlantic margin, the existence of which is largely the result of later tectonics, evidence of Late Jurassic activity is very variable along present strike. Some areas between the overprinted Jurassic rifts are almost devoid of Late Jurassic extension, or show minor fault displacements that could be attributable to oblique slip. For example, in the West Shetland Basin and adjacent parts of the Faeroe–Shetland Basin, a thin Upper Jurassic section with only minor thickness variations overlies the major mid-Jurassic unconformity (Stoker *et al.* 1993; Dean *et al.* 1999) and seismic sections provide very little evidence of syn-rift sedimentary expansion.

The Jurassic petroleum system of the Northern North Sea and Halten Terrace, combining an Upper Jurassic supersource, pre- and syn-rift reservoirs and major extensional fault traps, is well known. The entire Jurassic interval on the Atlantic margin was prone to the development of anoxia and hence to the deposition of source rocks. In addition to the widespread Upper Jurassic unit, Lower Jurassic source rocks are identified in mid-Norway (Koch & Heum 1995), the Sea of the Hebrides Basin and the Slyne and Erris troughs (Chapman *et al.* 1999), while Middle Jurassic source rocks are present in the Sea of the Hebrides and are inferred from oil types in the Faeroe–Shetland Basin (Holmes *et al.* 1999). Our model of an over-stepped rift system predicts the presence of remnant Jurassic rifts beneath the newer basins along the Atlantic margin, although these domains will frequently be deeply buried. Because of the highly transgressive nature of the Upper Jurassic rocks, the existence of a rift was not a prerequisite for a source rock. These points are emphasized by the presence of Upper and Middle Jurassic oils in the Faeroe–Shetland Basin, an area with little or no observable Late Jurassic rifting. Source rocks must be present at depth in the basin, either due to the existence of buried Jurassic rift segments or resulting from the deposition of source rocks outside of the main rifts.

Early Cretaceous extension

In Early Cretaceous times Tethyan seafloor spreading had ceased and was replaced by subduction on the northern margin of the ocean (Ziegler 1988). Atlantic spreading propagated northwards and by Aptian times oceanic crust was established between the north Iberian margin and the Grand Banks (Driscoll *et al.* 1995). Tectonics on the future Atlantic margin switched from a system dominated by N–S Tethyan rift propagation to one dominated by NE–SW rifting, an extension vector that was maintained intermittently through to break-up. The result was a broad zone of extension and subsidence stretching from the southwestern Rockall Trough to the western Barents Sea (Figs 1 and 6).

The considerable body of evidence for Early Cretaceous rifting has been assembled by Lundin & Doré (1997). Late Jurassic and Early Cretaceous rifting phases are often referred to in the literature as a single event because activity on some principally Late Jurassic faults persisted with waning strength into the Early Cretaceous – for example in the Porcupine Basin (McCann *et al.* 1995) and Halten Terrace (Blystad *et al.* 1995). We believe that this terminology is unfortunate, because it disguises one of the most fundamental events in the evolution of the north Atlantic margin – the rotation of the least principal stress direction from E–W to NW–SE in the early Cretaceous. Thus, the two rifting episodes may have been almost continuous in time, but were not coincident in space. On the Galicia margin, Boillot *et al.* (1989) date rotation of the stress vector to the Hauterivian. This fits well with observations on the margin further north, and places a small time interval between the cessation of Jurassic rifting – for example in the North Sea, where the main rifting probably waned in the Kimmeridgian (Rattey & Hayward 1993) – and the start of Cretaceous extension.

In the Irish Rockall Trough a series of elongate igneous complexes, the Barra Volcanic Ridge System (Fig. 3) has been proposed to be of Early Cretaceous age on stratigraphic and regional grounds (Scrutton & Bentley 1988). On the grounds of its proximity to Cretaceous ocean floor, and by analogy with similar features in the central Red Sea (Bonatti 1985) the ridge may represent an isolated spreading cell. Farther NE in the UK Rockall Trough (Fig. 2, section H), Musgrove & Mitchener (1996) describe an Early Cretaceous syn-rift succession in Well 132/15-1 in which Hauterivian sediments overlie crystalline basement. In the Faeroe–Shetland Basin (Fig. 2, section G) Early Cretaceous extension is associated with considerable syn-rift expansion and coarse clastic deposition in the hanging walls of NE-trending normal faults. Dean *et al.* (1999) constrain this motion to the Valanginian–Barremian interval. To the NE, a series of coeval NE–SW faults bounding the Magnus and Manet highs and Margareta Spur postdate the Viking Graben faults of Late Jurassic age and effectively delineate the southeastern margin of the Møre Basin (Fig. 2, section F). A Hauterivian rift unconformity is associated with thick scarp-derived Valanginian–Hauterivian sands in the Magnus Basin, and rotates and truncates the pre-existing Late Jurassic rift unconformity on the Margareta Spur (Rattey & Hayward 1993).

In the axis of the Møre Basin (Fig. 2, section E) crystalline crust is thinned to a few kilometres (Olafsson *et al.* 1992), almost becoming oceanic before the cessation of rifting (Fig. 3). A NE–SW row of positive magnetic anomalies along the axis of thinning was interpreted as a chain of precursory seafloor intrusions (seamounts) of mafic composition by Lundin & Doré (1997). Poor seismic resolution and shallow Tertiary sills obscure the geometry of most of these features, but to the north at the Møre–Vøring transition one of them is visible as a flat-topped positive feature truncated and transgressed by Cenomanian sediments. Onlap relationships and general parallelism with the basin-margin faults to the south (see earlier) suggest an Early Cretaceous age.

In the Vøring Basin, as in the Møre Basin, the Cretaceous fill is very thick and the age of faulting at the base of the section is not easily resolved (Fig. 2, sections B–D). However, on the southeastern Vøring margin we have observed offset of N–S Jurassic faults by NE-trending Cretaceous faults on 3D seismic data. Early Cretaceous faulting on the western margin of the Halten Terrace has also been reported by Blystad *et al.* (1995). Farther NE, major Early Cretaceous syn-rift sedimentary expansion is observed in the Ribban, northeastern Træna and Vestfjorden basins (Mokhtari & Pegrum 1992) (Fig. 2, section A). Shallow core data from the Ribban Basin (Hansen *et al.* 1992) again indicate a Hauterivian age for the rifting. The belt of rifting probably extends northeastwards through the Harstad Basin and terminates on the Barents Sea margin, where a major expansion of the Lower Cretaceous sedimentary section occurs in the Tromsø and Bjørnøya Basins (see Gabrielsen *et al.* 1990, their figs 7 and 13).

In summary, therefore, a major extensional event of approximately Hauterivian age is consistently identified along the margin. This rifting truncated the pre-existing Jurassic rift system and elevated the northern margins of these rifts, a pattern clearly suggested by Fig 1. For example, the NE–SW early Cretaceous faults in the Magnus area (Rattey & Hayward 1993) and Tampen Spur (Stewart *et al.* 1992) uplifted the late Jurassic turbidite reservoirs of the Viking Graben into the footwall. Similarly, the northern Porcupine Ridge and the Nordland Ridge are both marginal uplifts to Cretaceous basins, forming the northern terminations of the Jurassic Halten Terrace (against the Træna Basin) and Porcupine Basin (against the Rockall Trough), respectively.

In exploration terms, the Early Cretaceous extension resulted in deep burial of the overprinted Jurassic domains and rapid maturation of Jurassic source rocks. Invoking direct charging of younger reservoirs (e.g. Upper Cretaceous–Paleocene) from this source requires careful assessment of Cretaceous thicknesses in the generation kitchens along the proposed migration route. Given too great a Cretaceous thickness, remigration from intermediate reservoirs is required (Spencer *et al.* 1999). Syn-rift scarp sands of Early Cretaceous age form an additional reservoir target on the margin, while source rocks – for example in the Barremian interval – may possibly have developed locally in the rift axes based on evidence from the western Barents Sea (Doré *et al.* 1997*a*).

Middle Cretaceous extension

A number of tectonic and stratigraphic observations in the Vøring Basin reported by Lundin & Doré (1997) point to an extensional tectonic event of mid-Cretaceous age. In places, this event is narrowly time-constrained (approximately to the Cenomanian), while elsewhere there appears to have been some continuity through the late Cretaceous with the break-up rifting of approximately Paleocene age (see following section). The mid-Cretaceous event is seen on seismic data as a gentle to angular unconformity in the outer Vøring Basin (Gjallar Ridge and Nyk High), Træna Basin and Ribban Basin. The unconformity has been dated as Cenomanian from a shallow core in the Ribban Basin (Hansen *et al.* 1992). Expansions of the early Late Cretaceous section immediately east of the Utgard High (Fig. 2, section B) and Fles Fault Zone (Fig. 2, section C) also indicate significant extension.

The Gjallar Ridge (Fig. 1) consists of three structural culminations marked by gravity highs. Cenomanian–Paleocene strata in the Vigrid Syncline appear to converge along the southeastern flank of the ridge (Fig. 2, sections B and C and Fig. 7) suggesting that it was progressively uplifted and formed a hinge during deposition. The southern culmination of the ridge is deeply eroded (Fig. 2, section D), while the two northern highs are capped by low-angle normal faults throwing northwestward. Faulting is interpreted as Cenomanian to Paleocene in age, younging westward. The low-angle faults appear to sole out on a seismically-distinct updomed reflector at approximately 12 km depth. We interpret the Gjallar Ridge as a series of extensional core complexes, and the bowed-up mid-crustal reflector to represent a possible mylonite zone separating the sedimentary section from underlying plutonic

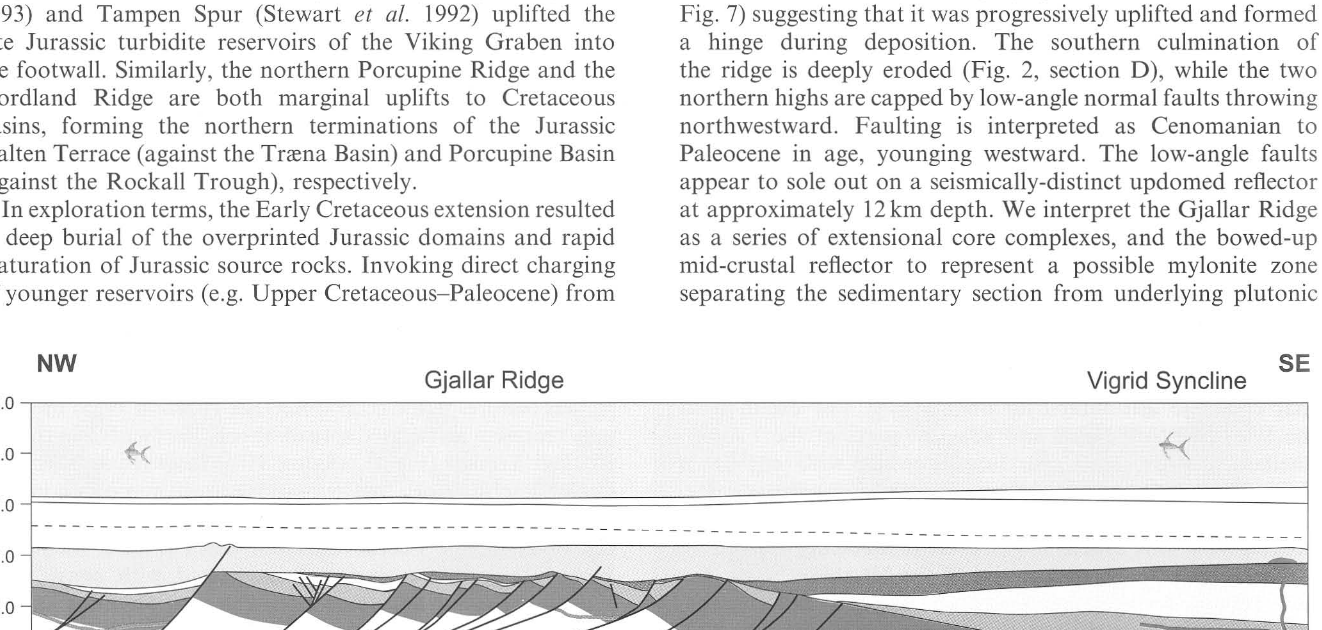

Fig. 7. Geoseismic profile illustrating uplift and extension over the Gjallar Ridge, northwestern Vøring Basin. The profile is located at the northwestern end of Fig. 2, profile C. Note: (1) convergence of Upper Cretaceous–Paleocene reflectors on the southeastern flank of the ridge; (2) low angle faults on the ridge of probable mid-Cretaceous to Paleocene age; and (3) probable soleing out of faults on updomed reflector at about 7.5 s. The reflector rises to three culminations along the ridge, coincident with positive gravity anomalies.

or metamorphic rocks (Lundin & Doré 1997). It cannot be established for certain whether development of the ridge was gradual or whether, as seen elsewhere in the basin, two separate events (mid-Cretaceous and Paleocene) took place. A Cenomanian age for inception of this movement, and for major subsidence against the Fles Fault Zone, is also indicated by the work of Bjørnseth *et al.* (1997).

While mid-Cretaceous extension is best observed in the Norwegian Sea, there is now evidence that this phase may have affected a wider area. For example in the UK sector, Well 219/28-2, drilled in the hanging wall of a normal fault bounding part of the Margareta Spur, contains a significant middle Cretaceous unconformity in which a thickened Upper Cretaceous section (Coniacian–Santonian) overlies a thin Hauterivian to Barremian carbonate sequence which in turn overlies peneplained crystalline basement. The unconformity is interpreted as representing middle Cretaceous down-faulting of a thin carbonate shelf sequence deposited on an earlier (Early Cretaceous) footwall. Farther southwest in the Faeroe–Shetland Basin, Dean *et al.* (1999) and Holmes *et al.* (1999) report substantial expansions of the sedimentary section and depocentre-switching against NE–SW faults as a result of Cenomanian–Santonian extension. In the Rockall Trough, evidence for a similar mid-Cretaceous episode remains equivocal, as a result of poor seismic resolution and limited stratigraphic control. However, some extensional faulting of Aptian–Albian age is recorded in the Porcupine and Jeanne d'Arc basins, probably associated with the northwards propagation of seafloor spreading between Grand Banks and Iberia (e.g. Sinclair 1995).

The mid-Cretaceous faulting and subsidence caused further rapid burial of the pre-Cretaceous basin systems and further maturation of any underlying Jurassic source rocks (see preceding section). In the Norwegian Sea, uplift associated with the extension caused input of potential reservoir sands into the basin flanks in Cenomanian and Turonian time (Lange and Lysing sandstones: Shanmugam *et al.* 1994; Doré *et al.* 1997*a*). In the northwestern Vøring Basin a major sand influx occurred in Late Santonian to Early Campanian times. These sandstones have recently been drilled on the Nyk High (Kittilsen *et al.* 1999). Heavy mineral studies on these and other Campanian sandstones cored in the northwestern Vøring Basin suggest derivation from Precambrian basement complexes exposed in Greenland (Roberts *et al.* 1999). This coarse clastic input may also indicate continued exhumation of parts of the NE Atlantic rift system close to the line of incipient break-up, as described earlier for the Gjallar Ridge. The general thinning of the middle–Upper Cretaceous section towards the NW flank of the Vøring Basin (Fig. 2, sections C and D) suggests that a central high probably separated the Vøring depocentres from other Cretaceous basins now situated on the East Greenland shelf, as shown schematically in Fig. 6. The existence of the central high – rather than a continuous Cretaceous basin across to East Greenland – is an important consideration in reservoir prediction in the Vøring Basin.

Paleocene magmatism, uplift and extension

'Paleocene extension' is used here as a shorthand for a tectonic episode that spanned the period from latest Cretaceous (probably Maastrichtian) to earliest Eocene break-up approximately at 53 Ma. As shown schematically in Fig. 6, by Early Paleocene, chron 27 time, seafloor spreading had penetrated from the southern North Atlantic into the Labrador Sea (Chalmers *et al.* 1993). Co-eval Paleocene rifting on the NW European Atlantic margin probably occurred in northwesterly areas close to the line of incipient break-up (Figs 1 and 6), but is best observed on seismic lines in the northern Norwegian Sea (Skogseid *et al.* 1992). West of Lofoten, the Utrøst Ridge (Fig. 2, section A) is a deeply eroded horst that was probably active as a sediment source for depocentres to the SE in Paleocene times (Lundin & Doré 1997; Doré *et al.* 1997*a*). In the Vøring Basin, mild Paleocene normal faulting, including reactivation of Cretaceous faults, is seen on the margins of the Utgard High and along the Fles Fault Zone (Fig. 2, sections B–D). This belt of activity is separated by the largely unfaulted Vigrid and Någrind synclines from a more intensely faulted area to the northwest. In this area, the Nyk High and Hel Graben (Fig. 2, section B) show significant rotation of pre-Paleocene strata and were largely formed by Paleocene faulting (although they were also reactivated in the mid-Cenozoic – see following section). As indicated earlier, low angle faulting and uplift on the Gjallar Ridge (Fig. 2, section C, and Fig. 7) also continued into Paleocene times. The updomed mid-crustal reflector beneath the Gjallar Ridge may be intimately associated with pre-opening underplating, believed to have occurred beneath the outer Vøring Margin (Skogseid *et al.* 1992). The underplating may have induced melting at higher crustal levels, which in turn facilitated detachment and development of the core complexes. This association between plutonism and core complex formation has been observed in the Basin and Range province by Lucchitta (1990) and in Papua New Guinea by Hill *et al.* (1995).

The well-studied igneous activity associated with Early Tertiary break-up is generally believed to result from migration of plume-generated mantle melts into the thinned axis of incipient opening (e.g. Eldholm *et al.* 1989; Skogseid *et al.* 1992). A possible early manifestation of this activity was the development of seamounts (Rosemary Bank and possibly Anton Dohrn) in the Rockall Trough, where basalts with a plume geochemical signature have been dated as Maastrichtian or earlier (Hitchen & Ritchie 1993). During the main igneous episode of Paleocene age further intrusive–extrusive complexes were emplaced in axial parts of the Rockall Trough and Faeroe–Shetland Basin (Fig. 3), while sill intrusion took place into the thick Cretaceous successions on the northwestern flanks of the Vøring, Møre and Faeroe basins, and throughout the Rockall Trough (Fig. 2). The marginal highs (Fig. 1) consist of highly intruded continental crust, capped by lava flows and bounded on their NW margins by oceanward-dipping reflector (ODR) sequences thought to represent subaerial extrusive complexes (Olafsson *et al.* 1992). The highs may have existed prior to the Paleocene–Eocene (see section on middle Cretaceous extension), but this concept is difficult to prove because of the magmatic overprint. The lava front shown on Fig. 1 represents the approximate southeasterly limit of basalt flows extruded in Paleocene–Early Eocene times (Danian–Early Ypresian). The latest and most extensive of these flows, corresponding to the Middle and Upper Series of the Faroes, were extruded in a geologically short period of time (*c.* 2 Ma) immediately prior to break-up at Anomaly 24b time (e.g. Hitchen & Ritchie 1993; Waagstein 1988: see also the reviews in Naylor *et al.* 1999 and Roberts *et al.* 1999). The lavas mainly emanated from subaerial fissure eruptions with maximum intensity around the thermally elevated line of incipient break-up. Major escarpments in the late-stage lava flows observed on seismic data probably represent the transition from subaerial to submarine lavas (e.g. Andersen 1988; Naylor *et al.* 1999).

The marginal highs and lava flows mask the underlying succession in the outer Møre Basin and Faeroes area (Fig. 2, sections E and G) and obscure any evidence of the Paleocene extension that might be expected to occur in such positions. A thickening of the Paleocene section in the southwestern part of the outer Møre Basin may, however, indicate tectonic uplift of the marginal high (Doré *et al.* 1997*a*). In parts of the Faeroe–Shetland Basin free from the basalt cover there is mounting evidence of Paleocene extensional activity on the basin-bounding faults, manifested as major offset of the Base

Tertiary relector (Dean *et al.* 1999). The Paleocene in this area has long been thought to represent a period of post-rift subsidence, and causes unassociated with extension have been sought to explain anomalous Paleocene subsidence rates (Hall & White 1994). New work, however, suggests that the Paleocene thickness changes result from genuine extension, with diffuse faulting distributed through a thick, ductile Cretaceous layer producing an atypical syn-rift geometry (see detailed arguments in Dean *et al.* 1999; also Holmes *et al.* 1999).

A suite of small-scale E–W normal faults, discordant to the main basin trend, are also widely evident on 3D seismic surveys in the Faeroe–Shetland Basin (e.g. Leach *et al.* 1999). They appear to have been active from mid-Paleocene to early Eocene time. Their place in the tectonic scheme is not readily apparent. Plausibly, they are transtensional faults resulting from a dextral component to Paleocene movement along the Atlantic margin trend, in turn resulting from seafloor spreading in the Labrador Sea and counter-clockwise rotation of Greenland (Fig. 6).

Farther SW in the Rockall Trough, the Geikie Escarpment appears to have formed a basin margin and controlled the thickness of the lavas in Paleocene times (Fig. 2, section H). It cannot at present be determined whether this represents fault reactivation of the margin or simply residual subsidence. Otherwise, there is very little evidence for Paleocene faulting in the trough. The Hatton Trough to the NW contains a thin, low-velocity sedimentary sequence of presumed Tertiary age overlying basement (Shannon *et al.* 1993). Based on position close to the continental margin, our interpretation on Figs 1 and 3 tentatively proposes a continuation of the Early Tertiary rift axis through the Hatton Trough. The Hatton Bank is flanked by an ODR sequence (e.g. Roberts *et al.* 1984; Keser Neish 1993) and is interpreted in Fig. 1 as a continuation of the 'marginal high trend'.

Paleocene extensional faulting created potential horst and tilted-block traps in the northern Vøring Basin and on the Gjallar Ridge. In the Faeroe–Shetland Basin, the E–W (?transtensional) faults enhance trapping and segment the reservoir in the Foinaven and Schiehallion fields (e.g. Leach *et al.* 1999). A significant uplift of provenance areas adjacent to the Atlantic margin took place in the Paleocene. The emergent area included much of the British Isles, where Paleocene successions are largely absent, portions of the Norwegian mainland (Riis 1996) and the volcanically active marginal highs. This uplift has been attributed to magmatic underplating associated with the proto-Iceland plume (White 1988; White & McKenzie 1989; Milton *et al.* 1990). Crustal modelling indicates the probability of underplating on the Vøring margin (Skogseid *et al.* 1992), the Møre margin (Olafsson *et al.* 1992) and Hatton Bank (White *et al.* 1987), while White & Lovell (1997) suggest that pulsed uplift from underplating of the northern British Isles gave rise to co-eval sand influxes into the Northern North Sea and Faeroe–Shetland basins. A key question is why underplating should have caused uplift of the cratonic areas (e.g. the Scottish Highlands) while the Faeroe–Shetland Basin, positioned between Scotland and the impacting plumehead, underwent anomalously rapid subsidence (Hall & White 1994). The most simple explanation involves extension-related subsidence in the Faeroe–Shetland Basin which, as indicated earlier, we believe can now be documented (Dean *et al.* 1999). An explanation is still required, however, as to how buoyant plume material could bypass this area of crustal thinning to cause significant underplating of the adjacent craton.

Coarse clastics of Paleocene age were shed into the Vøring Basin, Møre Basin, Faeroe–Shetland Basin and Rockall Trough from easterly provenances, and probably from the subaerially exposed marginal highs to the west. Their distribution was controlled by pre-existing basin geometry, by contemporaneous extensional faulting and by the cross-cutting NW-trending transfer zones (Rumph *et al.* 1993; Doré *et al.* 1997*a*). These sands constitute an exploration target along the entire margin.

Tectonic events after break-up

Intra-Cenozoic inversion

On plate separation in the early Eocene (chron 24b), a reversal of the horizontal stress patterns took place whereby NW–SE extension gave way to SE-directed compression, attributable to ridge push forces from the adjacent ocean (Fig. 6). As would be expected, *in situ* stress measurements show that this NW–SE compressive regime still exists at present in much of NW Europe. The stress pattern is also consistent with the relative motion of Europe and Africa, and hence with the Alpine closure (e.g. Zoback 1992; Müller *et al.* 1992).

The new compressive regime gave rise to widely-distributed inversion structures along the Atlantic margin (Fig. 8). They have been described in the Faeroes–Rockall area by Roberts (1989) & Boldreel and Andersen (1993), and in the Norwegian Sea by Hamar & Hjelle (1984), Brekke & Riis (1987), Blystad *et al.* (1995) and Doré & Lundin (1996). The most commonly observed inversion features are elongate domes which, although only gently deformed, are areally and vertically extensive. For example, the Helland Hansen Arch in the Norwegian Sea has a long axis of about 200 km, is 50 km wide and has a structural relief in the order of 1 km (Fig. 8). Reverse faulting is observed in the Norwegian Sea, where the Fles Fault Zone reversely reactivates a Cretaceous normal fault (Doré & Lundin 1996) and along the Wyville–Thompson and Ymir ridges in the Rockall Trough (Roberts 1989; Boldreel & Andersen 1993). A more general bulge of some of the Cretaceous depocentre axes is probably also attributable to Cenozoic compression (see for example the Någrind Syncline axis in Fig. 2, section B). As shown on Fig. 8, we attribute the present elevation of the Faeroe Islands and Shelf to long-wavelength Cenozoic compression superimposed on the Iceland hotspot 'trail' (Iceland–Faeroes Ridge).

Most of the structures show evidence of multiphase inversion. The timing of activity on the Norwegian Sea structures has been described by Doré & Lundin (1996), but has since been refined by detailed examination of 3D seismic data. The Ormen Lange Dome, at the Møre–Vøring transition (Fig.8), underwent its most significant period of deformation in the Late Eocene–Early Oligocene. Immediately to the north, the Helland–Hansen Arch underwent growth between the Late Eocene and the Early Miocene, while in the most northerly of the major structures, the Naglfar Dome, (Fig. 8) the main phase of development was as late as Early–Middle Miocene. These observations suggest a systematic younging of the inversion northwards. Inversion episodes of Oligocene and Mid–Late Miocene age are documented in the Faeroes–Rockall region (Boldreel & Andersen 1993). A Paleocene inversion phase (i.e. predating break-up) is described in the Wyville–Thompson Ridge area, but is not observed in the Norwegian Sea (Boldreel & Andersen 1993, Doré & Lundin 1996). Many authors (see for example Brekke & Riis 1987) correlate the Norwegian inversions with plate reorganization in the adjacent ocean of Oligocene–Miocene age. This readjustment began at approximately anomaly 13 times (35 Ma, Eocene–Oligocene boundary) with a change in relative plate motion between Greenland and NW Europe to a more ESE course (Fig. 6) and the transfer of spreading from the now extinct Aegir axis to the Kolbeinsey Ridge between Jan Mayen and East Greenland. Doré & Lundin (1996) observed that the N–S trend of many of the mid-Norwegian inversions can be explained by sinistral wrench motion along NW-trending transfers such as the Jan

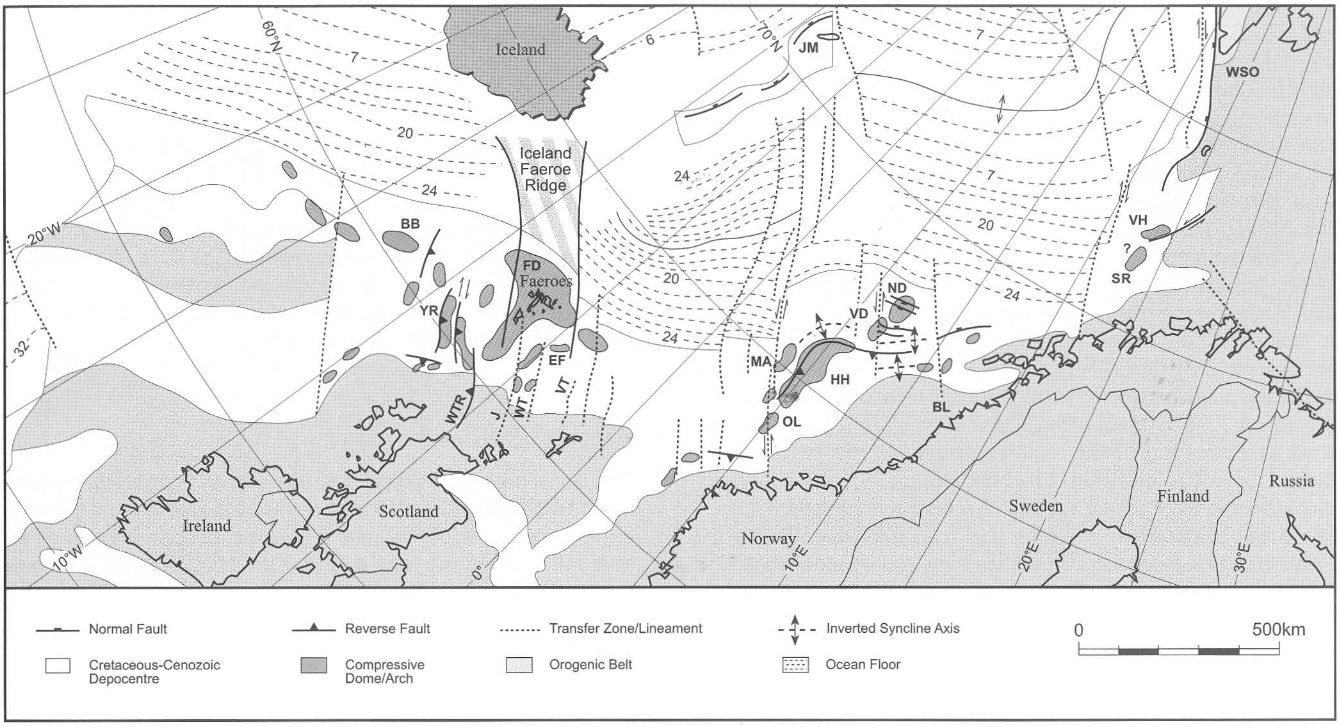

Fig. 8. Map of intra-Cenozoic inversions and related structures in Cretaceous–Cenozoic depocentres on the northwest European Atlantic margin. Note the probable relationship between compressive domes and major transfer zones such as the Jan Mayen Lineament, Judd Transfer and Wyville–Thompson Ridge. For abbreviations see Table 1.

Mayen Lineament, and suggested that this motion could have been set up by the change in spreading vector.

Roberts (1989) has proposed a connection between Oligocene inversion on the Irish–UK Atlantic margin and subduction north of Iberia (Pyrenean phase of the Alpine orogeny; Fig 6). There may also be an association between coupling of collision zone and foreland during the 'Late Alpine' Tethyan docking event and Miocene inversion on the Atlantic margin. It is possible to view these phenomena (Tethyan closure, Atlantic ridge development and inversion) as related in a platewide sense (Doré & Lundin 1996). However, it is worthy of note that most of the compressional structures on the margin involve only minor crustal shortening (1–2%), a deformation of the lithosphere that can probably be modelled using ridge-push alone (Boldreel & Andersen in press). The postulate of ridge-push as the primary compressive mechanism is strengthened by the observation of mid-Cenozoic compressional folds in East Greenland (Price *et al.* 1997), an area that was decoupled from the Alpine stress by an intervening spreading ridge.

Cenozoic inversion structures are of major exploration interest because of their size, simplicity and because they updome potential reservoir sands of mid–Late Cretaceous and Paleocene age. The structures are frequently basin-centred and could have provided a focus for newly generated hydrocarbons or, more likely, for hydrocarbons remigrating from deeper reservoirs. The NW–SE transfer faults, which are also implicated in the inversion, were aligned with the maximum horizontal stress direction. The minimum horizontal stress will have been across the lineaments, which therefore had the potential to act as migration conduits (see Doré & Lundin 1996 for a fuller account).

Mid-Cenozoic extension

Plate reorganization of Oligocene–Miocene age also gave rise to local renewed extension of the north Atlantic margin. Rifting

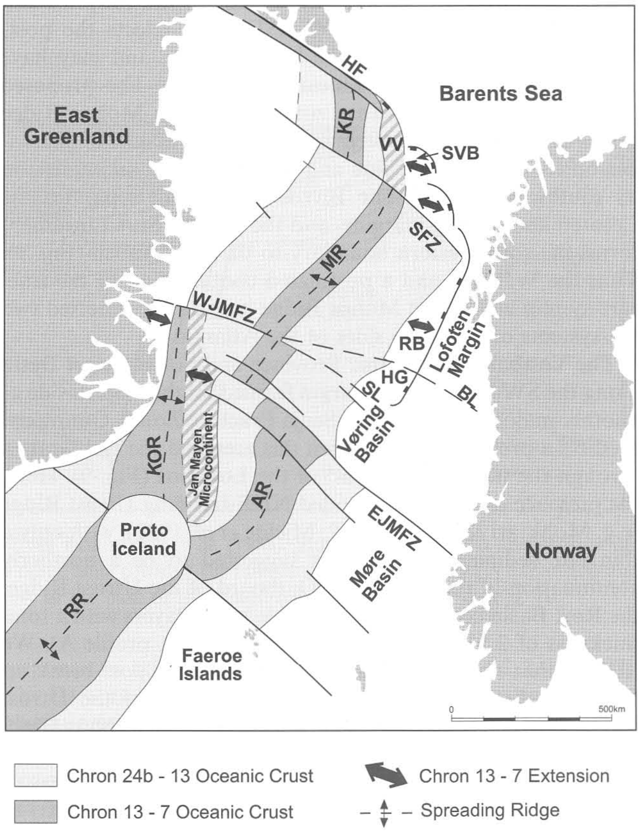

Fig. 9. Sketch map of a proposed mid-Cenozoic (?Oligocene–Miocene) linked extensional system affecting East Greenland, Jan Mayen, the northern Vøring Basin and the western Barents Sea. Plate reconstruction is to chron 7 time (25 Ma). For further explanation, see text. For abbreviations, see Table 1.

propagated from south to north between the Jan Mayen Block and SE Greenland, counterbalancing the fan-shaped spreading (widening northwards) along the Aegir Ridge (Figs 6, 8 and 9). The extension culminated in the separation of the Jan Mayen microcontinent along the Kolbeinsey spreading ridge, and extinction of the Aegir Ridge, at chron 7 time (25 Ma, Oligocene–Miocene boundary). Extensional faulting associated with this episode is postulated from seismic data over the Jan Mayen microcontinent (Kuvaas & Kodaira 1997) and is reported from the Traill Ø region of East Greenland (Price *et al.* 1997). Simultaneously, rifting occurred in Sørvestnaget Basin and Vesbakken Volcanic Province of the western Barents Sea. A new spreading centre (Knipovitch Ridge) developed in this area in chron 21 times (49 Ma) and a change from dextral shear to passive drift between Svalbard and Greenland took place in the chron 13-6 interval (35–20 Ma) (Faleide *et al.* 1993). Our work identifies a probable further element of this extension in the northern Vøring Basin. The Nyk High, a NE trending fault block on the SE flank of the Hel Graben, was affected by pre-break up (Paleocene) faulting but was subsequently highly rotated and truncated at its northeastern end by an Oligocene–Miocene unconformity. The unconformity is complemented in the hanging wall by a syn-rift sedimentary wedge of Oligocene–Miocene age. Seismic profiles in the Hel Graben show the presence of Oligocene–Miocene sills within the section onlapping the Paleocene break-up unconformity, and we postulate that these relate to the mid-Cenozoic extension. Similar late intrusions are identified in the Vestbakken Volcanic Province (Gabrielsen *et al.* 1990).

Regionally, the areas of mid-Cenozoic rifting appear to show a systematic relationship with the more easterly plate vector of post-Eocene time (Fig. 6). Based on this observation, we suggest that the three areas were rift systems linked by transform boundaries. In this model the Western Jan Mayen Fault Zone (WJMFZ), whose WNW–ESE trend relects the post-Eocene vector, linked with the Mohns Ridge and may have continued to the Bivrost Lineament (Fig. 9). The proposed continuation of this fracture zone east of the Mohns Ridge forms the boundary between well developed magnetic anomalies on its northeastern side and poorly defined anomalies on its southwestern side. The Bivrost Lineament separates the Lofoten and Vøring margins, and the parallel Surt Lineament forms the southwestern boundary to the Hel Graben (Fig. 9). Thus the WJMFZ and a postulated continuation of the fracture system east of the Mohns Ridge may have connected two rift systems on opposite sides of the Atlantic.

The Vestbakken Volcanic Province and Sørvestnaget Basin along the SW Barents Sea margin formed on the eastern side of another major transform (the Senja Fracture Zone). Our model predicts a probable link between this area and the Hel Graben through the narrow shelf west of the Lofotens (Fig. 9). Here, the presence of the deeply eroded NNE-trending Utrøst Ridge (e.g. Mohktari & Pegrum 1992; Mjelde *et al.* 1992), with only a thin late sedimentary cover, is suggested to be a northerly continuation of the Nyk High. Outboard of the Utrøst Ridge, the Røst Basin contains two probable basalt layers with a total thickness of 2.5 km (Mjelde *et al.* 1992; Fig. 2, profile A). We suggest that the lava sequence could include post-break-up Oligocene flows. The depth of peneplanation of the Utrøst Ridge gradually decreases southward along the Nyk High. Likewise, bed rotation of the Nyk High gradually decreases from north to south. Both are probably a consequence of decreasing extension (and hence decreasing footwall uplift) to the south.

In summary, we observe that the chron 13 change in relative plate motion created tensional regimes on the passive margins on both sides of the North Atlantic, and that this rifting was successful in East Greenland and in the Barents Sea. We propose that Oligocene rifting extending from the Sørvestnaget Basin to the Hel Graben was linked via the Bivrost and Surt lineaments to the WJMFZ and thereby to the rifting between East Greenland and Jan Mayen. Extension on the Norwegian margin may represent a failed attempt at splitting off a microcontinent similar to Jan Mayen. The relationship between the Cenozoic extension and inversion (see previous section) is not yet clear. As suggested by Doré & Lundin (1996), it is possible that these tectonic effects occurred simultaneously as transtensional and transpressional elements of a strike-slip regime. Our currently preferred hypothesis, however, is that the extension was a discrete event and interrupted a general background of mild compression deriving from ridge-push, as also suggested for East Greenland (Price *et al.* 1997).

Neogene uplift and erosion

The last major tectonic phase on the Atlantic margin, regional uplift of Neogene age (Fig. 10), was arguably one of the most important, not least because it shaped the distribution of sea and landmasses we see today. The phenomenon has been intensely studied in Norway, where it has had a critical effect on the petroleum system. This importance is exemplified by Fig. 11, a geoseismic profile running from the Møre Basin to Haltenbanken. Cretaceous and Cenozoic sedimentary units rise and are truncated close to the emergent basement of the Norwegian coast. A major sedimentary wedge of Pliocene age progrades away from the mainland, and is itself truncated by the unconformity at the base of the Quaternary. This pattern is consistent around most of the Norwegian mainland, which is ringed by concentric subcrops indicating domal uplift and late emergence.

Cenozoic uplift of Norway has now been quantified using numerous methods, including shale sonic interval velocities, apatite fission track, vitrinite relectance, mass balance and graphical reconstruction (e.g. Riis & Jensen 1992). It is also apparent that large portions of Norway's surrounding shelf, in particular the Barents Sea, have been subjected to similar uplift and erosion (e.g. Nyland *et al.* 1992). Net uplifts of up to 2000 m on the mainland, and 3000 m in the Barents Sea, are recorded (Fig. 8). There is now a reasonable consensus among Norwegian workers that initial uplift was tectonic in nature and occurred in several phases during the Cenozoic, but that the most severe uplift and erosion was in the Plio-Pleistocene and was closely associated with glaciations taking place in the last 2.5 Ma (Solheim *et al.* 1996).

Studies addressing Cenozoic uplift, cooling and erosion have been carried out for Ireland and the Porcupine Basin (McCulloch 1993), the Slyne Trough (Scotchman & Thomas 1995), Northern Ireland (Parnell 1991), the West Orkney Basin (Evans 1997) and the British mainland (e.g. Lewis *et al.* 1992; Green *et al.* 1993; Japsen 1997). Little has been done in the way of regional synthesis, as reflected in the lack of quantitative data outside Norway in Fig. 10. It is clear, however, that a similar event chronology took place and that the British Isles, like Norway, were part of a North Atlantic-scale exhumation. A significant part of this uplift occurred in the Neogene (e.g. Japsen 1997).

A suggested event sequence for uplift on the Atlantic margin is as follows: at the end of the Cretaceous, most of the landmasses bordering the margin were close to sea-level, due to progressive reduction in topographic elevation and the highly transgressive nature of the late Cretaceous seas. The Paleocene saw thermally generated uplift along the line of incipient Atlantic opening, regional uplift of the British Isles and localized uplift in Scandinavia (see section on the Paleocene and Fig. 10). Further uplifts of Oligocene–Miocene age took place in Norway (Ghazi 1992), offshore Ireland (Scotchman & Thomas 1995) and the UK (Roberts 1989). These uplifts were

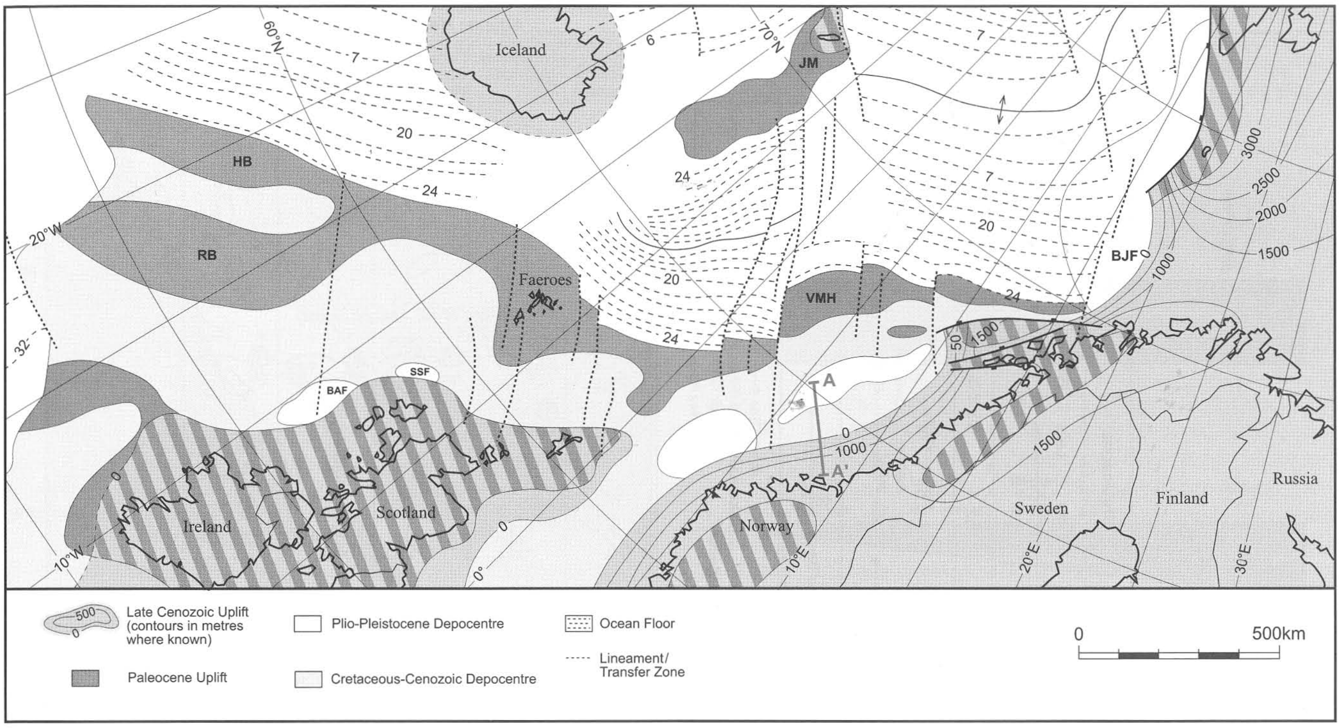

Fig. 10. Map showing Cenozoic uplift along the northwest European Atlantic margin. Paleocene uplift is shown in dark brown, and includes the volcanic highs along the line of continental break-up. Neogene uplift is shown in light brown. The uplift contours for Norway and its shelf are based on evidence from over 100 wells and the present topography of Norway. Major Plio-Pleistocene depocentres are shown in yellow. For abbreviations see Table 1.

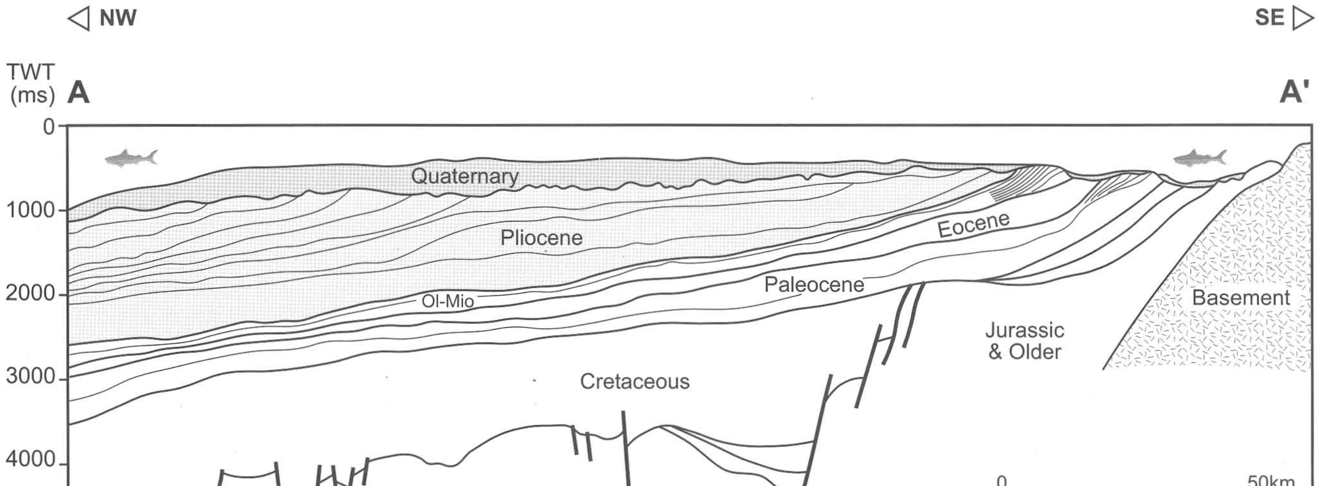

Fig. 11. Geoseismic dip cross-section over the Mid-Norwegian shelf adapted from Rokoengen *et al.* (1988), illustrating late uplift and erosion of Norway and inboard basins. Note the progressive truncation of Cenozoic and older units towards the mainland, major sedimentary expansion and progradation away from Norway in the Pliocene, and the marked unconformity at the base of the Quaternary. For location, see Fig. 10.

very probably associated with the same intraplate stress regime that produced the inversion structures described in the preceding section. However, it is important to distinguish between local uplifts caused by inversion and the uplift of a more regional nature that characterized the latest Cenozoic. This may have taken the form of a general uplift of cratonic areas as a long-wavelength effect of plate-wide compression, as suggested by Cloetingh *et al.* (1990). Climatic deterioration during this time caused nucleation of continental ice sheets on areas elevated by early and mid-Cenozoic tectonics. Rapid erosion took place as a result of multiple glaciations, while net uplift occurred during each interglacial as a result of isostatic response to lithospheric unloading (Riis & Fjeldskaar 1992). The Barents Sea, which was a subaerial platform prior to the glaciations, was reduced by subglacial scour to a shelf sea (Solheim *et al.* 1996). Deltas and fans containing vast quantities of Plio-Pleistocene sediments were shed on to the Barents Sea margin (Solheim *et al.* 1996), the mid-Norwegian shelf (Poole & Vorren 1993) and Hebridean margin (Stoker 1997; Figs 8 and 9).

Late Cenozoic uplift is often completely neglected in tectonic histories of NW Europe, and yet for many basins on the Atlantic margin it has had profound implications for the hydrocarbon system (Doré & Jensen 1996). A great deal is now

Fig. 12. Post-Carboniferous event chronology of basins on and adjacent to the NW European Atlantic margin. For abbreviations see Table 1.

known about these effects through study of the Barents Sea and basins marginal to the Norwegian coast. Regional tilting caused spillage from traps, while stripping of overburden resulted in seal failure and escape or remigration of hydrocarbons. Removal of confining pressure caused expansion of gas, exsolution of gas from pre-existing oil accumulations, and hence expulsion from traps. Source rocks were cooled and therefore stopped generating in areas of net uplift and erosion. Conversely, rapid generation took place in the new Plio-Pleistocene depocentres: for example, on the Halten Terrace (Koch & Heum 1995). Much of the UK–Irish portion of the margin was also subjected to glaciation (Stoker 1997), and a large area was deeply eroded by this and other Cenozoic events. This area includes the Slyne and Erris troughs, where a thin veneer of Tertiary sediments overlies deeply eroded Mesozoic units (see Chapman *et al.* 1999, Fig. 2), the Hebridean Basins and the West Shetland Basin (Fig. 1). The prognosis for these basins is not necessarily negative, since much of the world's hydrocarbon resource resides in uplifted basins (Doré & Jensen 1996).

Conclusions

(1) The increasing activity level and database on the north-west European Atlantic margin allows geological similarities and differences along trend to be examined in a systematic manner. This analysis reveals repeating structural patterns, tectonic events that are co-eval over the whole or large parts of the margin, and tectonic events of a more local nature. The succession of tectonic episodes on the margin is the key to understanding the petroleum system. The post-Carboniferous event chronology of the region is summarized in Fig. 12.

(2) Basement grain played an important role in structural development, in that NE Atlantic rifting and opening partially

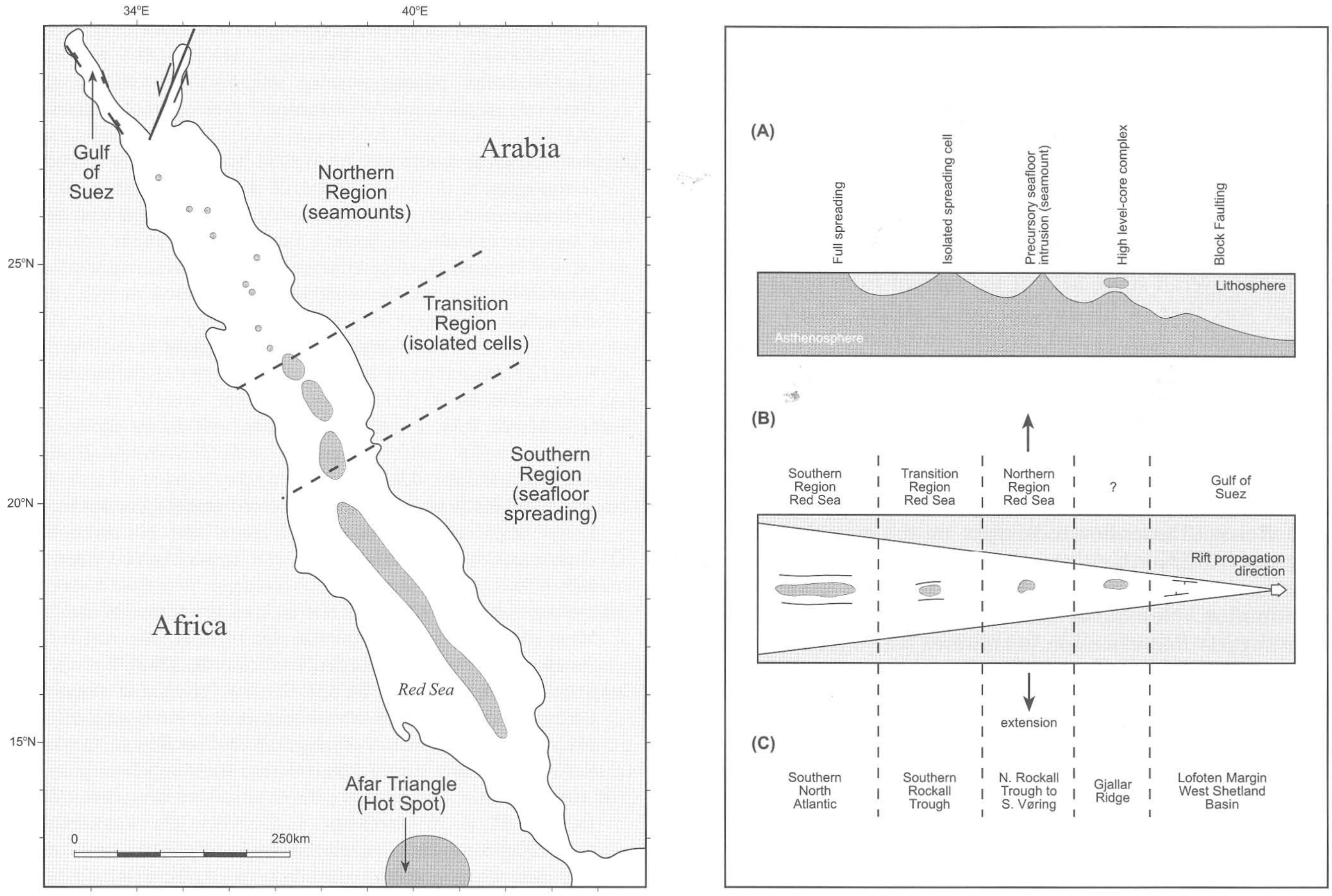

Fig. 13. Comparison of extensional phenomena on the northwest European Atlantic margin (block faulting, core complexes, seamounts, isolated spreading cells and full spreading) with those observed in the Red Sea (Bonatti 1985). Left panel: sketch map of the Red Sea with extensional/spreading phenomena. Right panel; (**A**) stages of crustal thinning; (**B**) their manifestation in the Red Sea; (**C**) their manifestation on the Atlantic margin.

exploited the Caledonian orogen. Most of the offshore lineaments can probably be explained in terms of Permian or later extension. However, certain onshore lineaments, particularly steeply dipping shears, show evidence of multiple reactivation. In general, Precambrian and Caledonian lineaments were selectively reactivated according to the extension direction. Major lineaments approximately orthogonal to the extension direction deformed by dip-slip or oblique slip, while major lineaments at a low angle to the extension direction predisposed the formation of transfer zones. Since basement reactivation can seldom be proven offshore, the most diagnostic area of study is on onshore basement faults that have offshore expression.

(3) The exceptionally long history of extension prior to plate separation (*c.* 350 Ma) is partially explained by changes in the extension direction, but mainly by lateral shifting of the successive rift axes towards the line of eventual opening. We propose that the episodic nature of the rifting allowed cooling of mantle material under stretched crust, strengthening of the lithosphere, and hence avoidance of the thinned areas by succeeding rifts rather than continuous necking. Extensional phenomena observed on the margin range from block-faulting, through core complexes, seamounts (precusory sea-floor intrusions) and isolated spreading cells, to plate separation. They represent successive stages in the extension process with early and intermediate stages frozen in place because of rift abandonment, and compare well with a similar suite observed in the Red Sea (Fig. 13).

(4) Extension began in the Devonian with post-Caledonian collapse/back-sliding, but the main observable extensional episodes offshore are of Permo-Triassic, (mainly Late) Jurassic, Early Cretaceous, 'middle' Cretaceous and Maastrichtian–Early Eocene. Permo-Triassic extension represents fragmentation of an uplifted and unstable Pangea and exploited the orogenic belts that welded the supercontinent together. By Jurassic times an overall E–W extensional stress field was imposed, which may be associated with seafloor spreading in northern Tethys. Both rift networks were strongly transected and overprinted by the Early Cretaceous rifting, which probably began in the Hauterivian. The extension reflected rotation of the least principal stress vector (to NW–SE over much of the NE Atlantic margin), an event associated with northward propagation of Central Atlantic spreading during the Early Cretaceous. This stress regime was maintained with minor modification through to break-up.

(5) Late Jurassic and Early Cretaceous rifting, often classed as a single event, represent two discrete events which, although only separated by a small time interval, represent a major rearrangement in space. Cretaceous basins of NE–SW trend such as the Vøring Basin, Møre Basin and Rockall Trough strongly truncated N–S Jurassic basins (Halten Terrace, Viking Graben and Porcupine basin, respectively). The Jurassic basins were uplifted on the southeastern flanks of the Cretaceous basins, while remnant Jurassic basins are predicted to exist beneath the Cretaceous depocentres.

(6) Mid-Cretaceous and Paleocene rifting is partially obscured by pre-break-up basalt flows, but both phases can be observed in the Vøring Basin. On the Vøring margin extension may have been continuous between these phases and led to the development of core complexes. There is increasing evidence that both the mid-Cretaceous and Paleocene phases

were important in basin development west of the Shetlands. Small-scale but widely distributed E–W Paleocene faults in this area are best explained by a dextral strike-slip component along the pre-Atlantic rift.

(7) Paleocene extension occurred contemporaneously with major basaltic magmatism, thermal elevation of the incipient spreading ridge and widespread uplift and exhumation of provenance areas. These events culminated with plate separation along the NW European Atlantic margin at 53 Ma in the early Eocene.

(8) The overall stress field of the margin from break-up to present was that of SE-directed compression, which caused basin inversion, doming and reverse rejuvenation structures in the Cretaceous–Cenozoic depocentres. The inversion structures developed in several phases. They are best explained by ridge push from the North Atlantic spreading centre but may also be linked with Oligocene–Miocene spreading reorganization, minor strike-slip on NW-trending transfer lineaments and, in a plate-wide sense, with Alpine closure phases.

(9) Renewed extension took place on the opposing passive margins of the North Atlantic in the Oligocene–Miocene as a consequence of a change from NW–SE to WNW–ESE relative plate motion. New observations from the northern Vøring Basin suggest that extension in this area was linked to rifting and spreading ridge development: (a) in the western Barents Sea; and (b) between Jan Mayen and East Greenland.

(10) A series of uplifts beginning in Paleocene times gave rise to the land–sea distibution observed today. A very significant period of uplift and erosion occurred in the Neogene. Initial uplift may have been the result of intraplate compressive stress, but was subsequently magnified by glacial erosion and isostatic readjustment repeated through numerous glaciations and interglacials. This episode affected the western Barents Sea and other basins along the Atlantic seaboard, where it had a radical effect on the hydrocarbon system. These effects are well-studied in Norway, and experience gathered there can be used to constrain risk elsewhere along the North Atlantic margin.

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