Neogene evolution of the Atlantic continental margin of NW Europe (Lofoten Islands to SW Ireland): anything but passive

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Abstract

A regional stratigraphic framework for the Neogene succession along and across the NW European margin is presented, based on a regional seismic and sample database. The stratigraphy provides constraints on the timing and nature of the mid- to late Cenozoic differential tectonic movements that have driven major changes in sediment supply, oceanographic circulation and climate (culminating in continental glaciation). The overall context for Neogene deposition on the margin was established in the mid-Cenozoic, when rapid, km-scale differential subsidence (sagging) created the present-day deep-water basins. The Neogene is subdivided into lower (Miocene–lower Pliocene) and upper (lower Pliocene–Holocene) intervals. The *lower Neogene* contains evidence of early to mid-Miocene compressive tectonism, including inversion anticlines and multiple unconformities that record uplift and erosion of basin margins, as well as changes in deep-water currents. These movements culminated in a major expansion of contourite drifts in the mid-Miocene, argued to reflect enhanced deep-water exchange across the Wyville-Thomson Ridge Complex, *via* the Faroe Conduit. The distribution and amplitude of the intra-Miocene movements are consistent with deformation and basin margin flexure in response to enhanced intra-plate compressive stresses during a local plate reorganisation (transfer of the Jan Mayen Ridge from Greenland to Europe). The *upper Neogene* records a seaward tilting (<1°) of the margin from the early Pliocene, in which km-scale uplift and erosion was accompanied by increased offshore subsidence, resulting in a major seaward progradation of the shelf–slope wedge as well as deep-marine erosion during a reorganisation of bottom current patterns. The large amplitude of tilting cannot be accounted for by intra-plate stress variations, but is consistent with a dynamic topographic response to upper mantle convection, in particular edge-driven flow beneath the continental margin. Sedimentary and oceanographic changes resulting from dynamic topographic responses to the evolution of upper mantle convective flow during ocean widening may be characteristic of the development of ‘passive’ continental margins.

Keywords:
Neogene, NW European Atlantic margin, tectonics, ocean circulation, glaciation

The complex bathymetry of the NW European continental margin between the Lofoten Islands and SW Ireland (Figs 1 & 2) is ultimately a reflection of the crustal thickness variations due to rifting and magmatism that culminated in the separation of Europe and Greenland in the early Eocene (e.g. Skogseid *et al*. 2000). The final localisation of extension along the continent-ocean boundary (Figs 1 & 2) took place during an overall northward propagation of seafloor spreading, in the Late Cretaceous along the Bay of Biscay–Labrador Sea axis and in the early Cenozoic along the Greenland–Norwegian Sea axis (e.g. Ziegler 1988; Doré *et al.* 1999). However, the great width of the margin (up to 800 km west of Ireland, 500 km west of Norway; Fig. 2) reflects an overall westward displacement of a 'proto-North Atlantic' rift axis through the Mesozoic (Doré *et al.* 1999), which left a chain of large, mid-Jurassic to Cretaceous deep-water sedimentary basins flanked by structural highs and by the inner continental shelf. The Vøring, Møre and Faroe-Shetland basins, in depths over 1000 m, and the underfilled Rockall and Porcupine basins with depths >2000 m (Figs 1 & 2) continued to accumulate sediment throughout the Cenozoic, but contain no tectonostratigraphic evidence of post-Paleocene extension (e.g. Roberts *et al*. 1999). The continental margin narrows to almost 300 km across the Møre Basin (Fig. 1), between the extensions of oceanic fracture zones that bounded the Cenozoic movements of the microcontinent that is the Jan Mayen Ridge to the northwest (Brekke 2000) (Fig. 2). Additional complexity in margin physiography has resulted from Cenozoic magmatism, which is responsible for the thickened crust of the Greenland-Scotland Ridge (GSR) flanking the Iceland hot-spot (Fig. 2) and for numerous igneous centres or 'seamounts' (Doré *et al*. 1999). The combination of crustal extension, intra-plate magmatism and seafloor spreading has contributed to a marked segmentation of the margin (Figs 1 & 2), which has had important consequences for its post-rift sedimentary and oceanographic dynamics.

The post-rift development of the continental margins bordering the NE Atlantic (Figs 1 & 2) is generally classed as passive (i.e. tectonically quiescent). However, the margins are known to have experienced tectonic movements during the Cenozoic, manifest as significant departures from the expected post-rift pattern of decaying subsidence due to cooling (e.g. Steckler & Watts 1978), including episodes of accelerated subsidence and inversion episodes that were, at least in part, coeval (e.g. Stuevold *et al*. 1992; Riis 1996; Doré *et al*. 1999, 2002; Japsen & Chalmers 2000). The tectonic episodes had visible consequences, in the uplift and erosion of broad epeirogenic domes in onshore and shelf areas (e.g. Vågnes & Amundsen 1993; Rohrman & van der Beek 1996; Rohrman *et al*. 2002), and in the formation of smaller but widespread compressional domes (Lundin & Doré 2002; Ritchie *et al*. 2003). The causes of the tectonic movements remain uncertain (see Doré *et al*. 2002), but two main classes of mechanism have been proposed, one driven by horizontal forces related to changes in lithospheric plate motions (e.g. Cloetingh *et al*. 1990; van Balen *et al*. 1998), the other by vertical interactions between the lithosphere and mantle convective motions, mainly in the hypothetical context of a plume beneath the Iceland hot-spot (e.g. magmatic underplating plus rifting, Hall & White 1994; lithospheric delamination and asthenospheric diapirism, Rohrman & van der Beek 1996, Nielsen *et al*. 2002; dynamic uplift above the plume axis, Clift 1996, Nadin *et al*. 1997). It has also been suggested that continental glaciation caused the late Neogene uplift of the margins (e.g. Eidvin *et al*. 2000; Peizhen *et al*. 2001; Faleide *et al*. 2002), or alternatively that it enhanced the underlying tectonic uplift (e.g. Hjelstuen *et al*. 1999; Nielsen *et al*. 2002). What is clear, at least on the NW European margin, is that the successive tectonic episodes have driven changes in oceanographic dynamics and in the patterns of downslope and alongslope sedimentation, which have in turn found expression from the shelf to the deep-water basins as regionally significant stratigraphic sequences bound by correlative unconformity surfaces (Stoker 1997; Jordt *et al*. 2000; Eidvin *et al*. 2000; Stoker *et al*. 2001, In press; McDonnell & Shannon 2001; Faleide *et al*. 2002).

As will be demonstrated in this paper, three main tectonic episodes have had an important influence on the Neogene stratigraphic record: i) in the late Eocene–Oligocene, strongly differential subsidence outstripped sedimentation along most of the margin, driving a deepening of well over a kilometre in the Rockall area, giving rise to the Neogene configuration of underfilled deep-water basins (Vanneste *et al*. 1995; Stoker 1997; Stoker *et al*. 2001; McDonnell & Shannon 2001); ii) in the late Oligocene–mid-Miocene, compressive tectonism resulted in the formation of inversion structures both on the Vøring Plateau and in the Faroe–Shetland and North Rockall areas, including the Wyville-Thomson Ridge Complex (WTRC) (Boldreel & Andersen 1995; Lundin & Doré 2002; Ritchie *et al*. 2003; Hoult *et al*. In press); and iii) from the early Pliocene, onshore uplift, maximal (1–2 km) within a series of broad epeirogenic domes (e.g. Rohrman & van der Beek 1996) was accompanied by accelerated offshore subsidence and the progradation of sedimentary wedges (Cloetingh *et al*. 1990; Riis 1996; Kyrkjebø *et al*. 2000; Japsen & Chalmers, 2000; Stoker, 2002).

The regional to local variations in subsidence and sediment supply associated with these tectonic movements had a pronounced effect on the patterns both of shelf-margin to deep-water sedimentation and of palaeoceanographic circulation. Two outstanding issues are important to our understanding of the Neogene evolution of the margin:

1. The Greenland-Scotland Ridge (Fig. 1) has a critical influence on the properties of the world ocean, by acting as a barrier to the exchange of deep-water masses between the Atlantic and Arctic oceans. This barrier was breached sometime following the Eocene to allow the overflow of Norwegian Sea Deep Water (NSDW) but it remains uncertain if this occurred during the late Eocene–early Oligocene (Miller & Tucholke 1983; Davies *et al*. 2001) or in the early Neogene (mid-Miocene) (Blanc *et al*. 1980; Bohrmann *et al*. 1990; Eldholm 1990). The deepest passageway is currently the Faroe Bank Channel (800–1200 m), between the east end of the GSR and the anticlinal folds of the WTRC and Faroe Bank, which, together with the Faroe-Shetland Channel, is herein termed the Faroe Conduit (Fig. 3).
2. The late Neogene uplift of the North Atlantic continental margins may have had a major impact on the changes in global climate that ultimately led to northern hemisphere glaciation (e.g. Japsen & Chalmers 2000). There is evidence that the onset of these movements coincided with an early Pliocene plate reorganisation (Cloetingh *et al*. 1990) that affected oceanic circulation patterns throughout the Atlantic Ocean (e.g. formation of the Isthmus of Panama) (Haug & Tiedemann 1998; Lear *et al*. 2003). On the NW European margin, however, uncertainty has surrounded the relationship of onshore uplift to the observed seaward progradation of large Plio-Pleistocene sediment wedges (Figs 2 & 4), the initiation of which has been suggested either to be a consequence of northern hemisphere glaciation (e.g. Eidvin *et al*. 2000; Faleide *et al*. 2002) or to pre-date glaciation and be a response to tectonically driven change (Cloetingh *et al*. 1990; Japsen & Chalmers 2000; Stoker 2002).

A satisfactory resolution of these issues has been inhibited by uncertainty over the timing of Neogene events along the margin, which has also prevented a proper evaluation of the cause of the tectonic movements. In this paper, a Neogene stratigraphic framework for the NW European Atlantic margin is presented, which documents the sensitive record of changes in palaeoceanographic regime and in depositional and erosional styles that is preserved in the deep-water sediment fills of the basins to the north and south of the GSR. The objective is to examine the potential linkages between tectonics and changes in sedimentation, deep ocean circulation and climate during the Neogene. The results provide constraints on the varying magnitude and character of the large-scale vertical movements, which in turn allow us to consider the causes of the tectonism.

Data and Methods

The study is based on the database assembled for the EC-supported STRATAGEM project (Stratigraphical Development of the Glaciated European Margin) (STRATAGEM Partners 2002, 2003; Evans *et al*. In press). The database comprises tens of thousands of line-kilometres of seismic reflection profiles (multi-channel and high-resolution single-channel data) and 76 sample stations (shallow boreholes and exploration wells). In Fig. 5, 13 boreholes/wells are presented as key sources of stratigraphic information, although it is stressed that the entire database was utilised in the development of the stratigraphic framework (STRATAGEM Partners 2002). The Neogene is taken to incorporate the Miocene to Holocene interval, following Berggren *et al*. (1995b). Biostratigraphic correlation is based on the calcareous nannoplankton zonal scheme of Martini (1971), in which the prefix NP applies to Palaeogene zones and NN to Neogene zones. The temporal ranges of the biozones are those of Berggren *et al*. (1995a), each having durations of a few million years. The error ranges associated with different Neogene bounding surfaces vary with stratigraphic level and from place to place, reflecting changes both in the geology and in the density of the database (Fig. 5).

In the construction of the regional stratigraphic framework, emphasis was placed on the identification of intervals bounded by regional (margin wide) surfaces of discontinuity, defined from discordant reflector relations according to the criteria established by Mitchum *et al*. (1977), and interpreted as unconformities or correlative conformities. The regional stratigraphic scheme (Fig. 6) represents the correlation of stratigraphic intervals within three study areas along the margin: 1) North Sea Fan–Vøring; 2) Faroe–Shetland; and 3) Rockall–Porcupine. These intervals, herein referred to as *megasequences*, are of informal stratigraphic status, but represent physically mappable units. Details of the megasequences within each study area are provided in Stoker *et al*. (In press) and are summarised in Table 1. Correlation of key reflectors between the areas reveals two regional boundaries that reflect major changes in margin evolution, here termed the Base Neogene and Intra-Pliocene surfaces (Fig. 5). These boundaries define two regional successions, informally referred to as the lower (early) and upper (late) Neogene successions that contain the Miocene–lower Pliocene and lower Pliocene–Holocene megasequences (Fig. 6). Other important breaks occur within the two successions, including the Intra-Miocene and Intra-Pleistocene (Glacial) unconformities, for which regional correlation remains ambiguous (see below). Thicknesses are presented in seconds (s) two-way travel time (TWTT); sound velocities in the Neogene succession are generally in the range of 1.5 to 2.0 km/sec, so that the thicknesses in seconds TWTT can be taken as maximum estimates in km (i.e. 0.5 s TWTT is ≤0.5 km).

Neogene stratigraphic framework

The geometry and stratigraphical range of the Neogene succession is depicted in Figs 4 & 5. The greatest thickness (locally >2 s TWTT) is preserved offshore Norway, mainly reflecting the massive build-out of the shelf–slope apron in the Plio-Pleistocene. The main elements of the stratigraphic framework are illustrated in Figs 7 & 8 and briefly summarised below (in ascending stratigraphic order), beginning with the Base Neogene boundary and the Intra-Miocene Unconformity (IMU). These surfaces are described together, as the interval that they bound represents the greatest uncertainty in dating and inter-correlation of the lower Neogene succession, due to early Neogene submarine erosion in the area of the WTRC (Fig. 5).

Base-Neogene and intra-Miocene surfaces

Unconformities corresponding to the Base Neogene boundary and the IMU are recognised across the north Faroe–Shetland and North Sea Fan–Vøring areas, where their ages are loosely constrained by biostratigraphic data as latest Oligocene–early Miocene (Base Neogene) and late early to mid-Miocene (IMU), respectively (Fig. 5). These surfaces converge across the WTRC, where the boundary between the Palaeogene and Neogene strata (Fig. 5) spans the latest Oligocene–mid-Miocene interval and is inferred to be a composite unconformity. In the central and southern Rockall area, there is no unconformity between the Palaeogene and Neogene strata but an important intra-Miocene surface is recognised (C20 reflector).

Base Neogene boundary. In the North Sea Fan–Vøring and Faroe–Shetland areas, the base of the Neogene corresponds to a mainly angular submarine unconformity separating Miocene (or uppermost Oligocene) from older Palaeogene strata (Figs 5 & 8a-b), corresponding to the Base Kai Unconformity (BKU) and the Top Palaeogene Unconformity (TPU) (Fig. 6). Although Davies *et al*. (2001) reported a conformable passage from the Oligocene into the Miocene from UK well 214/4-1 in the NE Faroe-Shetland Channel, a widespread, angular unconformity is observed on seismic profiles in the area of the well (Andersen *et al*. 2000; STRATAGEM Partners 2002; Hoult *et al*. In press). At the SW end of the Faroe-Shetland Channel, north of the WTRC, the TPU (locally composite with the IMU) is sculpted into a series of major scarps with hollows up to 200 m deep, termed the Munkagrunnur Falls (also referred to as the Judd Deeps) (Stoker *et al*. In press) (Fig. 7a). These are the most extreme expression of a regional angular erosion surface cut into Oligocene and Eocene strata, which is largely buried below the West Shetland Slope (Fig. 8b). Correlatives of the TPU are recognised in the northern Rockall Trough (Figs 5 & 8c), but farther south, the base of the Neogene lies within the RPc megasequence and does not correspond to a seismically defined boundary (Fig. 7c). In the Porcupine Basin, an early Miocene hiatus, dated as intra-NN2 biozone, effectively marks the Base Neogene boundary (Dobson *et al*. 1991), and corresponds to a mainly conformable seismic reflector (McDonnell & Shannon 2001) (Fig. 5).

Intra-Miocene Unconformity. This surface corresponds to angular unconformities and correlative conformities identified both in deep-water basins and on basin margins, including the mid-Miocene Unconformity (MMU) on the Norwegian margin (Brekke 2000), the Intra-Miocene Unconformity (IMU) defined throughout the Faroe–Shetland area (Andersen *et* al. 2000; STRATAGEM Partners 2002; Hoult *et al*. In press), and the C20 reflector in the Rockall–Porcupine area (Stoker *et al*. 2001). The angularity of the deep-water unconformities is locally enhanced where they are developed above, and mark the last major movement on, inversion domes/anticlines (Brekke 2000; Hoult *et al*. In press). In the North Sea Fan–Vøring area, the MMU corresponds to a widespread angular unconformity on basin margins (Jordt *et al*. 2000; Brekke 2000), correlating in well data to a ca. 7 Ma hiatus of late mid- to early late Miocene age (Eidvin *et al*. 2000). In the Faroe–Shetland area, the IMU lies in close proximity (slightly below) to the 'Mid-Miocene' unconformity of Davies *et al*. (2001) reported from UK well 214/4-1 (Ritchie *et al*. 2003). Across the WTRC, the cutting of the IMU may have reactivated the TPU as a consequence of compressional doming and deep-water erosion, resulting in a composite unconformity (e.g. Figs 7a & 8b-c). In the Rockall–Porcupine area, the C20 reflector is a regional submarine surface that onlaps the basin margins and has been dated as late early–early mid-Miocene (NN4–5 biozone) at ODP site 610, where it is diagenetically enhanced (see Stoker *et al*. 2001 and references therein). In the Porcupine Basin, C20 corresponds to one of several angular unconformities that grade into conformity in the basin centre (McDonnell & Shannon, 2001).

Lower Neogene succession

The lower Neogene succession includes a number of unconformity-bounded packages that vary in character and extent along the margin (Figs 4 & 6) including the Kai Formation, and the FSN-2 and RPb megasequences (Table 1). In deep-water areas, this succession locally exceeds 0.6 s TWTT in thickness and comprises the bulk of the Neogene sediments preserved under the Vøring Plateau, and in the Norwegian Basin, northern Faroe-Shetland Channel, Rockall Trough and Porcupine Basin. On the adjacent shelves, the succession has been extensively eroded in late Miocene–early Pliocene time, but not totally removed. Sediments exceeding 0.2 s TWTT occur locally beneath the Mid-Norwegian and East Faroe shelves (Fig. 4); up to 0.15 s TWTT of lower Neogene strata occur locally below the West Shetland Shelf.

The internal seismic character of the lower Neogene succession shows that deep-water sedimentation along the margin was strongly influenced by bottom-current activity. The most distinctive expression of deep-water currents is the accumulation of 'mounded' contourite sediment drifts and associated sediment waves, up to 40 m high and 2–3 km wavelength, along the length of the margin (e.g. inner Vøring Plateau, Fig. 8a; southern Rockall Trough,

Fig. 7c). A distinctive characteristic of the deep-water sediments is their variable geometry (Table 1), which is largely a response to the physiography of the margin, including a significant submarine topography created in areas subject to early/mid-Miocene folding and inversion, e.g. north Rockall–Faroe and mid-Norwegian areas (Lundin & Doré 2002) (Fig. 3). Here, sedimentation infilled the lows, onlapping and gradually burying the topography (Brekke 2000; Hoult *et al*. In press; Ritchie *et al*. 2003). In the West Rockall Trough, lower Neogene basinal strata have onlapped the eastern slope of Rockall Bank to a point close to the contemporary shelfbreak (Fig. 7b). In contrast, infilling drifts locally accumulated in the erosional deeps associated with the TPU/IMU in the Faroe–Shetland area (Fig. 7a).

Our regional study shows that the main development and accumulation of contourite drifts, both north and south of the WTRC, dates from the mid-Miocene. This is reflected by the coeval growth of large mounded drifts in the inner Vøring Plateau (Fig. 8a), above the TPU/IMU in the Faroe–Shetland area (Fig. 8b), and above C20 in the southern Rockall Trough (Fig. 7c). Sample data from the NW European Atlantic margin show that the deep-water sediments are predominantly biogenic clays and oozes, with bioclastic detritus atop the seamounts in the Rockall Trough; the shelf-margin deposits include transgressive glauconitic sands (Table 1).

Intra-Pliocene boundary.

The Intra-Pliocene boundary is a well-defined regional unconformity with a closely constrained early Pliocene age (Fig. 5). The boundary is defined by correlation of the Base Naust Unconformity (BNU) of the Norwegian margin with the Intra-Neogene Unconformity (INU) of the Faroe–Shetland area and the C10 reflector of the Rockall–Porcupine area (Fig. 6). The seismically defined surface extends from the shelf-edge into the adjacent deep-water basins (Fig. 4) where it is characteristically angular and cut into older Neogene strata (Figs 7c & 8a) by submarine erosional processes (Stoker *et al*. In press). Along the margins, the surface is progressively downlapped by clinoforms of the seaward prograding upper Neogene succession (Fig. 8). In parts of the Faroe–Shetland and Rockall–Porcupine areas, the boundary is, itself, eroded and truncated by the present-day sea bed. On the outer Vøring margin, the boundary is locally conformable with reflectors above and below.

In the Rockall Trough, the C10 reflector has been dated as early Pliocene in age, between 3.85 and 4.5 Ma based on biostratigraphic data from ODP site 981 (Stoker 2002). This age is consistent with a marked change in sedimentation style across C10 at DSDP 610 (Stoker *et al*. 2001) and an early Pliocene break reported from UK well 214/4-1, in the Faroe-Shetland Channel (Davies *et al*. 2001), close to, but slightly below, the level of the INU

(Fig. 5). An early Pliocene age has also been reported on the basis of biostratigraphic data from BGS boreholes 88/7,7a and 77/9 from the shelf-margin off NW Britain, where lower Pliocene strata immediately overlie both C10 and the INU in the proximal part of the prograding upper Neogene successions (Stoker 2002). On the Vøring margin, a late early–early late Pliocene hiatus recorded from Norwegian well 6407/1-2 corresponds to a regional hiatus on the Norwegian margin (Brekke 2000). Although this unconformity is usually assigned a late Pliocene age (Eidvin *et al*. 2000), it was dated as early Pliocene (ca. 4 Ma) in age by Poole & Vorren (1993).

Upper Neogene succession

The upper Neogene succession records a major seaward progradation of the NW European margin. The succession corresponds to strata of the Naust Formation and the FSN-1 and RPa megasequences (Table 1), which are dominated by the development of thick prograding wedges along most of the margin north of Ireland (Figs 2 & 4). The thickest accumulation of upper Neogene strata occurs off Mid-Norway, where the Mid-Norwegian Wedge and the North Sea Fan form the bulk of the Neogene succession, locally exceeding 1.6 s TWTT. Farther south, similarly discrete, albeit smaller, depocentres, such as the East Faroe, West Faroe, Rona and Foula wedges, and the Sula Sgeir and Barra–Donegal fans, commonly exceed 0.4 s (and locally 0.6 s) TWTT. This contrasts with the deep-water basins where the sediments are generally <0.2 s TWTT thick (Figs 4a-e & 8). The margin of the southern Rockall–Porcupine area was largely sediment starved during the late Neogene (Fig. 4f, g).

The deep-water basins preserve the most complete record of late Neogene sedimentation, spanning the entire early Pliocene–Holocene interval above the Intra-Pliocene boundary. In the Rockall Trough and Faroe-Shetland Channel, over 50 m of lower Pliocene strata have been proven (e.g. DSDP 610, ODP 981, and UK wells 164/25-2 and 214/4-1) to overlie the early Pliocene unconformity. Coeval strata on the adjacent Hebrides and West Shetland margins are reduced in thickness. On the upper Hebrides Slope, BGS borehole 88/7,7A recovered a lower Pliocene lag gravel overlying C10, whereas several metres of lower Pliocene sand were penetrated at the proximal part of the Rona Wedge in borehole 77/9 on the West Shetland Shelf (Stoker 2002). Lower Pliocene strata have also been reported from the proximal, inner part of the sediment wedges off Mid-Norway in well 6610/7-1(Poole & Vorren 1993) (Fig. 3). More typically, the prograding sediment wedges comprise expanded sections of upper Pliocene–Holocene strata, mostly younger than about 3 Ma (Poole & Vorren 1993; Eidvin *et al*. 2000; Stoker 2002).

The prograding wedges are composed predominantly of stacked accumulations of debris-flow diamictons interbedded with hemipelagic and contouritic marine/glacimarine muds and thin-bedded turbidites (Table 1).

Contourite sediment drifts continued to accumulate in the basins throughout the late Neogene, although some basinal areas (e.g. NW Rockall Trough) were subjected to widespread, persistent, deep-sea erosion (Fig. 7b). Ice-rafted detritus is a common component of the succession younger than about 2.5 Ma. Glacial tills are preserved on the shelves above the Intra-Pleistocene (Glacial) Unconformity (see below). A key feature of slope-apron development throughout this interval has been the interplay between downslope and alongslope (basinal) sedimentation, resulting in an overlapping sediment wedge/sediment drift depositional system. It may be no coincidence that the main sites of late Neogene mass failure along the margin occur in areas where the downslope prograding wedges overlap/interdigitate with the onlapping basinal strata, thereby producing a shelf-margin sediment pile with highly variable physical properties — a likely precursor to mass failure (Bryn *et al*. 2002) (Fig. 2).

Intra-Pleistocene (Glacial) Unconformity.

The Intra-Pleistocene unconformity is a planar to irregular, regional erosion surface in shelf areas. Informally termed the Glacial Unconformity (GU) it characteristically truncates older Plio-Pleistocene prograding strata, and is overlain by a flatter lying sequence that displays an aggrading geometry, preserves glacial moraines, and gives way on the slope to glacial-fed trough-mouth fans (Figs 8b-c). In general terms, the GU marks a regionally observed change from a prograding to a prograding–aggrading shelf-margin. This change in depositional style is here considered to mark the switch from restricted (down to coastline) to expansive (shelf-wide) glaciations. Sediments cored from above the GU in both the NW UK and Norwegian margins are younger than 0.5 Ma (Stoker *et al*. 1994; Rise *et al.* 2002). This does not discount more localised pre-mid-Pleistocene glacial advances, particularly offshore Norway.

Sedimentary and oceanographic responses to tectonic episodes

Previous studies of Cenozoic tectonism on the NW European margin have recognised two types of differential movement (e.g. Stuevold *et al*. 1992; Doré *et al*. 1999, 2002): large-scale epeirogenic deflections, involving domal uplift accompanied by offshore subsidence, with wavelengths of hundreds of kilometres and amplitudes of up to several kilometres (Riis 1996; Doré *et al*. 1999; Japsen & Chalmers 2000); and smaller-scale compressive deflections expressed as inversion anticlines, with wavelengths of up to tens of kilometres and amplitudes of up to a kilometre (Lundin & Doré 2002; Ritchie *et al*. 2003). Analyses of both types of movement have mainly focused on one area (e.g. southern Norway vs Britain & Ireland) and/or method (e.g. onshore vs offshore data) and/or episode (e.g. early vs late Cenozoic) (see Doré *et al*. 2002). Regional syntheses of one or more movements have been hampered both by the lack of a Cenozoic stratigraphic framework along the margin and by the limited temporal resolution of the onshore and offshore burial history methods used to quantify uplift and subsidence, particularly for the Neogene (see Doré *et al*. 2002).

Here, the chronology of relative movements along the NW European margin afforded by the megasequence stratigraphy documented above is integrated with regional data on uplift and subsidence in order to infer a succession of three mid- to late Cenozoic episodes of differential tectonism, each of differing character (Fig. 9; cf. Praeg *et al*. In press). The three types of differential tectonic movement shown schematically in Fig. 9 are referred to as (a) *sagging*, the consequence of differential subsidence (in the late Eocene–early Oligocene), (b) *compressive flexure*, which resulted in inversion domes and basin margin unconformities (in the early to mid-Miocene) and (c) *tilting*, which describes coeval uplift and basinal subsidence (from the early Pliocene). Sagging and tilting both involved epeirogenic movements with wavelengths of hundreds of kilometres and amplitudes up to several kilometres, while compressive flexure involved movements of lesser wavelength and amplitude (Fig. 9). The nature of the movements is inferred primarily from the external and internal geometries of the offshore megasequences (e.g. prograding wedges, anticlines, submarine unconformities, contourite drifts), which provide constraints on the changes in patterns of sedimentation and oceanographic circulation along and across the continental margin during the successive episodes of tectonism.

The timing of the movements is based on the age of the megasequence boundaries, which coincide with regional to local reorganisations of the North Atlantic plate system (Fig. 10), as previously recognised in the Rockall–Faroe area (Stoker 1997; Stoker *et al*. 2001). The available age constraints on the bounding surfaces (Fig. 5) indicate that the sedimentary responses to the successive tectonic movements were near-synchronous (within ca. 2-3 Ma), both across the margin (from shelf to deep-water) and along its length (to varying extents). The late Eocene–early Oligocene episode of sagging coincided with the abandonment of seafloor spreading in the Labrador Sea in favour of the NE Atlantic axis (Fig. 10); sagging pre-dates the Neogene, but is briefly described below as it established the context of deep-water basins that has dominated sedimentary and oceanographic processes to the present. Compressive flexure in the early to mid-Miocene involved movements (over at least 8 Ma, Fig. 5) that were coeval with a local plate reorganisation in the NE Atlantic involving the Jan Mayen Ridge (Figs 2 & 10); although of relatively small amplitude, the intra-Miocene movements had regional consequences for deep-water exchange through the Faroe Conduit and across the WTRC, as well as for successions on basin margins. The early Pliocene onset of tilting was coincident with a poorly-dated late Neogene North Atlantic-wide reorganisation of spreading directions and rates (Cloetingh *et al.* 1990), suggested to have closed the Central American Seaway to the Pacific in the early Pliocene (Lear *et al*. 2003); tilting affected the entire margin and resulted in significant changes both in sediment supply and in the patterns of deep-water current circulation.

Mid-Cenozoic sagging

Late Eocene–early Oligocene sagging is well documented in the northern Rockall Trough, where strongly differential subsidence outstripped sedimentation to drive a km-scale deepening (estimated at over 2 km in basinal areas; Vanneste *et al.* 1995), at the same time cutting off sediment supply to Eocene prograding wedges (Stoker 1997; Stoker *et al*. 2001). A comparable history is recognised for the Porcupine Basin (McDonnell & Shannon 2001) and a reduction in offshore sediment supply in the mid-Cenozoic is consistent with burial history studies of Ireland and Britain, which indicate episodes of uplift in the early and late Cenozoic (Japsen & Chalmers 2000; Green *et al.* 2002). Strongly differential subsidence is also recognised during the Oligocene across the conjugate east Greenland margin (Clift 1996). On the Norwegian margin, stratigraphic analyses of the northern North Sea Basin indicate increased subsidence from the early Oligocene (e.g. Jordt *et al*. 2000). It has been suggested that the Neogene domal uplift of southern Norway dates back to the early Oligocene (e.g. Rohrman & van der Beek 1996; Hjelstuen *et al*. 1999; Faleide *et al*. 2002), although this is based on deltaic wedges on the inner shelf west of Norway that may alternatively be of early Pliocene age (Poole & Vorren 1993; Henriksen & Vorren 1996). Wedges of undisputed late Oligocene age in the northern North Sea indicate relative uplift both of southern Norway and of the Shetland Platform (Brekke 2000; Faleide *et al*. 2002), which may be related to the onset of the compressional deformation that continued to affect the NW Rockall Plateau and the WTRC (Johnson *et al*. This volume) into the Miocene (see below).

An important consequence of sagging was the regional onset of deep-water current circulation and contourite drift deposition in the Rockall–Porcupine area (Masson & Kidd 1986; Wold 1994; Stoker 1997; McDonnell & Shannon 2001; Stoker *et al*. 2001), which many workers have suggested to record the onset of overflow of NSDW across the GSR from the late Eocene–early Oligocene (e.g. Miller & Tucholke 1983; Davies *et al*. 2001). However, Ramsay *et al*. (1998) presented ^{13}C and ^{18}O data showing that bottom-current circulation patterns in the Atlantic Ocean prior to the mid-Miocene were driven by Tethyan Outflow Water, as far north as the GSR and including DSDP site 610 (Figs 1 & 11a). The late Eocene to Oligocene onset of contourite drift accumulation in the Rockall–Porcupine area is therefore consistent with a northward extension of activity that had been ongoing farther south since the mid-Eocene (Ramsay *et al*. 1998; Norris *et al*. 2001).

Intra-Miocene compressive flexure

Tectonic movements in the early to mid-Miocene period found expression in two types of feature: compressional structures of relatively small scale but wide distribution (inversion anticlines in two main areas; Fig. 3) and multiple basin margin and deep-water unconformities of regional extent (Figs 5 & 6). The coeval development of anticlines and unconformities is here taken to indicate that compression caused flexure (or small scale tilting; see Fig. 9) of basin margins, which in turn forced changes in deep-water circulation patterns that resulted in submarine erosion. The most significant changes in current circulation took place across the WTRC, where erosion of a Base Neogene unconformity to the north, and of mid-Miocene surfaces both to north and south (see Fig. 5) was followed by a major expansion of contourite drifts that is attributed to differential tectonism leading to the formation of the Faroe Conduit as a passageway for deep-water exchange (Hoult *et al*. In press).

Inversion anticlines occur in the Vøring Plateau and the northern Rockall–Faroe area (Fig. 3). These two areas lie north and south of the Møre Basin (Figs 1 & 2), which remained tectonically quiescent during the Neogene, a distribution inferred to reflect strain partitioning by the Jan Mayen and Denmark Strait fracture zones and their projection into the continental margin as structural lineaments (Brekke 2000; Lundin & Doré 2002) (Fig. 2). These fracture zones bound the portion of the NE Atlantic containing the Jan Mayen Ridge (Fig. 11), across which a progressive transfer of seafloor spreading from the Aegir Ridge (to the SE) to the Kolbeinsey Ridge (to the NW) took place between anomalies 13-7 (33-25 Ma, early to late Oligocene), culminating in the separation of Jan Mayen and Greenland soon after anomaly 6, in the late early Miocene (Fig. 10) (Lundin & Doré 2002; Mosar *et al*. 2002).

The inversion anticlines both north and south of the Moré Basin are interpreted to record two major phases of compressional activity broadly ascribed to the mid-Eocene–early Oligocene and the early to mid-Miocene (Lundin & Doré 2002; Johnson *et al*. This volume). The timing of movements is better constrained for the younger phase. However, Ritchie *et al*. (2003) follow Boldreel & Andersen (1993) in suggesting that compression of the anticlines in the Faroe region persisted through the Miocene, based on apparent deformation of the IMU. In contrast, our observations are consistent with the creation of the IMU during compressive doming, followed by onlap of middle Miocene and younger strata (STRATAGEM Partners 2002, 2003; Hoult *et al.* In press; Johnson *et al*. This volume). This interpretation compares with that of the domes on the Vøring margin (Lundin & Doré 2002) and indicates an early Miocene age of last major compression in both areas. The inferred period of compressive tectonism is bracketed by the formation of the Base Neogene and IMU surfaces (Figs 5 & 6), which are separate unconformities in deep-water areas north of the WTRC, but merge on the North Sea Fan–Vøring margins (e.g. Jordt *et al*. 2000; Eidvin *et al*. 2000) and across the WTRC to form a composite unconformity of early to mid-Miocene age (Fig. 5).

A particular consequence of early to mid-Miocene inversion in the Faroe–Shetland area was to change the geometry of the WTRC so as to facilitate the opening of the Faroe Conduit as a passageway for the exchange of intermediate- and deep-water masses between the Atlantic Ocean and Nordic Seas (Fig. 11). This was concomitant with the overall subsidence of the GSR, which enabled additional overflow to occur between Iceland and the Faroe Islands (Fig. 11b). Hoult *et al*. (In press) propose that the shaping of the Faroe Bank Channel occurred in response to differential subsidence during compressional doming of the adjacent WTRC and Faroe Bank. An early Neogene onset or acceleration of overflow of NSDW is supported by the following: i) ^{13}C and ^{18}O data from DSDP sites, such as 116 and 610 (Fig. 1) suggest that NSDW overflow began in the late mid-Miocene (12–13 Ma) (Blanc *et al*. 1980; Ramsay *et al*. 1998); ii) analysis of Oligocene strata in cores from the Norwegian-Greenland Sea reveals minimal bioturbation but strong lamination, interpreted as an indicator of isolation, poor ventilation and oxygen deficiency of intermediate and deep waters north of the GSR in this interval (Thiede & Myhre 1996); iii) comparison of Oligocene deep-water agglutinated foraminifera from ODP site 985 (north of GSR) with ODP site 647 (south of GSR) (Fig. 1) revealed major taxonomic differences indicative of faunal isolation of the deep Norwegian Basin (Kaminski & Austin 1999); iv) ODP sites 907, 908, 909 & 913 (Fig. 1) show middle Miocene strata unconformable on Oligocene or older (Thiede & Myhre 1996) consistent with a mid-Miocene expansion of the current system; and v) the Denmark Strait most likely did not exist as a seaway prior to 18–15 Ma (Thiede & Eldholm 1983).

These data are consistent with our regional seismic-stratigraphic observations that show a massive expansion of sediment drift development north and south of the GSR from the late early–early mid-Miocene (Figs 7c & 8a). This change in deep-water sedimentation pattern coincides approximately with the opening of the Fram Strait between Svalbard and NE Greenland (Eldholm 1990; Jansen & Raymo 1996) (Figs 10 & 11b), and the coeval formation of the northern and southern gateways (Fig. 11b) is arguably the major factor in the creation of the Arctic–Atlantic thermohaline circulation pattern (Jansen & Raymo 1996). With the development of this oceanic circulation pattern there was a progressive cooling of northern hemisphere climate from the mid-Miocene linked to the development of the northern and southern gateways (Zachos *et al*. 2001) (Fig. 10).

Intra-Pliocene tilting

Burial history analyses show that continental margins around the NE Atlantic experienced ca. 1–2 km of tectonic uplift in the late Cenozoic (e.g. Rohrman & van der Beek 1996), coeval with accelerated basinal subsidence of several hundred metres from the early Pliocene (e.g. Cloetingh *et* al. 1990; Riis 1996; Doré *et al*. 1999; Japsen & Chalmers 2000). These movements correspond to tilting (Figs 9 & 11b) and had major consequences for sedimentation, the most dramatic being the offshore progradation of sediment wedges that resulted in the shelf edge migrating seaward by up to 100 km on the Norwegian margin (Figs 4a-b). In addition, changes in deep-water deposition and erosion record coeval modifications in oceanographic circulation patterns (Figs 7 & 8a).

Uplift was maximal within a number of large-scale domes, including one corresponding to Ireland and Britain and another to southern Norway (Rohrman & van der Beek 1996) (Fig. 11b). Burial history data (mainly apatite fission track analyses; see Doré *et al*. 2002) indicate that at least 1 km of material was removed from Ireland and Britain during the Neogene phase (Green *et al*. 2002), while late Cenozoic erosion of southern Norway is estimated at 2.0 ± 0.5 km, corresponding to about 1.5 km of tectonic uplift (Rohrman *et al*. 1995). The timing of the late Cenozoic movements is poorly constrained by the onshore data. Offshore, however, backstripped wells around the North Atlantic margins indicate acceleration in tectonic subsidence from the early Pliocene, including the northern North Sea margin (Cloetingh *et al*. 1990). This increase in subsidence is also recognised in offshore stratigraphic successions, in the form of seaward prograding Pliocene–Holocene sediment wedges (e.g. Henriksen & Vorren 1996; Japsen & Chalmers 2000). On the Norwegian margin, correlation of the base of the offshore wedges with onshore summit levels (e.g. Riis 1996) defines large-scale seaward-tilted (<1°) surfaces, with half-wavelengths of hundreds of kilometres and amplitudes of several kilometres.

Our stratigraphic framework provides fairly tight constraints on the timing of the responses to the Pliocene movements along the margin and indicates a regionally synchronous onset of tilting (Figs 5 & 10). The intra-Pliocene boundary, dated to late early Pliocene (about 4 ± 0.5 Ma), formed by a combination of tilting in shelf areas and bottom-current-induced submarine erosion in deep-water basins, forced by the distortion of the shelf-margin. Direct evidence of tilting is available on the West Shetland Shelf, where a planar erosion surface that truncates upper Miocene strata on the middle to outer shelf was tilted seaward by about 0.4º prior to (and possibly during) deposition of the overlying lower Pliocene–Holocene Rona Wedge that downlaps onto the tilted surface (Stoker 2002). In deep-water areas, a change in oceanographic circulation is manifest by a vigorous pulse of deep-water erosion that created the early Pliocene submarine unconformity. This truncated, and locally eroded into, lower

Neogene contourite deposits (e.g. Figs 7c & 8a). Subsequent patterns of deep-water sedimentation continued to be dominated by bottom-current activity albeit, locally, with a shift in depocentres, e.g. the northern Rockall Trough has undergone prolonged erosion in the NW of the basin (Fig. 7b), with contourite drift deposition having migrated to the NE onto the WTRC and Hebridean margin (Stoker *et al*. 2001).

The changes in deep-water currents are inferred to reflect both the global evolution of oceanographic circulation and modifications to bathymetric thresholds along the NW European margin. On a global scale, closure of the Central American Seaway by the formation of the Isthmus of Panama in the late Miocene–early Pliocene resulted in the replacement of a hitherto circum-equatorial circulation pattern by an inter-polar flow (Haug & Tiedemann 1998; Lear *et al*. 2003). The redirection of warm and saline water masses to high northern latitudes strengthened the formation of North Atlantic Deep-Water (NADW), the outflow of which was controlled by the topography of the GSR (see Lear et al. 2003). Consequently, submarine erosion along the NW European Atlantic margin in the early Pliocene may in part reflect an increase in the volume of NADW available to pass through the Faroe Conduit and across the WTRC. However, the intensity of current flow and submarine erosion is likely to have been enhanced by changes in the configurations of basins and the elevation of bathymetric thresholds, concomitant on the early Pliocene large-scale tilting of the margin. The early Pliocene reorganisation of bottom currents persists in the present-day circulation pattern, albeit at reduced current strength as no comparable deep-water erosion surface has subsequently developed.

The early Pliocene episode of tilting, both from the shelf-margin and deep-water records, pre-dates the onset of widespread northern hemisphere glaciation (from about 2.74 Ma; Jansen *et al*. 2000). Glaciation may have ultimately been triggered by the combination of increased atmospheric moisture, provided to the high northern latitudes by the reorganised thermohaline circulation pattern, and the increased elevations necessary for ice-sheet nucleation brought about by tectonic uplift (e.g. Eyles 1996). Whilst isostatic readjustment to glacial erosion is estimated to have raised mountain summits in southern Norway by up to 800 m, glaciation cannot explain the domal form of the uplift (Nielsen *et al*. 2002). Although glacially-derived sediments form a significant component of most of the prograding sediment wedges (Eidvin *et al*. 2000; Stoker 2002), glaciation (together with isostatic rebound) is inferred to have been a sustaining, rather than initiating, factor in late Neogene uplift.

Causes of Episodic Tectonism

Tectonic movements on the North Atlantic margins during the mid- to late Cenozoic involved ‘rapid’ subsidence, i.e. much greater than the underlying (exponentially decreasing) rates due to post-rift cooling of the lithosphere (e.g. Steckler & Watts 1978). Thus, during the early Pliocene episode of tilting, subsidence rates in wells around the North Atlantic margins increased by one or more orders of magnitude compared to the Oligo-Miocene (Cloetingh *et al.* 1990). An order of magnitude increase in subsidence rates can also be inferred from the amplitudes and durations of the epeirogenic and compressive tectonic episodes documented in this study: vertical displacements of hundreds of metres to a few kilometres (Fig. 9) took place over periods of <5–10 Ma at most (Fig. 10), corresponding to rates of the order of 100’s of m/Ma. This compares to rates of thermal subsidence (water- and sediment-loaded) on continental margins of at most several tens of m/Ma, for more than a few tens of Ma after rifting (e.g. Steckler & Watts; Keen 1985)

Rapid variations in subsidence/uplift on passive margins have been attributed to two sorts of intra-plate mechanism, driven either by plate forces or by mantle convection. Plate reorganisations (i.e. changes in spreading directions and/or rates) are associated with changes in horizontal compressive forces within the plates, predicted to cause flexural deflections across continental or basin margins, of opposite polarity and of up to a few hundred metres in amplitude (Cloetingh *et al.* 1990; van Balen *et al.* 1998). Mantle convection is associated with thermal (isostatic) effects and with dynamic forces, both capable of generating rapid km-scale vertical movements at surface (e.g. Lithgow-Bertelloni & Gurnis 1997). Intra-plate and mantle convective forces have both been applied to the tectonic movements observed on the conjugate NE Atlantic margins. Here it is argued that while stresses due to plate motions within the NE Atlantic region can explain the intra-Miocene phase of compressive tectonism, plate forces alone cannot account for the large amplitude of early Pliocene tilting (or of mid-Cenozoic sagging; Fig. 9). Rather, the magnitude and wavelength of epeirogenic movements are argued to be consistent with dynamic topographic responses to small-scale convection cells within the upper mantle.

Plate forces

The European plate has been in compression since break-up, and inversion anticlines of mid-Eocene to mid-Miocene age along the margin confirm the spatial and temporal importance of intra-plate stress variations (Doré *et al.* 1999; Lundin & Doré 2002). The intra-Miocene phase of compression coincided with a plate reorganisation in the NE Atlantic (Fig. 10), as the spreading ridge underwent a progressive transfer from one side of the Jan Mayen Ridge to the other (Lundin & Doré 2002; Mosar *et al.* 2002). The formation of anticlinal domes north and south of the Møre Basin in the early to mid-Miocene is consistent with a partitioning of compressive stresses by the fracture zones bounding the Møre Basin during the period of ridge transfer (e.g. Brekke 2000; Mosar *et al*. 2002). The coeval formation of unconformities on basin margins is here inferred to record flexural deflections during stress build-ups (predicted to result in basinal subsidence and marginal uplift), which may have preceded stress release during discrete phases of deformation (see van Balen *et al*. 1998). Comparable flexural deflections may have affected the NW European margin during other Cenozoic plate reorganisations (Fig. 10), but the means by which the required stresses are concentrated at certain locations and times (e.g. to form pre-Miocene inversion anticlines) remains unclear (see Lundin & Doré 2002; Mosar *et al*. 2002).

The late Cenozoic episode of tilting coincides with a plate reorganisation (Fig. 10), and the dramatic increase in tectonic subsidence recognised around the North Atlantic margins in the early Pliocene has also been proposed to record a flexural response to intra-plate variations in compressive stresses (Cloetingh *et al*. 1990; van Balen *et al*. 1998). However, the maximum amplitudes of deflection predicted by the intra-plate stress model are only a few hundred metres (see van Balen et al. 1998), too small to account for tilting of km-scale in the Pliocene (as noted by Nielsen *et al*. 2002). Neither can flexural deflections account for the magnitude, or form, of sagging in the late Eocene–Oligocene (Figs 9 & 10).

Mantle convection

The Neogene uplift of the NE Atlantic margins is associated with a series of large-scale domal uplifts, beneath which gravity and seismic tomography data suggest the possibility of mantle involvement (Vågnes & Amundsen 1993; Rohrman & van der Beek 1996; Rohrman *et al*. 2002). The domes have been proposed to record differential uplift (i.e. tilting) in response to some form of secondary convection, induced by the head of the Iceland plume meeting ‘cold’ upper mantle, resulting either in thermal erosion and underplating (Spitsbergen; Vågnes & Amundsen 1993) or lower lithospheric delamination and asthenospheric diapirism (south Norway; Rohrman & van der Beek 1996). However, both these models assume the ‘Neogene’ uplift of the continental margin to date back to the mid-Cenozoic, based on evidence of Oligocene sediment progradation onto the Norwegian shelf (e.g. Stuevold & Eldholm 1996; Brekke 2000; Faleide *et al*. 2002). The results presented here support alternate interpretations of the offshore stratigraphic record in which Neogene tilting of the margin dates from the early Pliocene. The timing of uplift is critical, as it is difficult to see that early Pliocene tilting of the margin can be reconciled with models driven by the impingement of an Iceland plume head.

The early Pliocene tilting of the NW European margin (Fig. 9), including the domal uplifts of Norway and Britain/Ireland, can be alternatively explained as a dynamic topographic response to the initiation of an edge-driven upper mantle convection cell along the continental margin, such as across the continent-ocean boundary or a deep-water basin (Fig. 12). Model results suggest that edge-driven convective cells can flow in either sense, depending on their interaction with larger scales of flow (King & Anderson 1998). One of the two possibilities is downwelling beneath the ocean margin and upwelling beneath the continent, the dynamic response to which would correspond to seaward tilting (Fig. 12). The wavelengths of tilting (Fig. 9) and the spacing of the domes (ca. 900 km; Rohrman & van der Beek 1996) are broadly comparable to the expected diameters of small-scale convective cells (e.g. Anderson 1998), although three-dimensional modelling of edge-driven convection has yet to be attempted. The mid-Cenozoic episode of sagging (Fig. 9) can also be explained in terms of a dynamic response to upper mantle circulation, as a loss of support due to the abandonment of an upwelling. Interestingly, sagging of the Porcupine–Rockall–Faroes region took place at the same time as rapid differential subsidence of the Greenland margin, attributed to a loss of dynamic support (Clift 1996), and these changes occurred as the Labrador Sea was abandoned in favour of the onset of spreading along the NE Atlantic axis (e.g. Doré *et al*. 1999) (Fig. 10). The early Pliocene episode of tilting also appears to have coincided with a plate reorganisation in and around the North Atlantic (Cloetingh *et al*. 1990), consistent with a recent reorganisation of the upper mantle convection system (King & Anderson 1998). Indeed, instabilities within upper mantle convective cells have been argued to be the cause of such rapid (<5 Ma) plate reorganisations (King *et al*. 2002).

Implications for passive margins

An interpretation of the NW European margin in terms of evolving dynamic topographic responses to upper mantle convective cells finds support on the eastern North American margin — the archetypal ‘Atlantic-type’ passive margin (Steckler & Watts 1978) — where the Cenozoic succession also contains evidence of episodic tectonic movements, involving episodes of rapid subsidence (rates >50–100 m/Ma) that coincided with changes in seafloor spreading rates and directions (Heller *et al*. 1982). The step-wise subsidence pattern has been attributed, along with coeval magmatism, to the development of small-scale upper mantle convective cells inferred to move with the North American plate, expressed as dynamic topographic uplifts hundreds of kilometres across and on the order of 1 km in amplitude (the Bermuda and Appalachian-Labrador rises; Vogt 1991). The history of episodic tectonic movements recognised on the NW European margin is therefore neither anomalous nor uniquely associated with an Iceland plume. Rather, it may be characteristic of the development of passive margins, a natural response to the evolution of upper mantle temperatures and flow patterns during ocean opening and widening, which in turn drive plate reorganisations (King & Anderson 1998; Boutillier & Keen 1999; King *et al*. 2002).

The Neogene succession on passive margins is not normally regarded as having direct hydrocarbon prospectivity, but the recognition of tectonic controls on the stratigraphy contains a number of implications worthy of consideration from a petroleum exploration viewpoint (see also Doré *et al.* 2002). The Neogene succession has generally been regarded as a relatively uniform, regional capping succession, but the presence of multiple unconformities and of variable sedimentary facies, particularly permeable strata deposited by geostrophic currents, is likely to result in a more complex capping system than hitherto anticipated. Neogene differential vertical movements are likely to have had a significant impact on hydrocarbon remigration, with possible breaching of pre-Neogene structures and the creation of new traps. Furthermore, the lithospheric driving mechanisms for the tectonism have implications for the understanding of the basinal heat flow, which, in turn, will influence predictions for the location of oil and gas windows and the timing and quality of hydrocarbon generation. Overall, a better understanding of the interrelationship between Neogene sedimentation, tectonics and climate in the deep-water basins of the Atlantic margin is likely to provide a useful analogue for older basinal systems.

Conclusions

A regional stratigraphic framework for the Neogene succession on the NW European Atlantic ‘passive’ margin shows that the sedimentary succession from Ireland to Norway is characterised by unconformity-bound packages, interpreted to record sedimentary responses to a succession of post-rift tectonic movements. The mid- to late Cenozoic evolution of the margin has been strongly influenced by both compressive and epeirogenic movements of up to kilometre scale, which have acted both to change the boundary conditions of deep-ocean current circulation and to provide the physiographic conditions favouring northern hemisphere glaciation. In particular:

- In late Eocene–early Oligocene, rapid differential subsidence (sagging) outstripped sedimentation to create the context of underfilled, deep-water sedimentary basins that persists to the present.
- In the early Miocene, tectonic movements of relatively small amplitude (100s metres) but wide extent resulted in compressive doming and basin margin unconformities, as well as changes in deep-ocean circulation that culminated in the expansion of contourite drifts on both sides of the Wyville-Thomson Ridge Complex.
- In the early Pliocene, uplift of onshore and shallow shelf areas was accompanied by accelerated offshore subsidence, a km-scale tilting of the margin that resulted in a major seaward progradation of shelf-slope sediment wedges as well as a change in oceanographic circulation patterns; these events are inferred to have

been important in creating the physiographic conditions that favoured the subsequent onset of continental glaciation in NW Europe.

- Plate forces are inferred to have driven the intra-Miocene phase of compressive tectonism, but cannot account for the larger amplitude of the early Pliocene tilting (or of mid-Cenozoic sagging). The amplitude and wavelengths of epeirogenic movements are proposed to record dynamic topographic responses to small-scale upper mantle convection, which evolved with the opening of the NE Atlantic.

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TABLE & FIGURE CAPTIONS

Table 1. Summary of main characteristics of Neogene stratigraphic units (after STRATAGEM 2002, 2003 and Stoker *et al*., In press, and references therein)

Fig. 1. Simplified map of NE Atlantic region showing: extent of NW European Atlantic continental margin (50º–70º N) covered in this study; the anomalously shallow Greenland-Scotland Ridge (grey); active mid-ocean spreading ridges; deep-water pathways (arrows); DSDP/ODP sites (solid black circles) referred to in the text; and the 1000 m and 2000 m bathymetric contours. RT, Rockall Trough; RP, Rockall Plateau; PB, Porcupine Basin, MB, Møre Basin; VB, Vøring Basin; *FC*, Faroe Conduit; *DS*, Denmark Strait; *FS*, Fram Strait; *COB*, Continent-Ocean boundary. The Møre and Vøring basins are presently buried beneath the Norwegian Shelf. In terms of the deep-water pathways, the Fram Strait represents the Northern Gateway whilst the Greenland-Scotland Ridge is the Southern Gateway.

Fig. 2. Bathymetric setting of the NW European Atlantic margin showing location of study area (boxed), main tectonic elements, oceanographic circulation pattern, and summary of large-scale sedimentary processes that have contributed to the shaping of the ocean margin during the Neogene. Study area is expanded in Fig. 3. NC, Norwegian Channel; FSC, Faroe-Shetland Channel; IFR, Iceland-Faroe Ridge; WTR, Wyville-Thomson Ridge; PB, Porcupine Basin; JMR, Jan Mayen Ridge.

Fig. 3. Detailed map of study area showing locations of sample sites, geoseismic sections and seismic profiles referred to in text and other figures.

Fig. 4. Interpreted geoseismic sections along the NW European Atlantic margin, focusing on the middle to upper Cenozoic stratigraphy. Sections (**a**) and (**b**) simplified from profiles D–D' and J–J' of Blystad *et al*. (1995); section (**c**) based on profile OF94-55a (Faroe margin) and BGS profile 84/05-10 (West Shetland margin); section (**d**) based on profile OF94-25a (Faroe margin) and BGS profile 83/04-29 (West Shetland margin); section (**e**) based on profile DG95-10; section (**f**) based on profile GSR96-0116; section (**g**) based on profile MS-81-25 and simplified from McDonnell & Shannon (2001). Location of sections shown in Fig. 3. Abbreviations: BNU, Base Naust Unconformity; INU, Intra-Neogene Unconformity; BKU, Base Kai Unconformity; TPU, Top Palaeogene Unconformity; IUEOC, Intra-Upper Eocene Unconformity; IMU, Intra-Miocene Unconformity. TWTT, two-way travel time.

Fig. 5. Stratigraphical-range chart of key boreholes and wells used in the calibration and correlation of key Neogene reflectors along on the NW European Atlantic margin. Timescale is from Berggren *et al*. (1995a). BN, Base Neogene in Porcupine Basin; TPU, Top Palaeogene Unconformity; IMU, Intra-Miocene Unconformity; MMU, Mid-Miocene Unconformity; INU, Intra-Neogene Unconformity. See text for details.

Fig. 6. Stratigraphic nomenclature (megasequences and key reflectors) for the middle to upper Cenozoic succession on the NW European Atlantic margin, based mainly on STRATAGEM (2002, 2003) but including information from Dalland *et al*. (1988), Andersen *et al*. (2000) and Brekke (2000). The inter-regional

megasequence boundaries are based on the correlation of the key regional reflectors from the North Sea Fan–Vøring, Faroe–Shetland and Rockall–Porcupine areas. BNU, Base Naust Unconformity; INU, Intra-Neogene Unconformity; BKU, Base Kai Unconformity; TPU, Top Palaeogene Unconformity; IMU, Intra-Miocene Unconformity; MMU, Middle Miocene Unconformity; IUEOC, Intra-Upper Eocene Unconformity. Timescale after Berggren *et al*. (1995a).

Fig. 7. (**a**) BGS airgun profile 83/04-32 showing the irregular nature of the TPU. Part of the surface is buried beneath an FSN-2 infilling drift and the lower part of the Rona Wedge slope apron (FSN-1); part remains open – the Munkagrunnur Falls (Judd Deeps). This surface is locally composite with the IMU. (**b**) BGS airgun profile 92/01-24 across the western flank of the central Rockall Trough showing erosional sea bed, the relict middle-Miocene–lower Pliocene upslope prograding sediment drift, and locally exposed Eocene strata. (**c**) Royal NIOZ profile 97-12 across the southern Rockall Trough, between Rockall and Porcupine banks, highlighting the Feni Ridge sediment drift, a smaller subsidiary drift adjacent to Porcupine Bank, sediment waves at sea bed, and wide erosional moats adjacent to the banks. Inset shows details of the basin-margin and moated areas, particularly the erosional nature of C10.

Fig. 8. (**a**) Profile NH9651-405 extending from the Mid-Norwegian Shelf onto the inner Vøring Plateau showing Naust Fm sediments of the Mid-Norwegian Wedge downlapping onto the mounded sediment drift deposits of the Kai Fm. (**b**) BGS airgun profile 83/04-31 extending from the West Shetland margin into the Faroe-Shetland Channel showing the erosional nature of the TPU (possibly composite with the IMU) and the prograding Rona Wedge. Note the upslope prograding nature of the FSN2 strata on the lower slope (inset) and the truncated FSN-2 shelf deposits, eroded by the INU that is tilted seaward on the outer shelf. The sequence above the GU preserves submarine end-moraines. (**c**) BGS airgun profile 83/04-6 across Hebridean margin showing RPa slope apron of the prograding Sula Sgeir Fan overlying and partly interbedded with upslope prograding contourite-drift and sediment wave deposits. Submarine end-moraines preserved above the GU. The TPU represents a hiatus from late Oligocene to mid-Miocene, comparable with the TPU/IMU composite surface in (**b**). SBM, sea-bed multiple; BP, bubble pulse.

Fig. 9. Types of differential vertical movements recognised on the NW European margin in the mid- to late Cenozoic: (**a**) sagging (mid-Cenozoic); (**b**) compressive flexure (early–mid-Miocene); (**c**) tilting (early Pliocene).

Fig. 10. Neogene tectonostratigraphic framework for the NW European Atlantic margin (see text for details). Timescale from Berggren *et al*. (1995a).

Fig. 11. Schematic reconstructions of NE Atlantic region for (**a**) late Oligocene–early/mid-Miocene, and (**b**) mid/late Miocene–early Pliocene intervals (see text for details). Plate tectonic framework based on Ziegler (1988). Abbreviations as in Figs 1 & 2 except: NSDW, Norwegian Sea Deep Water; TOW, Tethyan Outflow Water; MOW, Mediterranean Outflow Water; *RR*, Reykjanes Ridge; *KR*, Kolbeinsey Ridge; *AR*, Ægir Ridge; *MR*, Mohns Ridge; *KpR*, Knipovich Ridge; *SFZ*, Senja Fracture Zone; *JMR*, Jan Mayen Ridge.

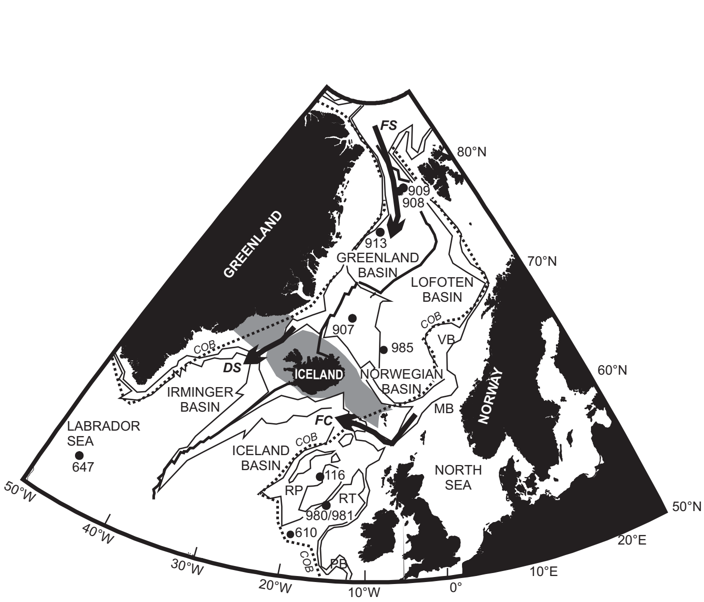
Fig. 12. Conceptual diagram (not to scale) showing the interaction of forces within the upper mantle and lithosphere across a developing ocean basin, along with the differing structural and topographic responses hypothesised for the NW European continental margin in the late Palaeogene and Neogene. Upper mantle convective cells may arise due to temperature inhomogeneities at the base of the lithosphere, such as across the ocean-continent boundary or a deep-water basin; the inferred dynamic topographic response to edge-driven flow corresponds to the late Eocene–early Oligocene sagging and early Pliocene tilting observed along the margin. Variations in horizontal forces within the European plate resulted in compressive flexure throughout the Cenozoic, culminating in the early to mid-Miocene development of inversion anticlines and basin margin unconformities. MOR, Mid-Ocean Ridge.

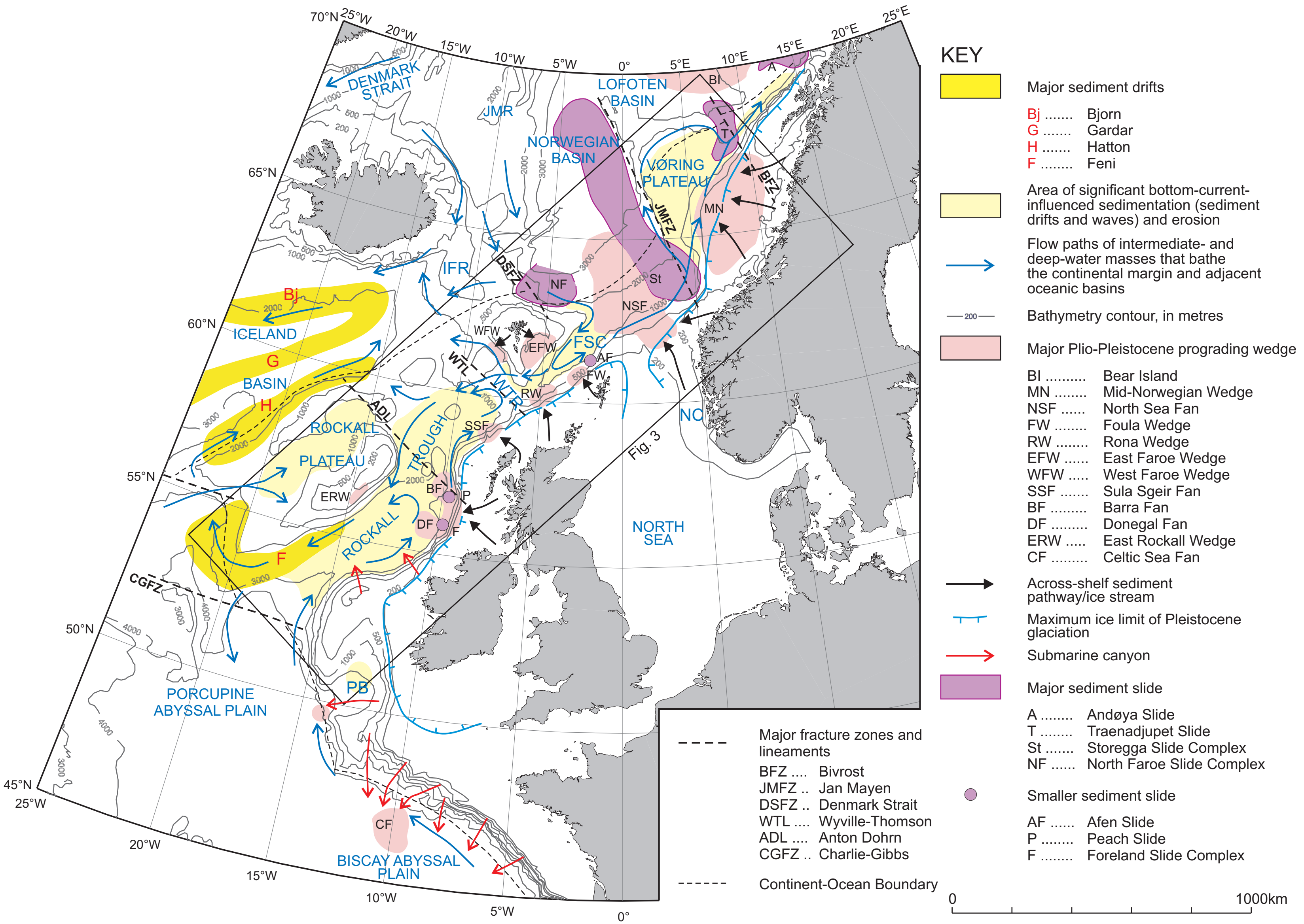
Table 1. Summary of main characteristics of Neogene stratigraphic units (after STRATAGEM 2002, 2003 and Stoker *et al.*, In Press, and references therein)

Stratigraphy	Distribution, form & thickness	Seismic character	Lithofacies	Age
<u>UPPER NEOGENE</u>				
Naust Formation	Series of coalescing prograding wedges (North Sea Fan to Mid-Norwegian Wedge) extending seaward from coast into Norwegian Basin, which overstep pre-Neogene Møre and Vøring basins. Locally >1.6 s thick along shelf-margin; <0.2 s thick in basin. Wedge geometry locally destroyed by major slides.	Complex sigmoid-oblique stratal pattern comprising packages of lensoid units (stacked debris-flow deposits) separated by continuous, onlapping/upslope prograding basinal reflections (mainly contourite deposits). Prominent aggradation of outer shelf in last 0.5 Ma. Structureless-chaotic, sheeted and mounded deposits comprise aggrading topsets. Slide deposits are massive and chaotic.	Glacial tills on shelf reworked and re-deposited as mass-flow diamictons on slope, e.g. wells 6607/5-1, 6610/7-2, 34/8-3A, 219/20-1 & DSDP 341; latter interbedded with muddy contourite drift and hemipelagic deposits, e.g. well 6305/5, and borings 6606/3-GB1 & 8903 (Troll). IRD in basinal muds, e.g. ODP 642–644.	Late Pliocene to Holocene
FSN-1 megasequence	Discrete progradation from West Shetland (Foula & Rona wedges) and Faroe (East & West Faroe wedges) margins, overstepping pre-Neogene Faroe-Shetland Basin. Locally >0.6 s thick off Faroe margin; 0.2–0.4 s thick west of Shetland. Slope apron locally modified by small slides. Thinner basinal section, locally absent in SW Faroe-Shetland Channel. Thin to absent on Munkagrunnur, Wyville-Thomson and Fugloy ridges and adjacent banks.	Prograding wedges display parallel-oblique to sigmoid-oblique clinoforms, cut by the GU and overlain by flat-lying aggrading topsets. Internally, wedges dominated by chaotic–structureless, sheeted and mounded shelf glacigenic units and lensoid, debris-flow deposits on slope. Basinal section shows parallel reflections that drape the basin floor and onlap/prograded (migrating sediment waves) up the slopes. Common interdigitation between wedges and basinal strata in slope apron.	On West Shetland Shelf, the GU separates sands and muds with IRD in prograding section from overlying topsets dominated by muddy glacigenic diamictons, e.g. BGS boreholes 77/9, 82/10 & 84/2. Slope apron preserves muddy debris-flow diamictons interbedded with glacimarine and contouritic muds and sands, e.g. BGS boreholes 85/1 & 99/3, wells 208/15-1A & 208/27-1 and BGS Vibrocore 60-06/42. Basinal section is mainly muds, e.g. well 214/4-1.	Late early Pliocene to Holocene
RPa megasequence	Discrete progradation from Hebrides–Malin shelves (Barra-Donegal and Sula Sgeir fans), where >0.6 s thick. Wedge geometry locally destroyed by slides. Beyond fans, thin basinal section: mostly <0.2 s in Rockall Trough and <0.1 s in Porcupine Basin. Commonly absent in western Rockall Trough, though discrete wedge (East Rockall Wedge: 0.1 s thick) identified. Veneer of sediment caps Rosemary Bank, Anton Dohrn and Hebrides Terrace seamounts.	Prograding wedges display oblique-parallel clinoforms with aggrading topsets above the GU. Internally, dominated by chaotic–structureless, sheeted and mounded shelf glacigenic units, with lensoid debris-flow and chaotic slide deposits on slope. Parallel, flatlying to undulatory reflections maintain active, broad sheeted to elongate mounded sediment drifts and associated sediment waves in the basins. Common interdigitation between wedges and basinal strata in slope apron.	Sands, muds and IRD in prograding section below GU; muddy glacigenic diamictons in overlying topsets, e.g. BGS boreholes 85/5B, 90/11 & 90/13. Debris-flow diamictons, hemipelagic and contourite muds and turbidite sands dominate fans, e.g. BGS gravity core 59-08/42, IMAGES core MD95-2006; glacimarine contourites on slope between fans, e.g. BGS borehole 88/7,7A. Basinal muds near fans, e.g. well 164/25-2; ooze, muds and IRD on Feni Ridge, e.g. DSDP 610 & ODP 980/981.	Late early Pliocene to Holocene
<u>LOWER NEOGENE</u>				
Kai Formation	Best preserved seaward of outer Mid-Norwegian and Møre shelves; sheeted geometry that thickens up to 1.0 s on Vøring Plateau where discrete depositional build-ups are formed. Thin to locally absent in areas affected by mid-Cenozoic compressional doming, e.g. Helland Hansen Arch & Vema Dome, and over other positive structural features, such as Vøring Marginal High.	Parallel-laminated reflection configuration. Continuity disrupted by closely spaced faults. Regional internal discontinuity marked by MMU, which is onlapped by younger Kai reflections in areas of doming. Post-MMU strata include the discrete mounded build-ups on the Vøring Plateau; these display internal erosion surfaces and multi-phase deposition, and onlap the adjacent slope. A lowstand wedge is reported from the Møre margin.	Basinal strata on Vøring Plateau dominated by siliceous and calcareous oozes and muds, e.g. ODP 642 & 643 and well 6704/12GB-1. At shallower depths, including the northern North Sea, the MMU separates basinal mudstones from glauconitic mudstones and sandstones, e.g. wells 6407/1-2, 6507/10-1, 6506/12-4, 6607/5-1 & 34/8-3A.	Latest Oligocene/early Miocene to 'mid' Pliocene
FSN-2 megasequence	Depocentres N and S of Fugloy Ridge exceed 0.6 s thick. N of Ridge, wedge-shaped deposit thickens into Norwegian basin, disrupted by later mass failure; S of Ridge, linear, ENE–WSW, basinal, sheeted to mounded deposit extends from northern Faroe-Shetland Channel under present Faroe Shelf. Fragmentary to south: eroded sheet on West Shetland Shelf (<0.2 s); discrete accumulations in Faroe Bank Channel (0.5 s) and locally infilling basin-floor deeps. Absent on ridges and banks.	Parallel-laminated reflection configuration. Continuity disrupted by closely spaced faults and by diagenetic reflector. Regional internal discontinuity marked by IMU, an angular erosion surface, which divides FSN-2 into FSN-2a (upper) and FSN-2b. Post-IMU strata most expansive, with mounded waveforms onlapping slopes of Channel. Upslope-migrating deltaic wedges on West Shetland Slope. Fan deposits may flank Munkagrunnur Ridge. Low-angle transgressive onlap onto West Shetland Shelf.	Glauconitic sandstones with subordinate mudstones and lignites dominate the succession on the West Shetland Shelf and upper slope, e.g. BGS boreholes 77/7, 77/9 & 90/3 and wells 202/8-1 & 208/15-1. In the Faroe-Shetland Channel, diatomaceous muds comprise sheeted contourite drift deposits, e.g. well 214/4-1.	Early Miocene to early Pliocene
RPb & upper RPc megasequence	Largely restricted to Rockall Trough and Porcupine Basin, with ponded infill 0.6–0.8 s thick. Commonly mounded; locally significant upslope progradation. Three styles of contourite drift: (1) broad, sheeted to gently domed basin floor drifts; (2) elongate mounded drifts on flanks of basins; (3) giant, elongate Feni Ridge. Outliers on Hebrides and Malin shelves; veneer caps Rosemary Bank, Anton Dohrn and Hebrides Terrace seamounts; absent over Alpin Dome in NW Rockall Trough.	Parallel-laminated reflection configuration. Continuity disrupted by closely spaced faults. Reflector C20 separates RPb and RPc: marks an upward change from flatlying to mounded reflections. Above C20, gently domed to undulatory and waveform reflections occur on basin margins and around seamounts. Some undulations form large sediment waves up to 40 m high and 2–3 km wavelength. In the shallower parts of the basins, upslope progradation reached close to contemporary shelfbreak.	In SW Rockall Trough, Feni Ridge consists of nannofossil chalk and ooze, e.g. DSDP 610 and ODP 981. Bioclastic sand and gravel in erosional moats, e.g. BGS borehole 94/1. Basinal sand in sheeted drift in NE Rockall Trough, e.g. well 164/25-2. Sand, mud and ooze cap seamounts, e.g. BGS boreholes 90/15 & 90/18; glauconitic sandstones on Hebrides–Malin margin, e.g. BGS boreholes 88/7,7A, 90/13 & 90/12,12A and well 19/5-1. Basal conglomerate in Porcupine Basin, e.g. well 35/13-1.	Late early/early mid-Miocene to late Early Pliocene (RPb) and early Miocene (upper RPc)

All thicknesses in seconds (s), two-way travel time. Sample sites are located in Fig. 3. GU, Intra-Pleistocene (Glacial) Unconformity; MMU, Mid-Miocene Unconformity; IMU, Intra-Miocene Unconformity.

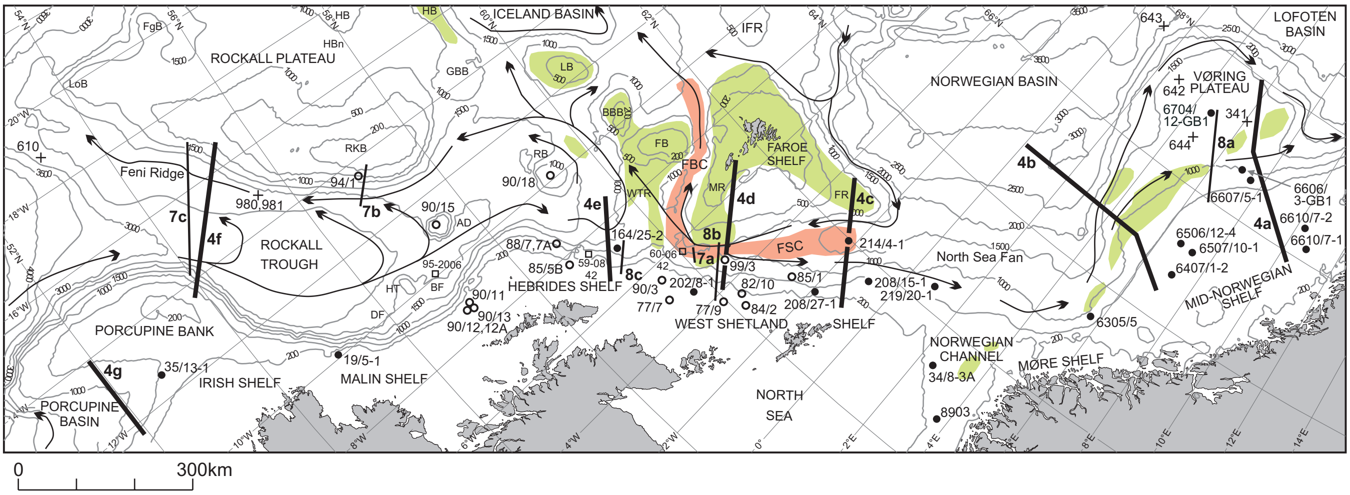
Stoker *et al*. Fig. 1





Stoker *et al.* Fig. 2

Stoker *et al*. FIG. 3



Key

Faroe Conduit

Compressive dome/arch

Flow paths of modern intermediate- and deep-water masses that bathe the continental margin

Bathymetric contours (in metres)

Location of geoseismic sections in Fig. 4

Location of seismic profiles in Figs 7 & 8

Commercial wells

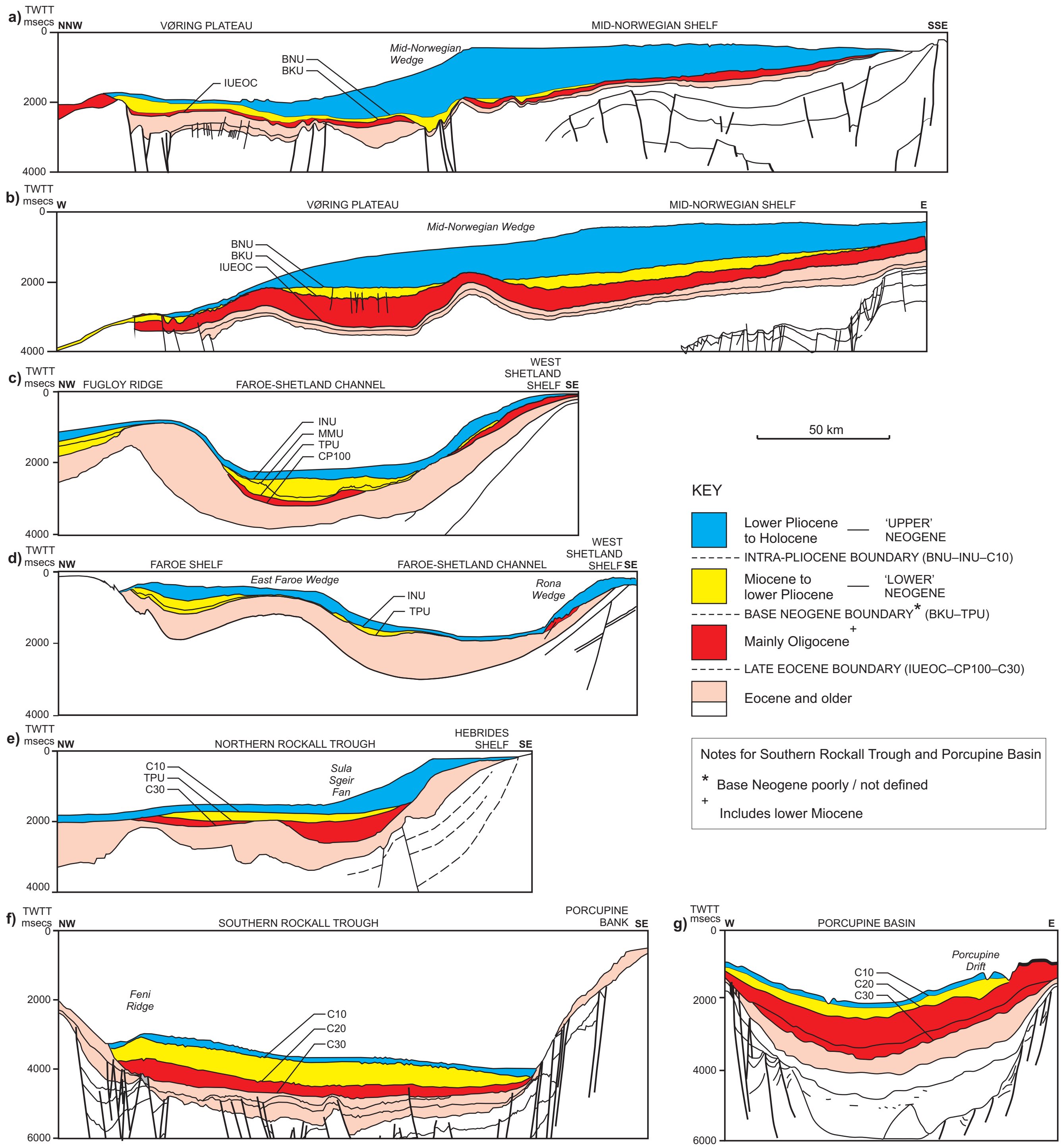
BGS boreholes

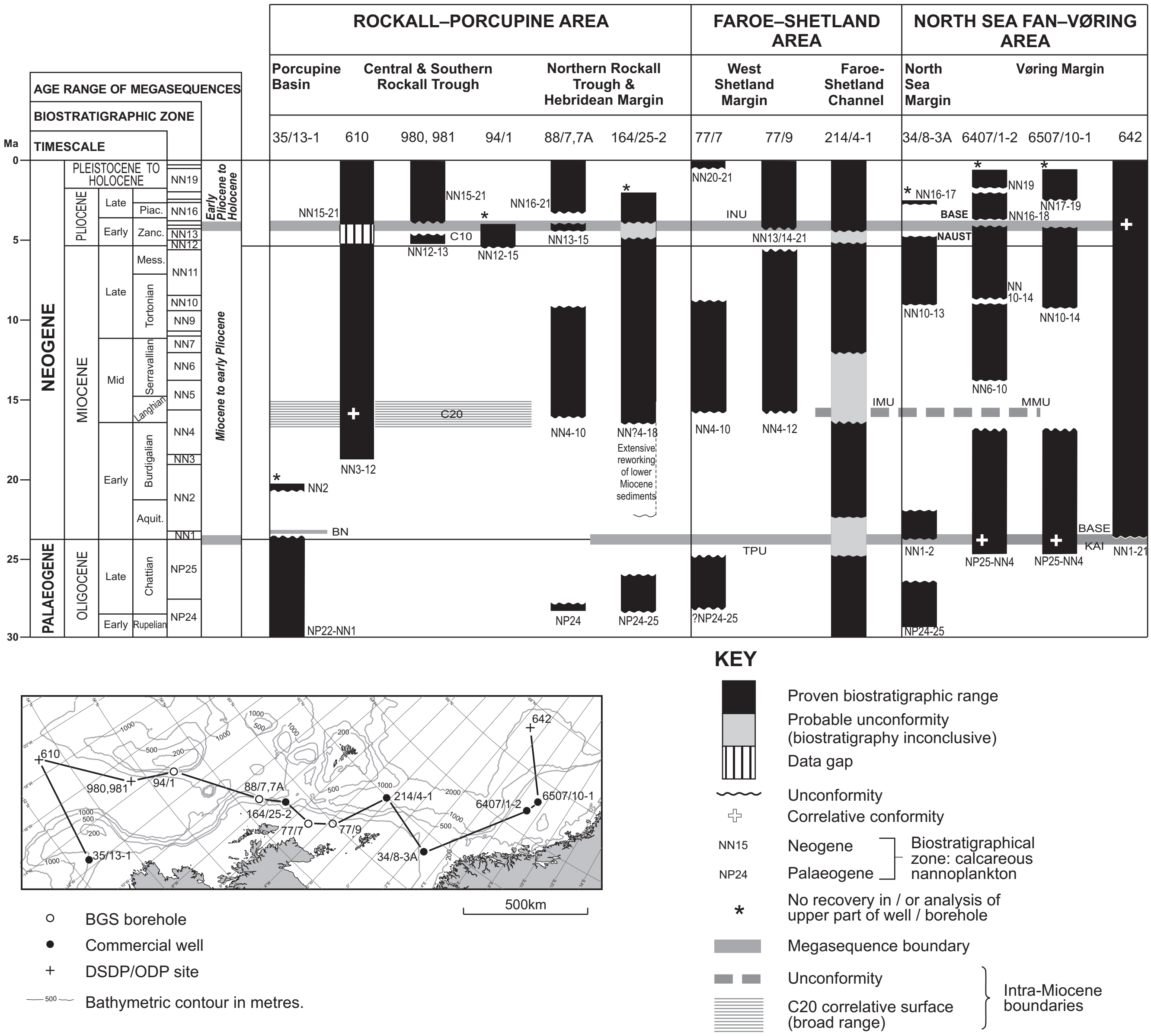
DSDP/ODP

BGS/IMAGES short cores

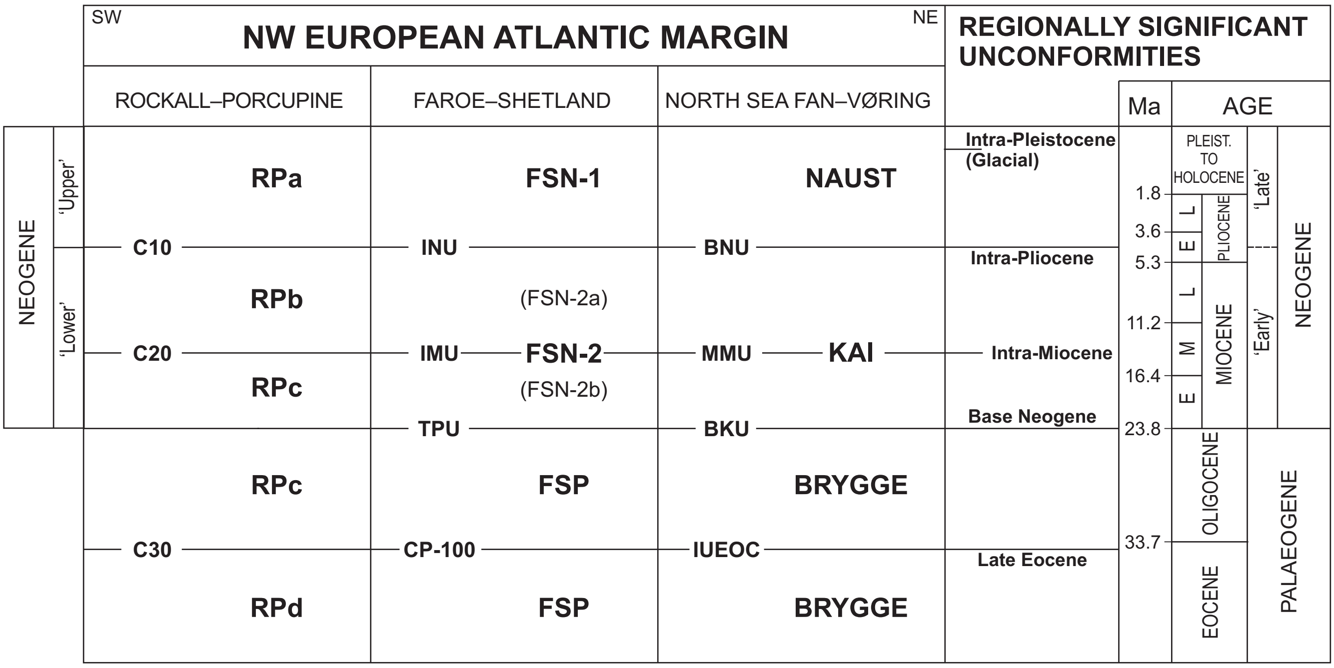
RKB	Rockall Bank	MR	Munkagrunnur Ridge
GBB	George Bligh Bank	FR	Fugloy Ridge
RB	Rosemary Bank Seamount	FBC	Faroe Bank Channel
AD	Anton Dohrn Seamount	FSC	Faroe-Shetland Channel
HT	Hebrides Terrace Seamount	LoB	Lorien Bank
IFR	Iceland-Faroe Ridge	FgB	Fangorn Bank
WTR	Wyville-Thomson Ridge	HB	Hatton Bank
FB	Faroe Bank	HBn	Hatton Basin
LB	Lousy Bank	BF	Barra Fan
BBB	Bill Bailey's Bank	DF	Donegal Fan

Stoker *et al*. FIG. 4

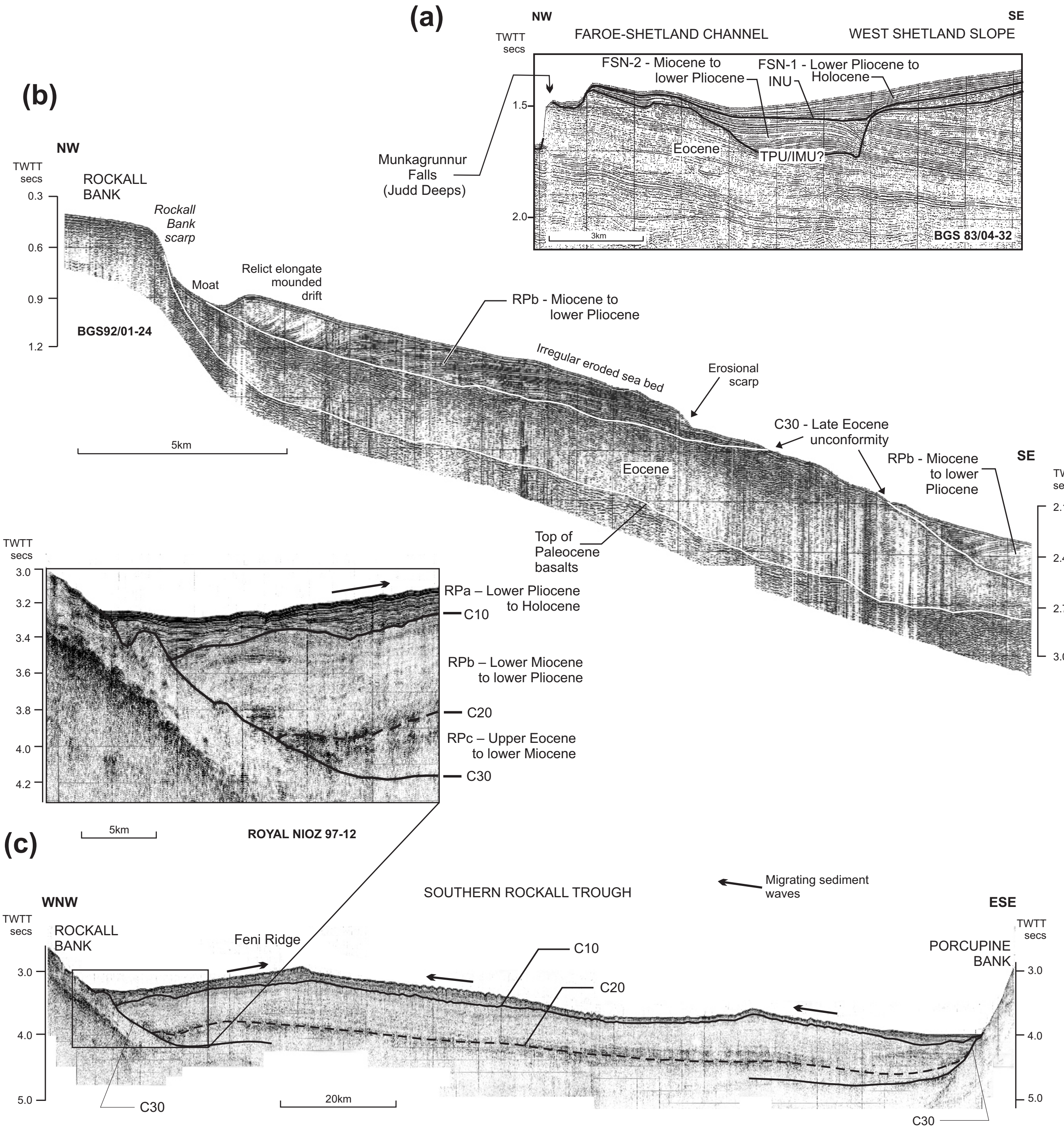


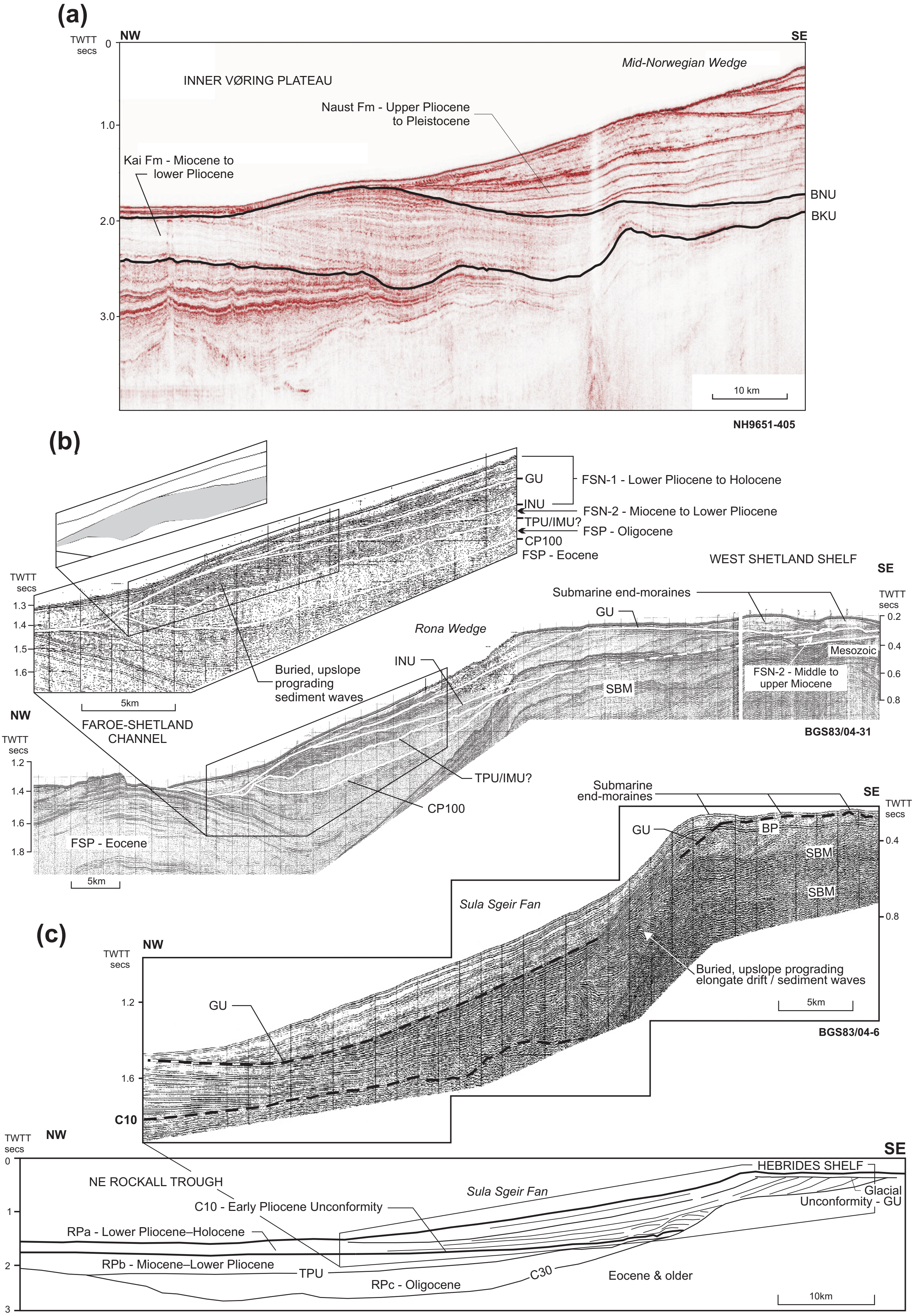

ROCKALL–PORCUPINE AREA
FAROE–SHETLAND AREA
NORTH SEA FAN–VØRING AREA
Porcupine Basin
Central & Southern Rockall Trough
Northern Rockall Trough & Hebridean Margin
West Shetland Margin
Faroe-Shetland Channel
North Sea Margin
Vøring Margin
AGE RANGE OF MEGASEQUENCES
BIOSTRATIGRAPHIC ZONE
TIMESCALE
Ma
35/13-1
610
980, 981
94/1
88/7,7A
164/25-2
77/7
77/9
214/4-1
34/8-3A
6407/1-2
6507/10-1
642
NEOGENE
PALAEOGENE
PLEISTOCENE TO HOLOCENE
PLIOCENE
MIOCENE
OLIGOCENE
Late
Early
Mid
Piac.
Zanc.
Mess.
Tortonian
Serravallian
Langhian
Burdigalian
Aquit.
Chattian
Rupelian
NN19
NN16
NN13
NN12
NN11
NN10
NN9
NN7
NN6
NN5
NN4
NN3
NN2
NN1
NP25
NP24
Early Pliocene to Holocene
Miocene to early Pliocene
NN15-21
NN15-21
C10
NN12-13
NN12-15
NN16-21
NN13-15
NN3-12
C20
NN4-10
NN?4-18
Extensive reworking of lower Miocene sediments
NN2
BN
NP22-NN1
NP24
NP24-25
NN20-21
INU
NN13/14-21
NN4-10
NN4-12
TPU
?NP24-25
IMU
MMU
NN16-17
BASE
NAUST
NN19
NN16-18
NN17-19
NN 10-14
NN10-13
NN10-14
NN6-10
BASE
KAI
NN1-2
NP25-NN4
NP25-NN4
NN1-21
NP24-25
KEY
Proven biostratigraphic range
Probable unconformity (biostratigraphy inconclusive)
Data gap
Unconformity
Correlative conformity
NN15
Neogene
NP24
Palaeogene
Biostratigraphical zone: calcareous nannoplankton
No recovery in / or analysis of upper part of well / borehole
Megasequence boundary
Unconformity
C20 correlative surface (broad range)
Intra-Miocene boundaries
610
980,981
94/1
88/7,7A
164/25-2
77/7
77/9
214/4-1
34/8-3A
6407/1-2
6507/10-1
642
35/13-1
500km
BGS borehole
Commercial well
DSDP/ODP site
Bathymetric contour in metres.

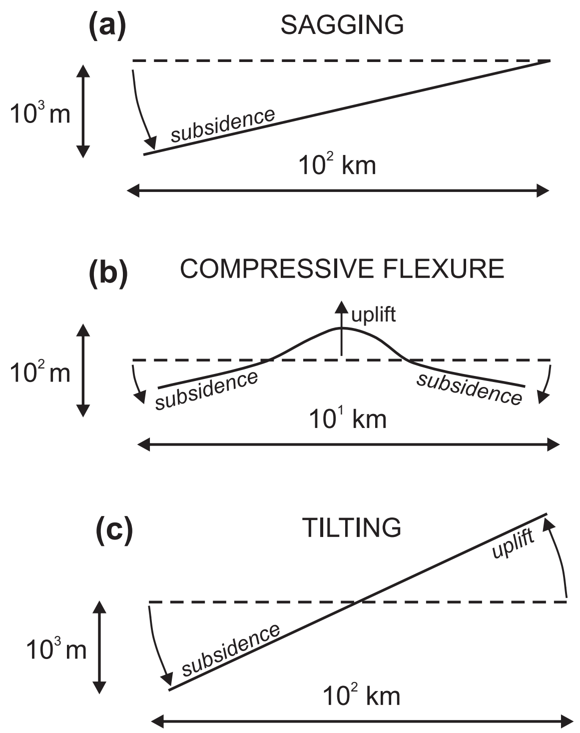
Stoker *et al*. Fig. 6

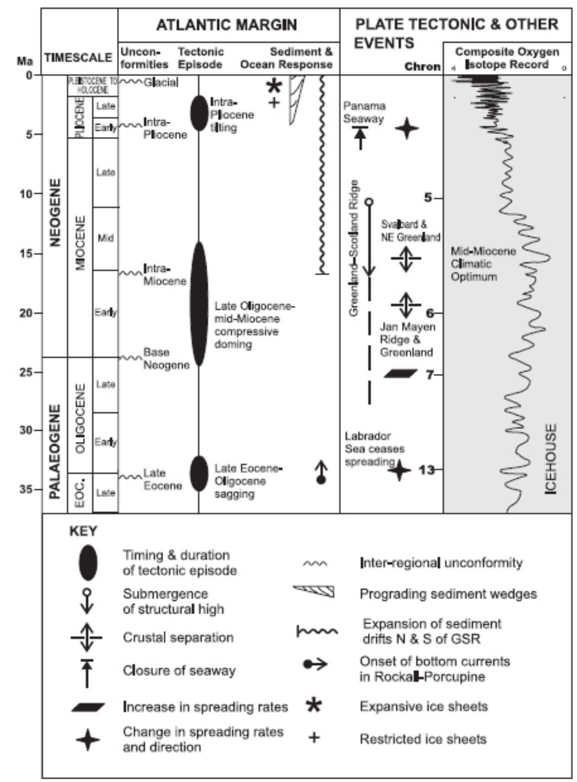


Stoker *et al*. FIG. 7



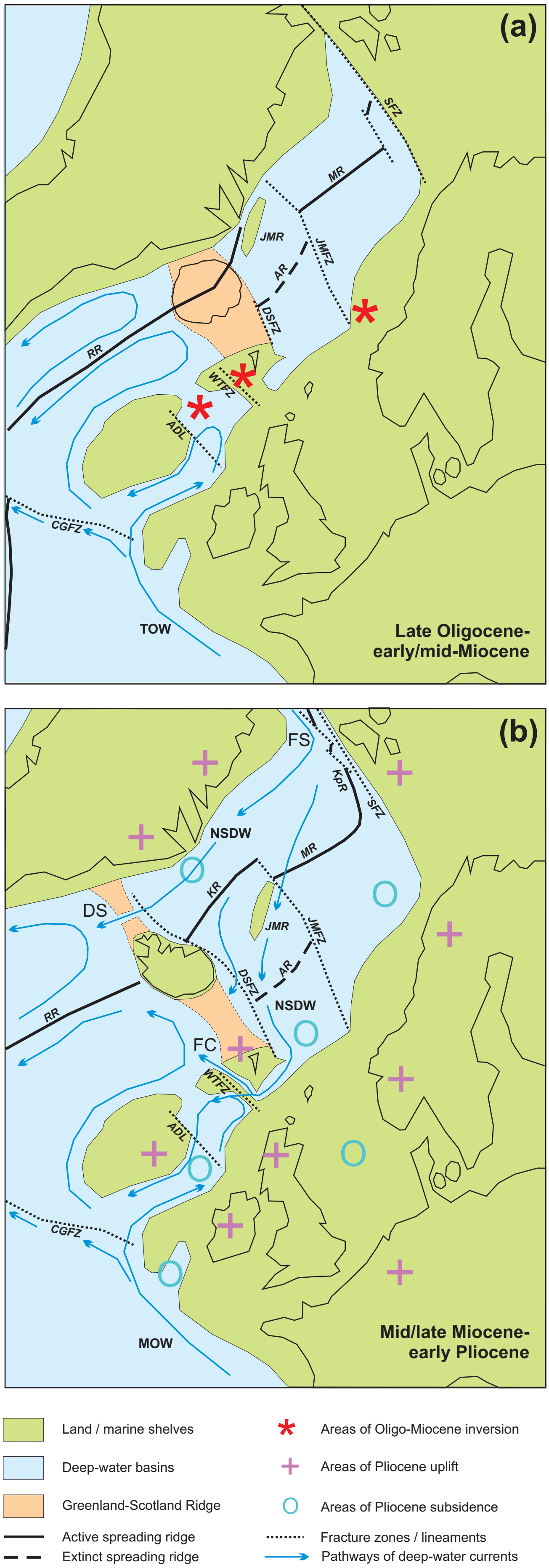

(a)
TWTT secs
NW
SE
INNER VØRING PLATEAU
Mid-Norwegian Wedge
Naust Fm - Upper Pliocene to Pleistocene
Kai Fm - Miocene to lower Pliocene
BNU
BKU
10 km
NH9651-405
(b)
GU
INU
TPU/IMU?
CP100
FSP - Eocene
FSN-1 - Lower Pliocene to Holocene
FSN-2 - Miocene to Lower Pliocene
FSP - Oligocene
WEST SHETLAND SHELF
SE
Submarine end-moraines
Rona Wedge
Mesozoic
FSN-2 - Middle to upper Miocene
SBM
Buried, upslope prograding sediment waves
5km
NW
FAROE-SHETLAND CHANNEL
BGS83/04-31
TPU/IMU?
CP100
FSP - Eocene
Submarine end-moraines
BP
SBM
Sula Sgeir Fan
(c)
Buried, upslope prograding elongate drift / sediment waves
BGS83/04-6
C10
NE ROCKALL TROUGH
C10 - Early Pliocene Unconformity
RPa - Lower Pliocene–Holocene
RPb - Miocene–Lower Pliocene
TPU
RPc - Oligocene
C30
Eocene & older
HEBRIDES SHELF
Glacial Unconformity - GU
10km


(a)
SAGGING
10^3 m
subsidence
10^2 km
(b)
COMPRESSIVE FLEXURE
uplift
10^2 m
subsidence
subsidence
10^1 km
(c)
TILTING
uplift
10^3 m
subsidence
10^2 km



TIMESCALE
ATLANTIC MARGIN
Uncon-formities
Tectonic Episode
Sediment & Ocean Response
PLATE TECTONIC & OTHER EVENTS
Chron
Composite Oxygen Isotope Record
Ma
NEOGENE
PALAEOGENE
PLEISTOCENE TO HOLOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOC.
Late
Early
Mid
Glacial
Intra-Pliocene
Intra-Miocene
Base Neogene
Late Eocene
Intra-Pliocene tilting
Late Oligocene-mid-Miocene compressive doming
Late Eocene-Oligocene sagging
Panama Seaway
Greenland-Scotland Ridge
Svalbard & NE Greenland
Jan Mayen Ridge & Greenland
Labrador Sea ceases spreading
Mid-Miocene Climatic Optimum
ICEHOUSE
KEY
Timing & duration of tectonic episode
Submergence of structural high
Crustal separation
Closure of seaway
Increase in spreading rates
Change in spreading rates and direction
Inter-regional unconformity
Prograding sediment wedges
Expansion of sediment drifts N & S of GSR
Onset of bottom currents in Rockall-Porcupine
Expansive ice sheets
Restricted ice sheets

Stoker *et al*. FIG. 11



Stoker *et al*. FIG. 12