Late Cenozoic palaeogeography of the eastern North Sea Basin: climatic *vs* tectonic forcing of basin margin uplift and deltaic progradation

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The late Eocene to middle Pleistocene development of the eastern North Sea Basin is described by a series of palaeogeographic maps. The maps are based on published information integrated with recent investigations of seismic and well data from the eastern North Sea. The maps provide overviews of the basin geometry at late Eocene, late Oligocene, middle Miocene, late Miocene, late Pliocene and middle Pleistocene time. In post-Eocene time, the eastern and central North Sea Basin was progressively filled by large deltas, which built out from the eastern basin margin. These deltas were fed by ancient rivers from southern Norway (late Paleocene-Oligocene and Pliocene), southern Norway and Sweden (early Miocene), the Baltic region (middle Miocene-early Pleistocene), and finally by rivers flowing northward through the northwest European lowland (middle Pleistocene).

It is argued that the Cenozoic evolution of the eastern North Sea Basin may be explained by a 'self-perpetuating' passive model. This model involves isostatic uplift of source areas due to erosional unloading of a relief generated by early Palaeogene uplift. The erosional unloading accelerated at the Eocene/Oligocene transition, in the middle Miocene and in the Plio-Pleistocene corresponding to periods of global climatic cooling and long-term eustatic lowering as indicated by $\delta^{18}O$ records. The passive model diminishes the need for hypothetical Neogene tectonic events, although the influence of tectonic events cannot be excluded.

Previous estimates of Neogene uplift and erosion of the northeastern Danish North Sea of the order of 500–1000 m do not agree with seismic geometries or with the regional palaeogeographic development. This indicates that previous estimates of Neogene uplift and erosion of the northeastern Danish North Sea may be several hundred metres too high.

Keywords: Cenozoic, North Sea Basin, Climate, Eustasy, Tectonics.

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More than 2000 m of Palaeogene and Neogene sediments, and approximately 1000 m of Quaternary sediments accumulated in the centre of the North Sea Basin, while the basin margins are characterized by uplift and erosion (Nielsen et al. 1986, Jensen & Schmidt 1992, Jensen & Michelsen 1992, Jordt et al. 1995, Michelsen et al. 1995, 1998, Japsen 1998, Clausen & Huuse 1999). The age of the base Quaternary subcrop increases towards the basin margins; from conformable strata of Neogene siliciclastic sediments in the main part through truncated Palaeogene siliciclastic sediments and upper Cretaceous-Danian limestone to lower Cretaceous and Jurassic rocks in the Sorgenfrei-Tornquist Zone to the ENE (Sorgenfrei & Berthelsen 1954, Jensen & Michelsen 1992, Japsen 1998, Huuse & Lykke-Andersen 2000).

In recent years, numerous studies have focused on the Cenozoic lithostratigraphy (Kristoffersen & Bang 1982, Nielsen et al. 1986, Vinken 1988, Clausen et al. 2000), or sequence stratigraphy (Galloway et al. 1993, Michelsen 1994, 1996, Jordt et al. 1995, Michelsen et al. 1995, 1998, Sørensen & Michelsen 1995, Jürgens 1996, Danielsen 1997, Danielsen et al. 1997, Sørensen et al. 1997) of the central and eastern North Sea. Lithostratigraphic studies of the adjacent land areas have been going on for more than a centuryUssing 1899, Ravn 1922, Quitzow 1953, Larsen & Dinesen 1959, Rasmussen 1961, 1966, Gripp 1964, Hinsch & Ortlam 1974, Heilmann-Clausen et al. 1985, Vinken 1988, Koch 1989, Friis 1995, Friis et al. 1998, Clausen et al. 2000), while sequence stratigraphic studies of the onshore succession have only just begun to emerge

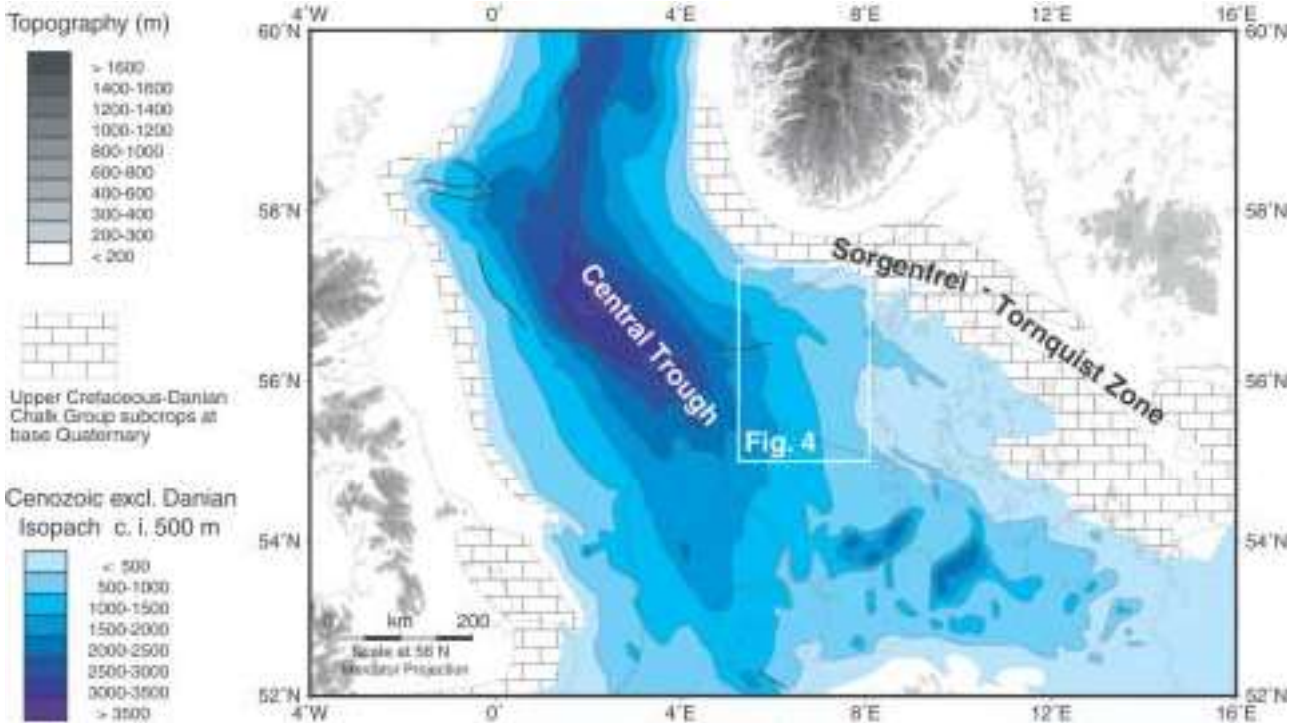

Fig. 1. The Cenozoic North Sea Basin (modified after Ziegler 1990 and Japsen 1998).

during the last decade (Michelsen 1994, 1996, Michelsen et al. 1995, 1998, Rasmussen 1996, 1998, Danielsen 1997, Danielsen et al. 1997).

Regional palaeogeographic studies are comparatively few and are mostly based on well and outcrop data (Quitzow 1953, Spjeldnæs 1975, Gramann & Kockel 1988, Kockel 1988), although Ziegler (1990, 1994) presented a series of palaeogeographic maps of western and central Europe, based on 'all available information'.

The main objective of the present paper is to describe the late Eocene to middle Pleistocene palaeogeographic development of the eastern North Sea Basin. The description is based on a series of regional palaeogeographic maps covering the entire North Sea Basin south of 60°N (Fig. 1). The maps are compiled from a variety of sources with special emphasis on the integration of seismic and well data from the eastern North Sea with published data from Denmark, northern Germany, the Netherlands and southern England. Published information from the Norwegian, Danish, German, Dutch and UK offshore sectors was also utilized. Apart from illustrating the late Cenozoic development of the North Sea Basin, the palaeogeographic maps provide regional geological constraints on integrated basin modelling (cf. Nielsen 2002).

Climatic *vs* tectonic forcing of basin margin uplift and deltaic progradation: rationale

The second objective of the paper is to discuss the late Cenozoic development of the eastern North Sea Basin and whether it can be explained in terms of a 'self-perpetuating' passive model (cf. Doré 1992). This model involves erosional unloading of pre-existing source areas in response to global climatic cooling and long-term eustatic lowering, and does not involve late Cenozoic tectonic events.

Previous investigations of the Cenozoic development of the North Sea Basin have invoked rather dramatic sea-level and tectonic events in order to explain regional unconformities, onshore sedimentary facies successions (Fig. 2), and the distribution of depocentres (Fig. 3). These events include:

- Late Cretaceous-Paleocene inversion of the Sorgenfrei-Tornquist Zone and other structural elements (Liboriussen et al. 1987, Vejbæk & Andersen 1987, Ziegler 1990).
- Late Paleocene-Early Eocene tectonic uplift of Scotland and Norway related to the opening of the North Atlantic (e.g. Ziegler 1990).
- Late Eocene/Early Oligocene tectonic uplift of Fen-

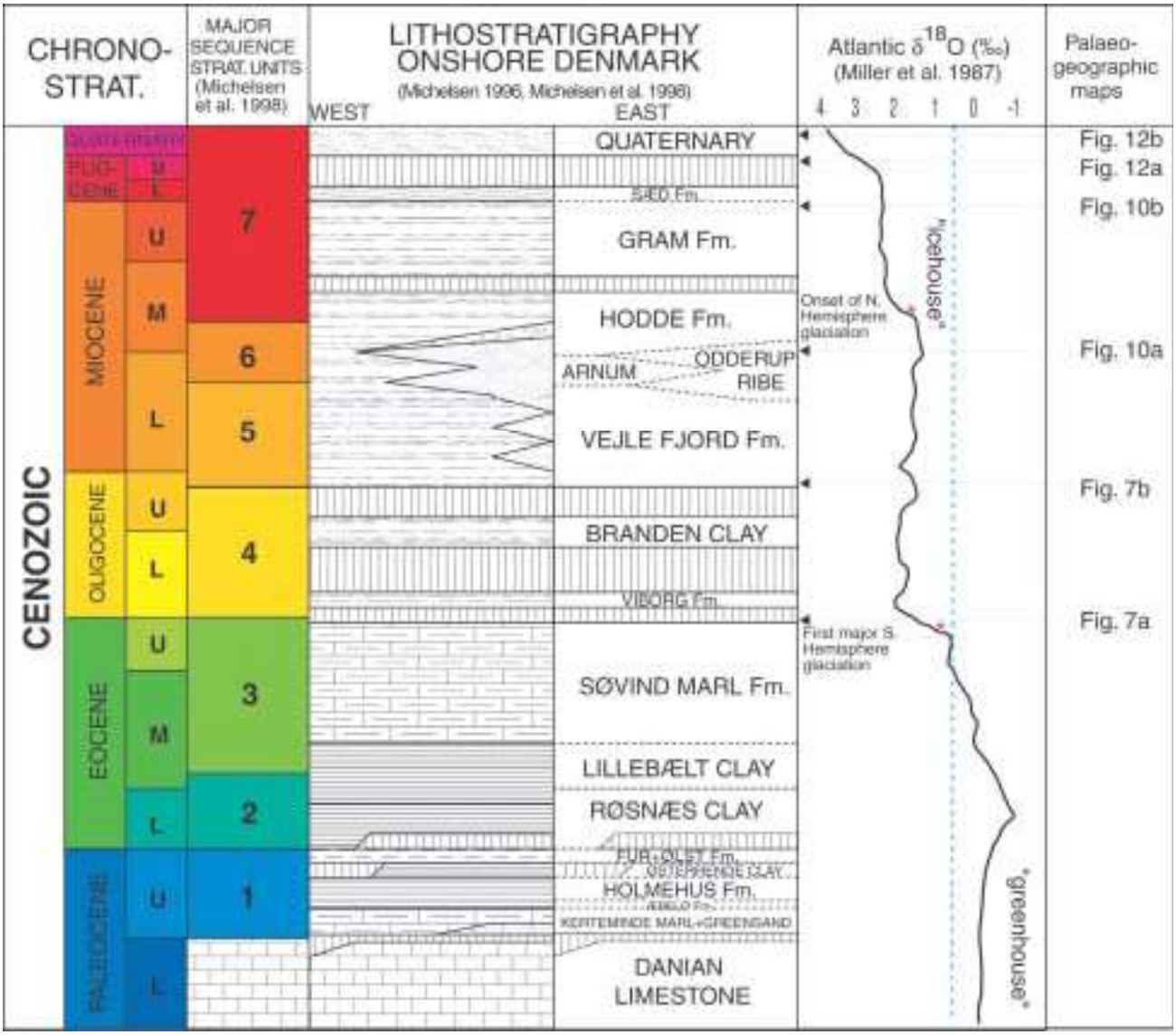

Fig. 2. Sequence stratigraphic subdivision of the Cenozoic succession of the eastern North Sea and lithostratigraphy onshore Denmark (modified from Heilmann-Clausen 1995, Michelsen et al. 1995, 1998, Michelsen 1996). The composite $\delta^{18}O$ curve for the Atlantic (Miller et al. 1987) is shown for reference. Note that two distinct breaks in the $\delta^{18}O$ curve at the Eocene/Oligocene transition and in the middle Miocene roughly correlate with the boundaries between major sequence stratigraphic units 3/4 and 6/7.

noscandia (Jordt et al. 1995, Michelsen et al. 1995, 1998)

- a marked Middle or Late Oligocene eustatic fall (Vail et al. 1977, Michelsen et al. 1995, 1998).
- Late Oligocene uplift of Fennoscandia (Jordt et al. 1995, Clausen et al. 1999).
- post-Middle Miocene accelerated tectonic subsidence of the Central Trough (e.g. Michelsen et al. 1995, 1998, Clausen et al. 1999, Japsen & Chalmers 2000).
- Neogene tectonic uplift of Fennoscandia (e.g. Spjeldnæs 1975, Cloetingh et al. 1992, Doré 1992, Jensen & Schmidt 1993, Rohrman et al. 1995, Stuevold & Eldholm 1996).
- a mid-Miocene sea-level rise of 300–500 m (Gramann & Kockel 1988, Jürgens 1996).
- Plio-Pleistocene accelerated tectonic subsidence of the Central Trough (Cloetingh et al. 1990, 1992).

The early Palaeogene events (uplift and inversion) are well documented and are therefore not questioned here. However, as for the remainder of the proposed events listed above a number of observations indicate that alternative interpretations should be considered. These observations include:

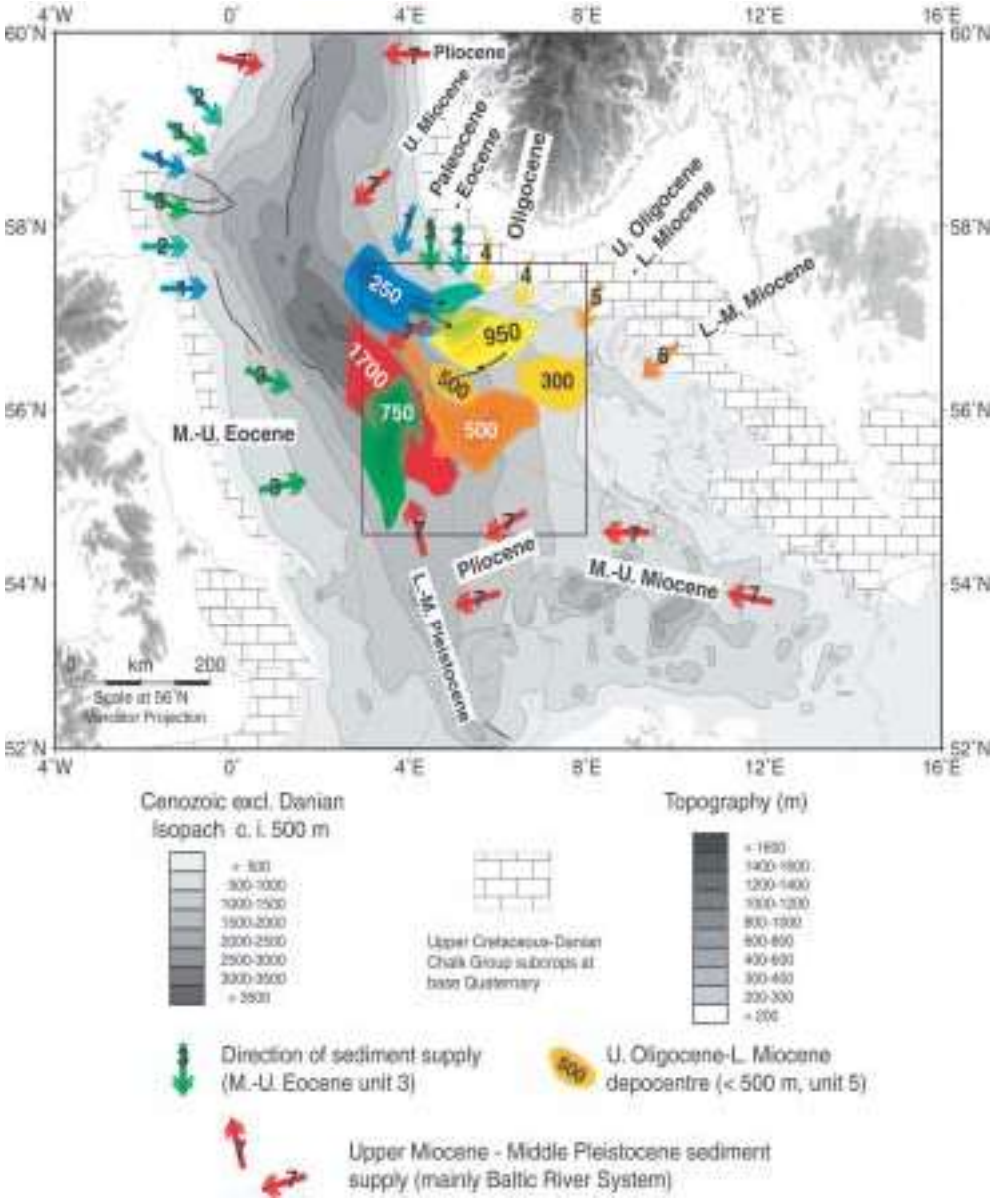

Fig. 3. Depositional centres in the eastern North Sea Basin (modified after Bidstrup 1995, and Michelsen et al. 1995, 1998 to include own observations south of Norway). Note that depocentres also exist outside the area (indicated by the black rectangle) investigated by Michelsen et al. (1995, 1998) (cf. Jordt et al. 1995, Bowman 1998). The depocentres are defined by the contour representing c. 2/3 of the maximum thickness of each unit. Directions of sediment supply through time is indicated by arrows colour-coded according to Figure 2. Note that continuous southward progradation from southern Norway caused a succession of c. 250 m thick Upper Paleocene, Lower-middle Eocene and middle-Upper Eocene depocentres (units 1-3), and a more than 900 m thick Oligocene depocentre (unit 4).

- Recent estimates of short-term eustatic amplitudes are generally well below hundred metres in amplitude, while a long term Cenozoic fall in sea level is estimated at 150–200 m (Miller et al. 1998). Their estimates support the results of Hay et al. (1989), who estimated Gulf coast sea-level amplitudes of about half those of the eustatic curve published by Haq et al. (1987). Estimates of North Sea sea-level fluctuations of several hundreds of metres amplitude (Vail et al. 1977, Gramann & Kockel 1988, Jürgens 1996, Michelsen et al. 1998) thus appear to be unrealistic, unless tectonic mechanisms are invoked.
- Palaeoclimatic studies based mainly on oxygen isotope ($\delta^{18}O$) records indicate that climate in the North Sea region deteriorated throughout the middle to late Cenozoic with rather sudden deteriorations taking place at the Eocene/Oligocene transition, in the middle Miocene, and in the Plio-Pleistocene (Buchardt 1978). This pattern is markedly similar to the pattern of global climatic cooling as indicated by Atlantic or and by global $\delta^{18}O$ records (Fig. 2, see Miller et al. 1987, Abreu & Anderson 1998, Miller et al. 1998). The composite $\delta^{18}O$ records indicate that the terminal Eocene cooling event was preceded by more gradual cooling during the middle to late Eocene, corresponding to the first evidence for an ice sheet on Antarctica (Keigwin 1980, Browning et al. 1996, Abreu & Anderson 1998). Middle to late Eocene gradual

cooling, rather than a single terminal Eocene event, is also indicated by floristic evidence from southern England (Collinson et al. 1981). Note the remarkable coincidence between the timing of the major $\delta^{18}O$ events and the timing of several of the inferred tectonic events listed above.

- Recent results of three-dimensional basin modelling indicate that the large-scale geometry of the North Sea Basin may be explained by lithospheric stretching in the Jurassic to early Cretaceous followed by thermal subsidence centred along the former rift axis. The rapid post-Middle Miocene subsidence of the central North Sea is reproduced by increasing the sediment flux into an overdeepened basin, i.e. without invoking renewed tectonic subsidence of the Central Trough (Nielsen 2002).

The effects of global climatic and eustatic events on sedimentary systems have been recognized in many areas around the world (e.g. Donnelly 1982, Miller et al. 1987, 1996, 1998, Bartek et al. 1991, Séranne 1999). However, despite their apparent synchronicity with inferred tectonic events, climatic events have generally received little attention by North Sea researchers. A re-evaluation of the post-Eocene development of the North Sea Basin, taking well-documented climatic and eustatic events into account, is therefore timely.

Geological setting

During the Cenozoic, the North Sea Basin developed as an epeiric sea centred above the Jurassic to early Cretaceous Central Graben (Nielsen et al. 1986, Ziegler 1990). The basin is bordered to the east and northeast by the Fennoscandian landmass, central Europe to the south and the British Isles to the west (Fig. 1). The eastern part of the Cenozoic North Sea Basin is located above a number of late Palaeozoic and Mesozoic structures: the Ringkøbing-Fyn High, the Central

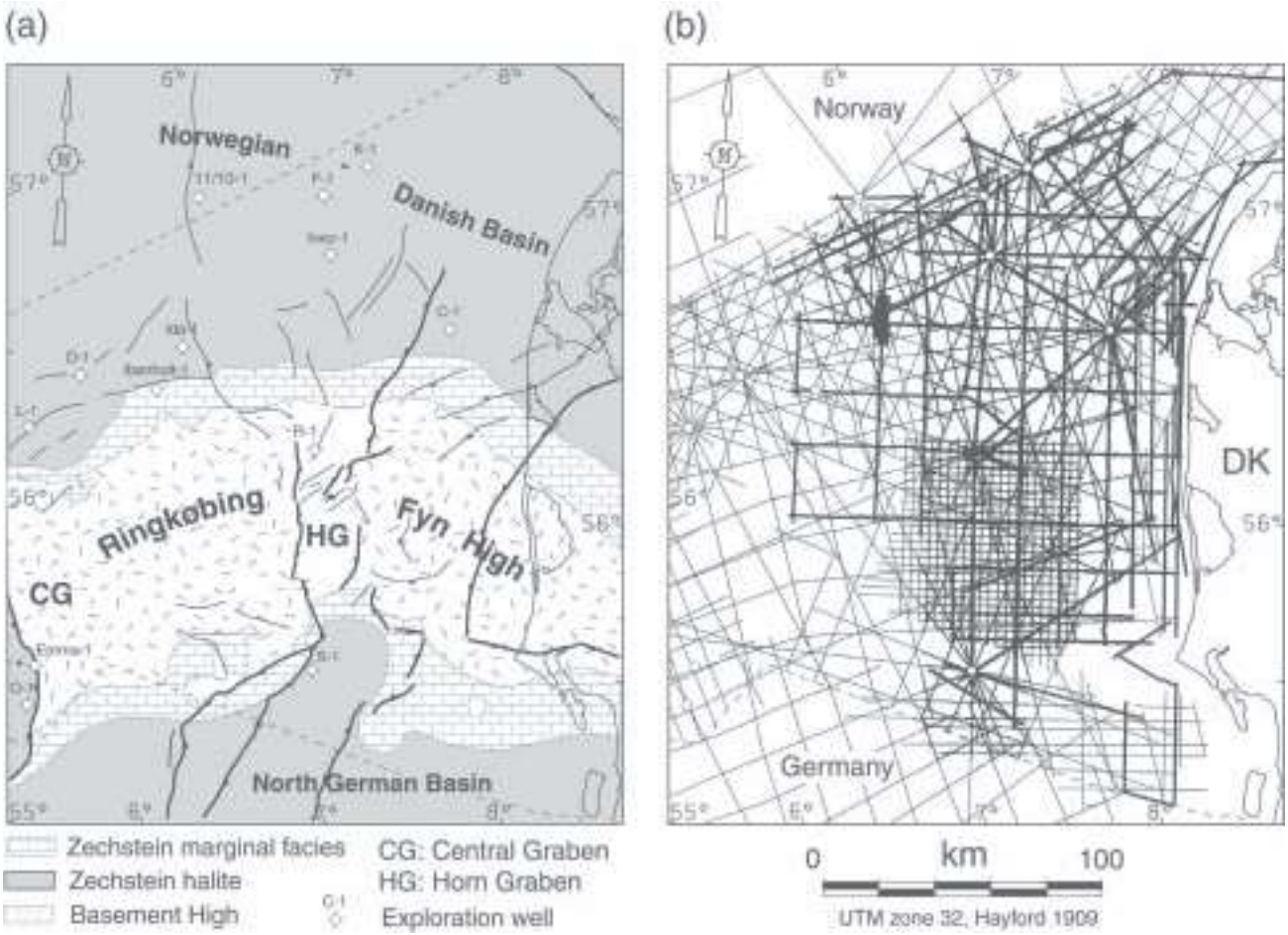

Fig. 4. (a) Well locations and Late Palaeozoic-Mesozoic structural elements of the eastern North Sea (after Vejbæk 1990, and Vejbæk & Britze 1994), (b) conventional seismic data (thin lines) and high-resolution seismic data (thick lines) in the eastern North Sea.

Graben, the Horn Graben, the North German Basin, and the Norwegian-Danish Basin (Fig. 4a, Vejbæk & Britze 1994). The relatively smooth saucer shape of the Cenozoic North Sea Basin indicates that differential subsidence across underlying basement structures, other than the Central Graben, had largely ceased to control the regional distribution of depocentres.

The Sorgenfrei-Tornquist Zone to the northeast suffered inversion in the Late Cretaceous-Paleocene and may have constituted a topographic barrier in the early Palaeogene (Liboriussen et al. 1987, Hansen et al. 2000, Gemmer et al. 2002). Such a barrier could have diverted fluvial supply of clastic sediments from Fennoscandia to the northwest and southeast of the Danish area (Liboriussen et al. 1987, Clausen & Huuse 2002).

During the Late Cretaceous and Danian, a thick limestone succession was deposited in the North Sea Basin (Ziegler 1990). In the eastern North Sea, limestone deposition was followed by a comparatively thin succession of hemipelagic clays and marls during the Late Paleocene and Eocene (units 1–3, Fig. 2). In the Central Trough area a thick succession of pelagic and hemipelagic clays accumulated during the middle to late Eocene (unit 3, Fig. 3, Michelsen et al. 1998). Minor deltaic wedges of Late Paleocene-Eocene age accumulated southwest of Norway, at the NW tip of the Sorgenfrei-Tornquist Zone (units 1–3, Fig. 3). In the northwestern part of the basin, massive deltaic wedges prograded towards the east and southeast from the Shetland Platform during the late Paleocene and Eocene (Bowman 1998).

During Oligocene to middle Pleistocene time, the eastern and central North Sea Basin was filled by prodeltaic and deltaic sediments supplied from N (Oligocene), NE (early Miocene), E (late Miocene-early Pliocene), SE (late Pliocene), SSE (Pleistocene) (Fig. 3, Spjeldnæs 1975, Bijlsma 1981, Gibbard 1988, Cameron et al. 1993a, 1993b, Funnell 1996, Jürgens 1996, Michelsen 1996, Sørensen et al. 1997, Michelsen et al. 1998, Clausen et al. 1999: fig. 9).

Database, eastern North Sea

A large amount of conventional seismic data were available in the eastern North Sea, including the regional surveys: CGT81, DCS81C, RTD81, SP82, SNST83, NP85N, GR86 (Fig. 4b). Well information comprising drill cuttings and geophysical logs was available from the relatively small number of exploration wells drilled outside the Central Trough in the eastern Danish and Norwegian North Sea (Figs 4a, 4b). During 1994–1998, approximately 6400 km of high-resolution multichannel seismic data were acquired in the eastern Danish North Sea by the Department of Earth Sciences, University of Aarhus (AU): DA94, DA95, DA96, and by AU and the Geological Survey of Denmark and Greenland: GR97, GR98 (Fig. 4b). The seismic equipment consisted of a 70 cu. inch (~ 1.1 l) sleeve gun fired every 12.5 m, and a 24 channel (DA94-DA96) or 96 channel (GR97-GR98) streamer with a channel separation of 6.25 m. Post-stack bandwidth of the migrated seismic data is 40–180 Hz (DA94) or 40–250 Hz (DA95, DA96, GR97, GR98). Penetration is of the order of 1–2 s two-way traveltime (TWT) corresponding to depths of 1–2 km. The data provide a vertical resolution of the order of 5–10 m in the uppermost 1 s TWT, corresponding to the uppermost kilometre subbottom. Thus in the upper 1 s TWT the resolution is 2–3 times better than the resolution of the available conventional seismic data, depending on the noise level of individual profiles.

Construction of the palaeogeographic maps

The palaeogeographic maps were initially compiled from palaeogeographic maps of local to regional extent. Additional published information was then incorporated, including sedimentary facies distributions, locations of depocentres, palaeobathymetric data, etc. The compiled maps were subsequently integrated with interpretations of offshore well- and seismic data from the eastern North Sea (Fig. 4b).

Palaeobathymetry

Palaeobathymetry may be inferred from clinoform heights observed on seismic data and from biostratigraphic data. In a study combining seismic and biostratigraphic analyses in the Danish Central Trough, Laursen et al. (1997) showed that clinoform height provides a reasonable measure of palaeo-water depth for the late Neogene deposits in that area. Such detailed studies combining seismic geometries and biostratigraphic data are rare and should be given more attention in the future, as the integration of data sets provide much more palaeogeographic information than each method used separately.

Several factors may cause uncertainties when using the height of ancient clinoforms as a proxy for palaeo-water depth, including: post-depositional compaction of the clinoforms, differential compaction

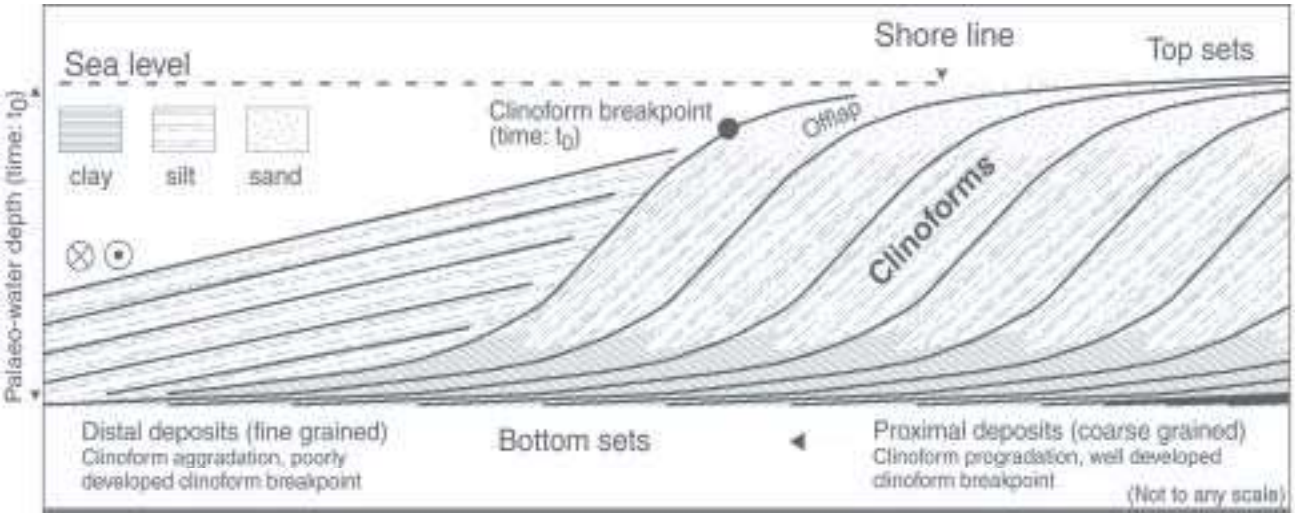

Fig. 5. Schematic cross-section through a typical delta of the North Sea Cenozoic. Initially, proximal deposition results in a thick progradational succession. Subsequent abandonment of the active delta lobe at time: t_o results in onlap of an aggradational succession deposited distally with respect to a point source of sediment. Note that clinoform breakpoints are absent in the distal succession as sediments did not build up to base level (after Emery & Myers 1996, and Driscoll & Karner 1999).

of the clinoform substrate, post-depositional tilt, salt movement, etc. However, the palaeobathymetric estimates from clinoform heights generally agreed with those from biostratigraphic data, and the above factors thus seem to be of relatively minor importance in the present study. The 'clinoform breakpoint' (preferred here to the term 'offlap break') is usually formed in a few tens of metres water depth (Fig. 5, Emery & Myers 1996). Clinoform height measured as the vertical distance between bottomsets and the

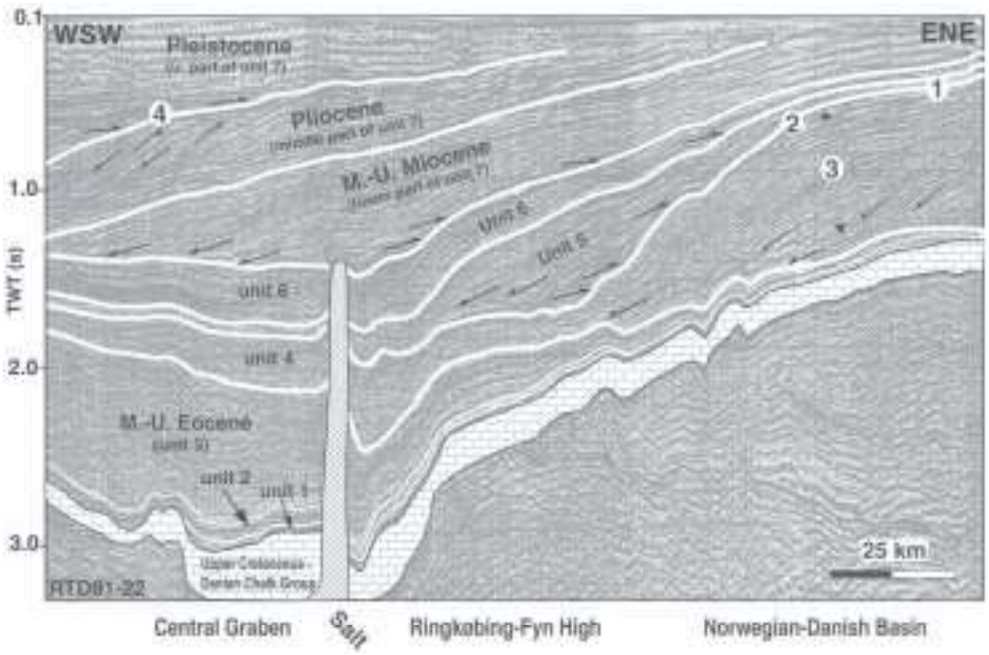

Fig. 6. Conventional seismic profile (RTD81-22) along the Norwegian-Danish sector boundary (ENE-WSW) showing progradational clinoforms of the Oligocene and Pliocene deltas. The Miocene succession is mainly aggradational, and was probably deposited some distance away from a point source located further to the southeast in the eastern Danish North Sea. Legend: (1) late Oligocene shoreline (tentative), (2) late Oligocene clinoform breakpoint (proximal deposition), (3) clinoform height indicating late Oligocene palaeo-water depth in the central North Sea (> 500 m), (4) late Pliocene clinoform breakpoint and shoreline (tentative). Compare seismic geometries with drawing in Fig. 5 and N-S seismic profile in Fig. 8. For location see Fig. 7b.

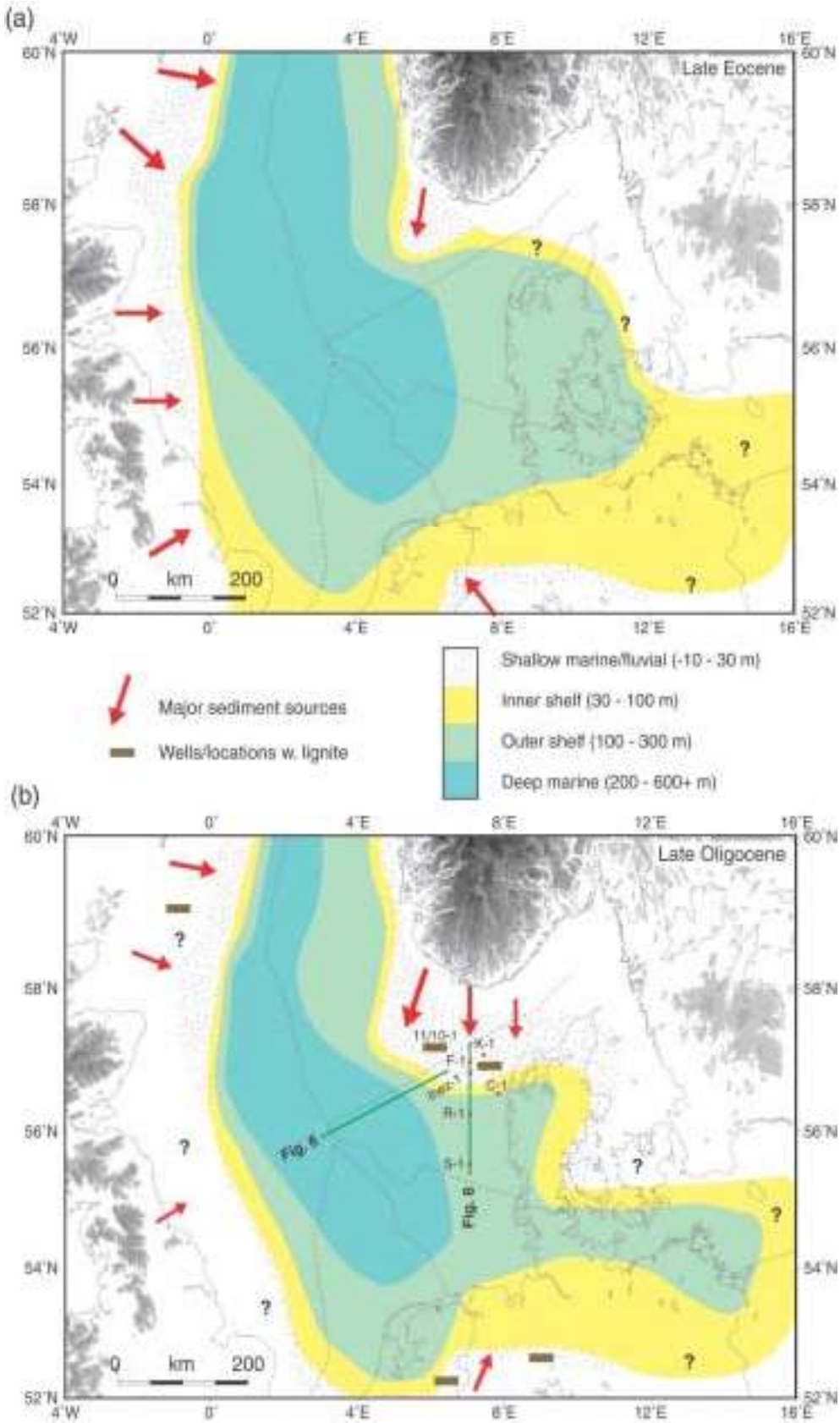

Fig. 7. (a) Late Eocene palaeogeography of the North Sea Basin. Compiled from regional maps by Kockel (1988) and Ziegler (1990), regional clay-mineralogy trends (Nielsen 1995, pers. comm. 1998), Bowman (1998), and own observations (upper Eocene delta south of Norway). (b) Late Oligocene palaeogeography of the North Sea Basin. Compiled from regional maps by Quitzow (1953), Kockel (1988) and Ziegler (1990), regional clay-mineralogy trends (Nielsen 1995, pers. comm. 1998), studies by Zagwijn & Hager (1987), Danielsen et al. (1997), Friis et al. (1998), Clausen et al. (1999), and own observations. Locations of key wells and seismic sections mentioned in the text are shown for reference. The late Oligocene clinoform breakpoint is located just landward of and parallel to the zone of 'inner shelf' water depths.

clinoform breakpoint or topset beds (if present) can thus be considered a reasonable measure of minimum palaeo-water depth (Fig. 5).

When estimating palaeo-water depth from clinoform height it is important to distinguish clinoforms in proximal deposits from clinoforms in distal deposits (cf. Figs 5, 6, Driscoll & Karner 1999: fig. 7). The presence of seismic offlap and a well-developed clinoform breakpoint indicates that sediments had filled all available accommodation, i.e. that the succession had built up to near sea level (i.e. to wave base). Distal clinoforms, on the other hand, often lack clinoform breakpoints, indicating that they did not build up to wave base (units 5, 6, Fig. 6). Distal clinoforms thus contain little geometric information about palaeo-water depth.

Palaeobathymetry may also be estimated from benthic foraminifera and other benthos, as these are sensitive to a number of factors such as: nutrients, oxygen, salinity, temperature, current energy, substrate type, and photic intensity (Emery & Myers 1996). These factors are usually related to water depth, but environmental conditions should also be considered before estimating palaeo-water depth from benthos (Emery & Myers 1996). Despite their possible ambiguity, palaeo-water depths derived from biofacies analyses are very useful in successions characterized by aggradational seismic geometries, as such geometries may be produced in both deep and shallow marine, and even in fluvial settings. Biostratigraphic data are, of course, also important as independent indications of palaeo-water depth when seismic geometries can be used to infer palaeobathymetry. Palaeobathymetric and palaeoenvironmental investigations by Laursen (1995), Laursen et al. (1997), Michelsen et al. (1998), and Eidvin et al. (1999) were utilized in the present study.

Sedimentary facies

Sedimentary facies is most useful for distinguishing between depositional settings above and below wave base, and for locating the shoreline.

The occurrence of lignite has been reported from various parts of the Cenozoic succession in exploration wells located in the eastern North Sea (e.g. King 1973, Rasmussen 1974, 1978, Strass 1979). As lignite is often found in abundance immediately landward of the palaeo-shoreline (Einsele 1992), the occurrence of significant quantities of lignite may be used to indicate proximal deposits.

Siliciclastic sediments deposited below wave base are generally characterized by silt and clay-sized material and thus provide little information about palaeobathymetry. However, regional clay-mineralogy trends derived from such deposits may be used to indicate the trend of the shoreline and its migration through time (Spjeldnæs 1975, Nielsen 1995).

General considerations

The palaeogeographic maps are generally constructed in order to illustrate the basin configuration during regressive conditions. The time interval depicted in each map is variable and difficult to quantify due to the variety of data used (maps, seismic-, well- and outcrop data). The more recent maps generally span less time, approaching less than 0.5 Myr for the mid-Pleistocene. The pre-Pleistocene maps may span more than 5 Myr, as it was generally necessary to include data from a wide time interval in order to achieve sufficient spatial coverage of each map. The time span included in each map is therefore likely to encompass several regressions and transgressions of the shoreline. Each map thus represents a qualitative average of several regressions within each time interval depicted. To compensate for the potentially large lateral fluctuations of the shoreline within each time interval, and due to the variable accuracy of the available data, it was chosen to indicate the approximate shoreline location by a wide zone characterized by shallow marine to fluvial deposition, rather than drawing the actual shoreline itself.

The juxtaposition of a variety of published and unpublished data can easily cause palaeogeographic maps to become cluttered with uneven levels of detail. In order to provide as clear palaeogeographic overviews as possible, and due to the compressed scale of the maps, some detailed information has been left out. More detailed information can be found in the cited references. Though the palaeogeographic maps are grossly simplified, they are consistent with the available data and are generally believed to be representative of the late Cenozoic development of the North Sea Basin. Future investigations should lead to refinement and increased accuracy of the maps.

In the following account, the palaeogeographic maps provide overviews of the basin configuration at discrete time intervals while the accompanying text describes the palaeogeographic development more or less continuously.

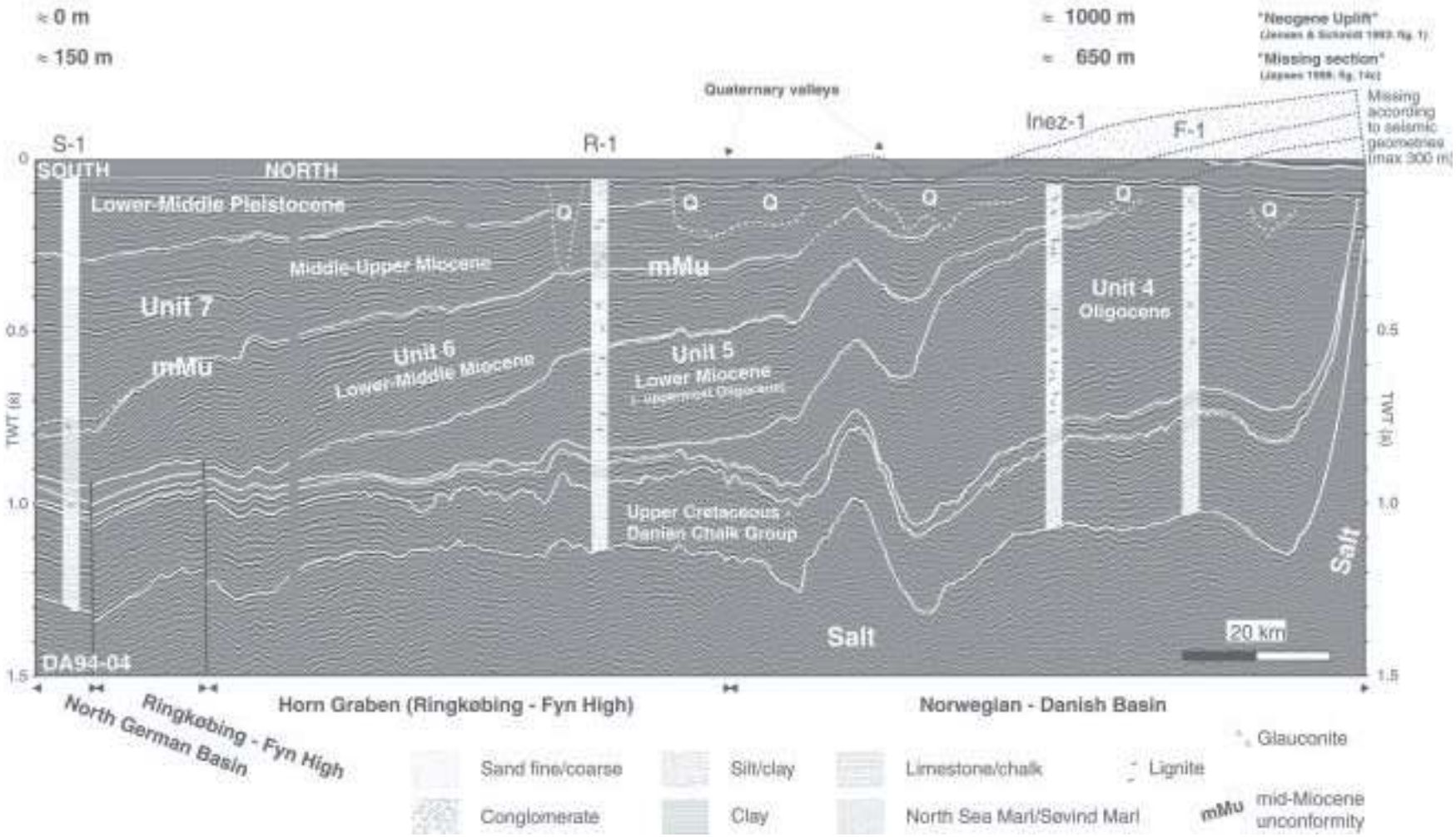

Fig. 8. High-resolution multichannel seismic profile (DA94-04) showing southward progradation of Oligocene and lower-middle Miocene clinoforms. Drill cuttings from the F-1, Inez-1 and R-1 wells have yielded sandy, lignite-bearing sediments, supporting seismic interpretations of a deltaic environment. Note that the progradational lower Miocene deposits are coeval with aggradational deposits to the NW (cf. Fig. 6). Values of 'Missing section' (Japsen 1998: fig. 14c) and 'Neogene uplift' (Jensen & Schmidt 1993: fig. 1) along the profile are shown for reference. The seismic geometries indicate that their estimates may be too high by a factor of 2-3. For location see Figs 7b, 10a.

Late Cenozoic palaeogeography of the eastern North Sea Basin

Late Eocene

A tentative late Eocene palaeogeographic map is presented in Fig. 7a, based mainly on regional compilations by Kockel (1988) and Ziegler (1990), and on clay mineralogy trends (Nielsen 1995). The main depocentre of the middle-upper Eocene unit 3 is located in the Central Trough (Fig. 3). This depocentre contains disrupted aggradational reflections representing pelagic and hemipelagic clays (Fig. 6, Michelsen et al. 1998). A separate depocentre has been observed and mapped on seismic data between the Central Trough and southern Norway (unit 3, Fig. 3). The minor depocentre contains progradational clinoforms and is similar in size to the late Paleocene and early to middle Eocene depocentres in this area (units 1 and 2, Fig. 3), indicating that sediments were supplied more or less continuously from southern Norway during the Late Paleocene and Eocene.

The middle to upper Eocene deposits onshore Denmark consist of hemipelagic clays and marls, indicating a relatively deep and distal marine environment (Fig. 2, Spjeldnæs 1975, Heilmann-Clausen et al. 1985). Coeval deposits in northern Germany (Gramann & Kockel 1988), the Netherlands (Zagwijn, 1989), and in the London Basin (Collinson et al. 1981) contain sandy sediments deposited in shallow marine and near-shore environments. The absence of proximal middle and upper Eocene deposits in the Danish area could be due to the inverted Sorgenfri-Tornquist Zone diverting any fluvial supply of sediments to the northwest and southeast of the Danish area.

Oligocene

The Eocene/Oligocene boundary is observed as a marked downlap surface on seismic data from the Norwegian-Danish Basin (base unit 4, Fig. 6). The greater thickness and more markedly progradational geometries of the Oligocene deposits in the Danish area (unit 4, Figs 3, 6) indicates that the supply of clastic sediments from southern Norway increased markedly at the Eocene/Oligocene transition. In the Danish area the Eocene/Oligocene transition is generally characterized by a marked shift in sedimentary facies, from hemipelagic clays and marls to silty micaceous clays (Fig. 2, Michelsen 1994, 1996, Heilmann-Clausen 1995, Michelsen et al. 1998). In the southeastern North Sea, the transition is marked by an unconformity with largely identical sediments above and below the boundary (Gramann & Kockel 1988, Letsch & Sissingh 1983, Zagwijn 1989).

A number of exploration wells located in the Norwegian-Danish Basin (11/10-1, F-1, Inez-1, K-1, Fig. 4a) have penetrated thick successions of possible deltaic sands and pro-deltaic clays with lignite fragments (Fig. 7b, Rasmussen 1974, 1978, King et al. 1978, Strass 1979). The proximal character of these sediments indicates that the Oligocene shoreline was located, at least intermittently, within this general area. Sedimentary facies maps based on a large number of wells (including the above) indicate a similar shoreline location during much of the Oligocene (cf. Danielsen et al., 1997). A similar location is inferred from the position of the final clinoform breakpoint of the major sequence stratigraphic unit 4. The clinoform breakpoint largely coincides with the transition between shelf and shallow marine/fluvial sediments in Figure 7b.

Lignite bearing coastal deposits of Oligocene age occur in the Lower Rhine Embayment (Zagwijn & Doppert 1978), but the majority of the Oligocene deposits preserved onshore northwestern Europe were largely deposited in shelf or outer shelf environments (Fig. 7b), indicating that the Oligocene shorelines were located at or beyond the present limit of Oligocene deposits. The Oligocene deposits encountered in the central North Sea were generally deposited in relatively large water depths, as indicated by benthic foraminifera (Michelsen et al. 1998, Eidvin et al. 1999). Substantial water depths are also indicated by the Oligocene clinoform heights, which are of the order of 3–400 m high, increasing towards the basin centre to the east (cf. Figs 6, 8).

Latest Oligocene – early Middle Miocene

An up to 500 m thick uppermost Oligocene-lower Miocene depocentre characterized by aggradational seismic geometries (unit 5, Figs 3, 6) is present to the SW of the Oligocene depocentre (unit 4, Figs 3, 6). The aggradational geometries indicate that the latest Oligocene-early Miocene shoreline did not prograde significantly towards the SW in this area. An up to 300 m thick depocentre of unit 5 is located in the easternmost Danish North Sea (Fig. 3). Seismic profiles through this depocentre display well-developed southward prograding clinoforms (Fig. 9), indicating that the latest Oligocene to early Miocene shoreline prograded rapidly towards the south along the present west coast of Jutland. Thus it appears that deltaic progradation shifted along strike with respect to the basin centre in the latest Oligocene, leading to the formation of two depocentres. The eastern depocentre was controlled by its proximal location,

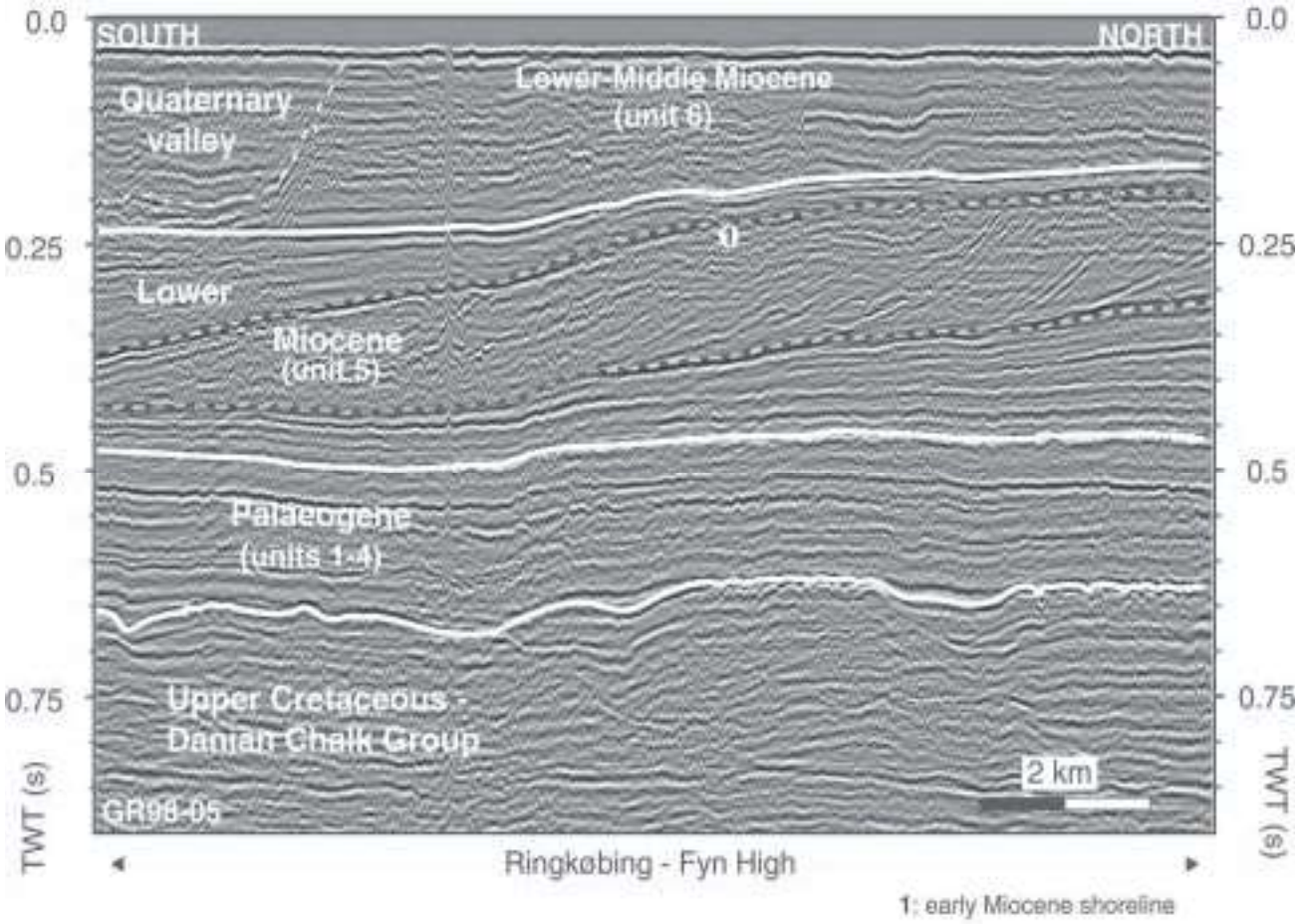

Fig. 9. Zoom-in on a high-resolution multichannel seismic profile off the westcoast of Jutland. The profile shows lower Miocene southward prograding deposits with well-developed offlap, indicating bypass and probably erosion of the delta top. The delta is coeval with the upper part of the Vejle Fjord Formation (uppermost Oligocene-Lower Miocene) onshore Denmark and the middle part of unit 5 of Michelsen et al. (1995, 1998, cf. Fig. 2). For location see Fig. 10a.

whereas the location of the distal depocentre to the west was controlled by the available accommodation, which increased towards the basin centre. Seismic data indicate that the lower Miocene deltas in the eastern Danish North Sea prograded southward along the west coast of Jutland until approximately 60 km north of the Danish/German border (Figs 9, 10a).

The uppermost Oligocene-Lower Miocene Vejle Fjord Formation is the first evidence of proximal deposition in the onshore Danish area since the deposition of the upper Paleocene Lellinge Greensand (cf. Larsen & Dinesen 1959, Friis et al. 1998, Clausen & Huuse 2002). Outcrop and borehole investigations onshore Denmark indicate that the shoreline was oriented N-S in the latest Oligocene to earliest Miocene (Larsen & Dinesen 1959, Rasmussen 1961, 1966, Spjeldnæs 1975, Rasmussen 1996, Friis et al. 1998).

Extensive lower and middle Miocene lignite deposits occur along the eastern and southeastern margins of the North Sea Basin (Fig. 10a). The distribution of lignite and fluvial sands of the Odderup and Ribe Formations in Denmark (Rasmussen 1961, 1966), the 'Braunkohlensande' in northern Germany (Quitzow 1953, Hinsch & Ortlam 1974), and the Lower Rhine Brown-coal Formation of the Netherlands (Zagwijn & Hager 1987) indicate that coastal lowlands expanded into the former shallow shelf areas, accompanied by extensive peat formation (cf. Bijlsma 1981, Zagwijn 1989).

Sandy deposits of early and middle Miocene age containing traces of lignite were encountered in offshore wells (C-1, R-1) in the area covered by the lower to middle Miocene delta (Fig. 10a). These deposits probably represent offshore analogues to the fluvial-deltaic sands of the onshore Odderup and Ribe Formations (Fig. 2, DGU 1975, Laursen 1995). Similar deposits were not encountered further south in the S-1 well, which yielded fine-grained distal deposits (Figs

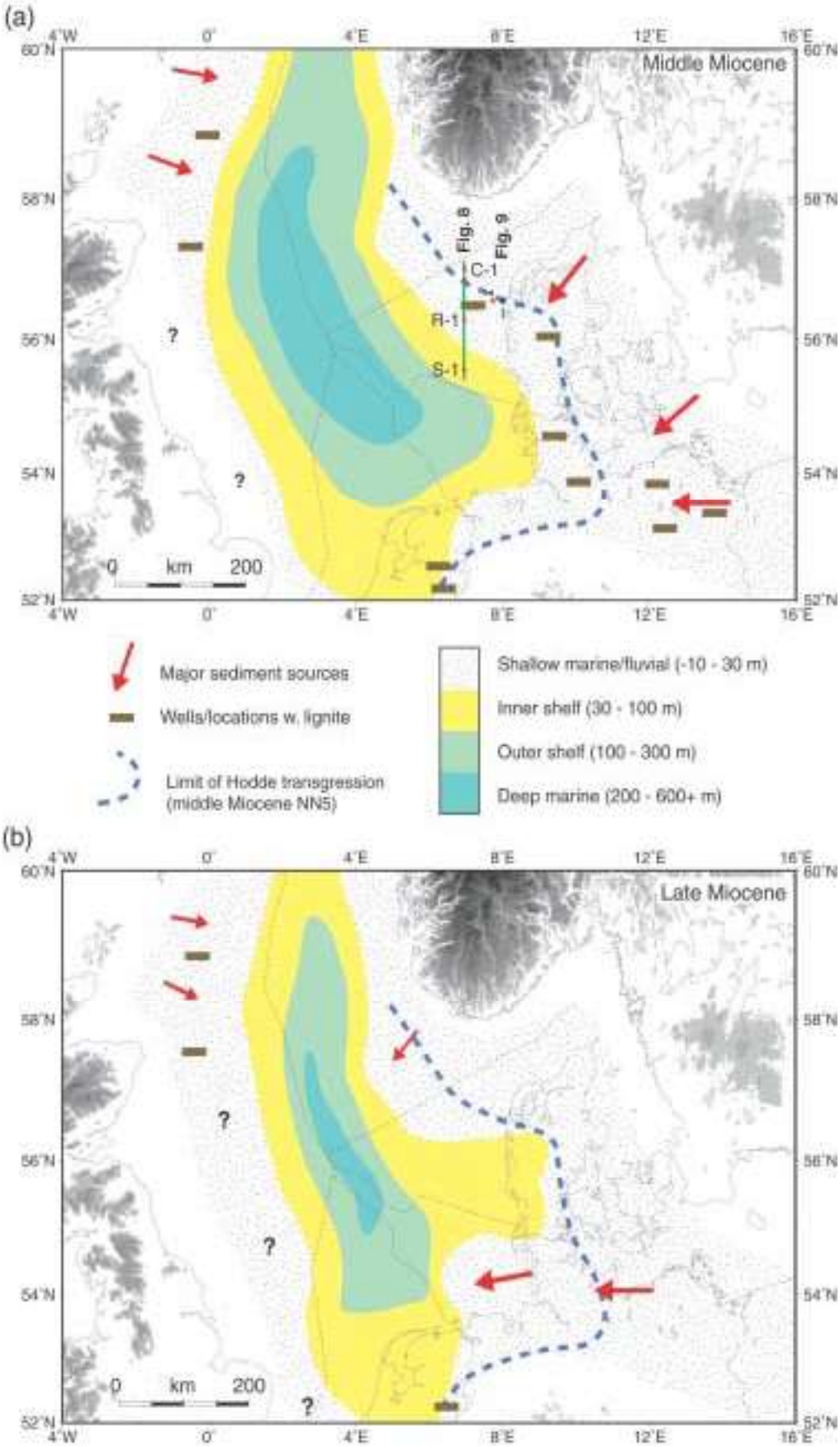

Fig. 10. (a) Early Middle Miocene palaeogeography of the North Sea basin. The map shows the situation at the maximum extent of the Odderup regression. The extent of the ensuing Hodde transgression in Denmark and northern Germany is indicated by a dashed line. Compiled from regional maps by Quitzow (1953), Kockel (1988) and Ziegler (1990), regional clay-mineralogy trends (Nielsen 1995, pers. comm. 1998), studies by Rasmussen (1961), Zagwijn & Hager (1987), Koch (1989), Nielsen & Nielsen (1995), Rasmussen (1996), Clausen et al. (1999), and own observations. Locations of key wells and seismic sections mentioned in the text are shown. (b) Late Miocene palaeogeography of the North Sea Basin. Note that progradation of a large delta in the German Bight fed by the Baltic River system (Bijlsma 1981) is coeval with marine conditions in SW-Denmark. The extent of the preceding Hodde transgression in Denmark and northern Germany is indicated by a dashed line. Compiled from regional maps by Quitzow (1953), Kockel (1988) and Ziegler (1990), regional clay-mineralogy trends (Nielsen 1995, pers. comm. 1998), studies by Rasmussen (1961), Bijlsma (1981), Zagwijn & Hager (1987), Jürgens (1996), Rasmussen (1996), Laursen et al. (1997), Clausen et al. (1999), and own observations.

8, 10a, DGU 1975). Sedimentary facies variations thus indicate that the early Middle Miocene shoreline reached a position between the R-1 and S-1 wells, as also indicated by seismic geometries.

Late Middle – Late Miocene

A middle Miocene marine transgression (the 'Hodde transgression') led to the termination of peat formation in most of the northwest European lowland as the extensive swamp areas were flooded. The transgression led to deposition of the fine-grained clays of the marine Hodde and Reinbek Formations on top of the former fluvial deltas in Denmark and northern Germany (Quitzow 1953, Rasmussen 1961, Gramann & Kockel 1988, Koch 1989).

In the Netherlands the transgression caused deposition of the lower part of the Neurath Sand Formation and peat formation was terminated. In the Lower Rhine Embayment peat formation continued into late Miocene-Pliocene time, resulting in one of the world's largest single occurrences of browncoal (Zagwijn & Hager 1987).

The Hodde transgression appears to correlate with the mid-Miocene unconformity, which is recognized as a marked downlap surface on seismic data from the southern North Sea, and as an onlap surface in the areas characterized by Oligocene to early Middle Miocene deltaic deposition to the northeast and east (Figs 6, 8, Huuse & Clausen 2001).

Marine conditions prevailed in Denmark after the Hodde transgression, leading to the deposition of the Gram Formation, a coarsening-upwards succession overlain by the uppermost Miocene/lowermost Pliocene Sæd Formation (Fig. 2, Rasmussen 1961, Buchardt-Larsen & Heilmann-Clausen 1988, Friis 1995). Detailed biostratigraphic correlation of the Hodde Formation in Denmark with the composite $\delta^{18}O$ record of Miller et al. (1987, 1998) indicates that the Hodde transgression occurred in response to a relatively minor eustatic rise approximately 1 Ma prior to the onset of long-term climatic cooling and eustatic fall (Huuse & Clausen 2001). Thus, the overall regressive character of the upper part of the Hodde Formation and of the ensuing Gram Formation (Kock 1989, Friis 1995) probably reflects deposition during long-term climatic cooling and eustatic fall (Fig. 2, Huuse & Clausen 2001).

While marine deposition prevailed in Denmark during the late Miocene, the Baltic River System (Bijlsma 1981) supplied huge amounts of sediment to the northern German area, leading to the formation of a large westward prograding delta (Fig. 10b). This

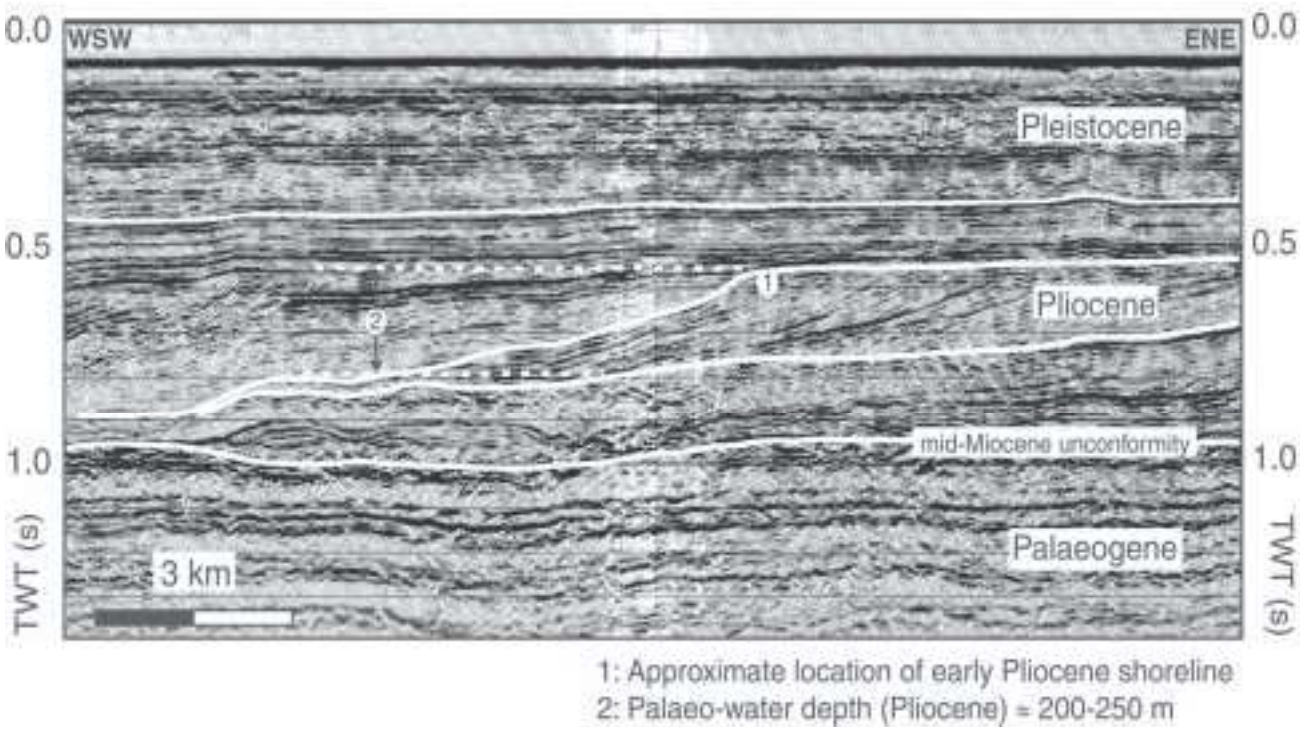

Fig. 11. Conventional seismic profile showing 150-250 m high westward prograding lower Pliocene clinoforms in the eastern part of the Dutch North Sea. These clinoforms are coeval with Pliocene clinoforms in the Danish Central Trough (cf. Figs. 6, 12a). For location see Figure 12a.

delta developed clinoforms up to 3-400 m high in the western part of the German North Sea sector during late Miocene time (Gramann & Kockel 1988: fig. 266, Kockel 1995, Jürgens 1996: fig. 3).

The height and the progressive southward progradation of the clinoforms indicate that relatively deep marine conditions prevailed in the Dutch and the western German North Sea during the Oligocene-Middle Miocene (Figs 7a, 7b, 10a). The previously sediment starved embayment was then filled by a large prograding delta during the late Miocene and Pliocene (cf. Figs 10b, 11, 12a, Kockel 1995). The height of the upper Miocene and Pliocene clinoforms (lower part of unit 7) thus seems to be an effect of a sudden abundant supply of sediment into a several hundred metres deep previously sediment-starved basin. Hence, there is little reason to invoke dramatic middle-late Miocene sea-level rises of several hundred metres to explain clinoform heights in the southern North Sea, especially since $\delta^{18}O$ records indicate that this was a time of relatively low global sea level (Fig. 2).

Plio–Pleistocene

After a long period of sediment starvation during the Miocene, the Dutch North Sea sector became the site of rapid progradation of deltaic sediments in the Pliocene to middle Pleistocene (Cameron et al. 1993a, Kockel 1995, Funnell 1996, Sørensen et al. 1997, Breiner 1999). These deposits are characterized by 150–250 m high clinoforms, decreasing in height towards the west (Fig. 11, Cameron et al. 1993a, Breiner 1999).

Further north, deltaic sediments from southern Norway were fed directly into the northern part of the Danish Central Trough (Laursen et al. 1997, Sørensen et al. 1997). The combination of two sediment sources led to an almost linear trend of westward prograding clinoforms during the Pliocene (Sørensen et al. 1997: fig. 12). The shoreline probably reached the eastern flank of the Central Trough (Fig. 12a).

Pliocene deposits are almost absent in the eastern Danish North Sea and onshore Denmark. Since progradational deposits are located further west, the eastern Danish North Sea probably constituted a transition zone of sediment bypass during much of the Pliocene (Fig. 12a, DGU 1975). A rather thin succession of shallow marine and fluvial sediments were deposited on top of the thick upper Miocene succession in northern Germany and in the German North Sea (Bijlsma 1981, Cameron et al. 1993a, Jürgens 1996).

In the northern North Sea, the Pliocene succession consists of thick wedges of progradational clinoforms, which represent a marked increase in the sediment supply from southern Norway and Scotland (Jordt et al. 1995, Gregersen et al. 1997). This increase in sediment supply is largely contemporaneous with the first major Northern Hemisphere glaciations (cf. Jansen & Sjøholm 1991, Jordt et al. 1995).

In the Middle Pleistocene deltaic sedimentation reached the UK part of the Central Trough, and the North Sea Basin was characterized by fluvial sedimentation as far north as 56°N (Fig. 12b, Cameron et al. 1993b, Funnell 1996).

Maximum thickness of the Early-Middle Pleistocene succession reaches more than 900 m in the central part of the Central Trough (Cameron et al. 1987, Zagwijn 1989). The lower progradational part of this thick succession probably reflects the last phase of infill of the increasingly narrow basin in the central North Sea (cf. Figs 12a, 12b). The upper aggradational part of the succession is draped over a much wider area, and reaches a thickness of 3–400 m on top of the late Miocene-middle Pleistocene deltas, which had previously filled all available accomodation (Fig. 11). The aggradational succession largely consists of fluvial to shallow marine sediments (Cameron et al. 1989b).

Since middle Pleistocene time the North Sea Basin has experienced at least three major glaciations causing the formation of vast ice sheets which repeatedly covered all or parts of the basin (e.g. Ehlers 1990). The advance and melting of the ice sheets caused the formation of deeply incised valleys in much of the North Sea Basin (Huuse & Lykke-Andersen 2000: fig. 4). During interglacials the globally rising sea level interacted with glacial rebound to produce numerous transgressions and regressions across the present-day lowland and shelf areas, leading to deposition of thin veneers of marine clays and sands (e.g. Cameron et al. 1989b, 1993b). The present-day North Sea Basin is generally characterized by water depths less than one hundred metres, and there is thus very little accommodation space left to be filled in the North Sea (cf. Huuse & Lykke-Andersen 2000: fig. 1).

Climatic *vs* tectonic forcing of basin margin uplift and deltaic progradation: discussion

Molnar & England (1990) argued that much of the evidence used to infer late Cenozoic tectonic uplift of mountain ranges around the world could be attributed to global climatic cooling. Such evidence includes

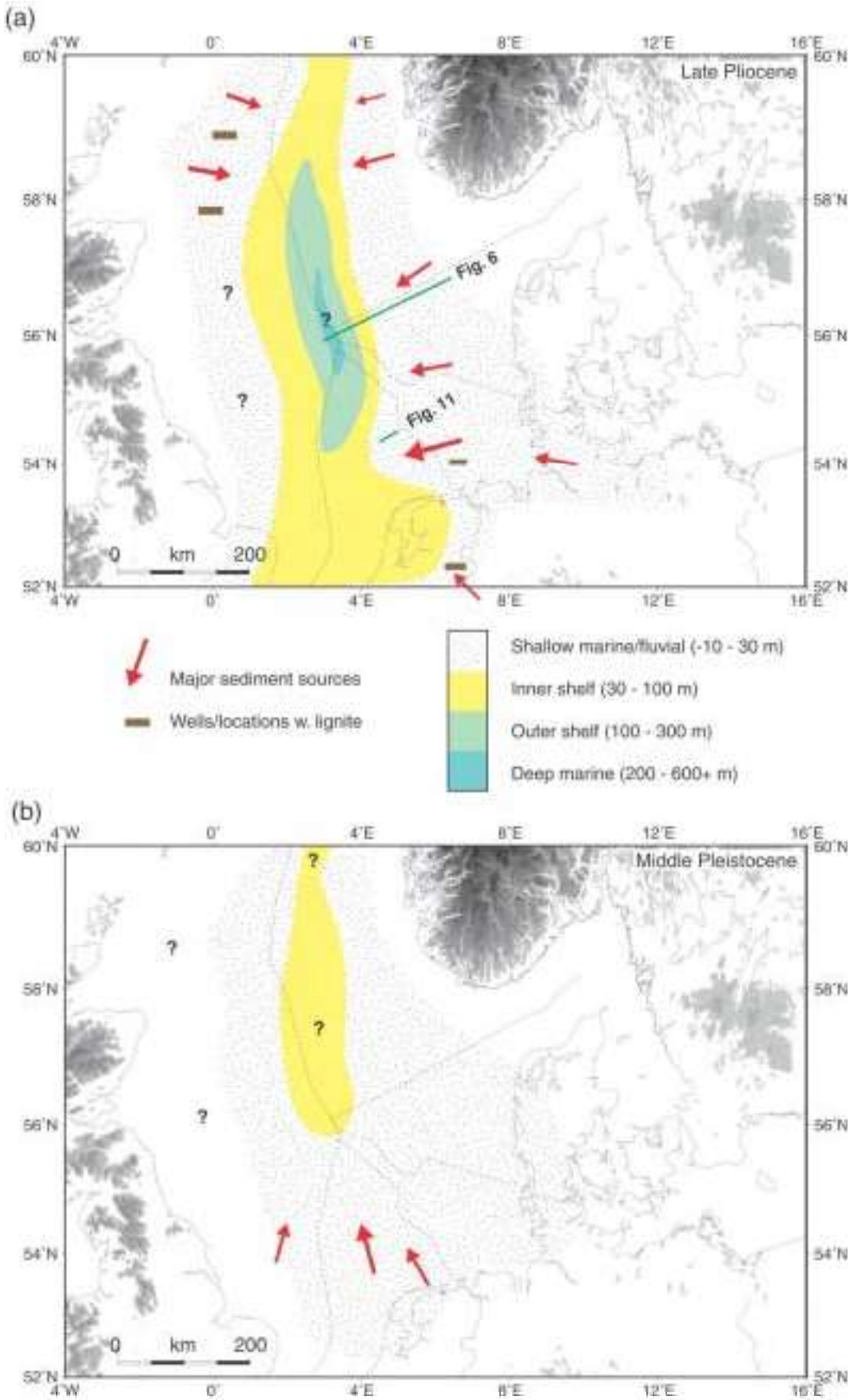

Fig. 12. (a) Late Pliocene palaeogeography of the North Sea Basin. Compiled from regional maps by Quitzow (1953), Kockel (1988) and Ziegler (1990), regional clay-mineralogy trends (Nielsen pers. comm. 1998), studies by Zagwijn & Doppert (1978), Bijlsma (1981), Gibbard (1988), Jordt et al. (1995), Funnell (1996), Jürgens (1996), Rasmussen (1996), Gregersen et al. (1997), Laursen et al. (1997), Sørensen et al. (1997), Breiner (1999), Clausen et al. (1999), and own observations. (b) Middle Pleistocene palaeogeography of the North Sea Basin. Compiled from studies by Zagwijn & Doppert (1978), Bijlsma (1981), Cameron et al. (1987), Gibbard (1988), Funnell (1996), Laursen et al. (1997), Breiner (1999).

deep incision and recent denudation of mountain ranges, abundant late Cenozoic coarse sediment adjacent to the mountain ranges, and palaeobotanical evidence for a warmer climate in mountainous areas now characterized by cold climate (Molnar & England 1990).

Oxygen-isotope data indicate that periods of rather abrupt climatic cooling occurred three times during the Cenozoic: at the Eocene/Oligocene transition, in the middle Miocene and in the Plio-Pleistocene (Fig. 2, Buchardt 1978, Miller et al. 1987, 1998, Molnar & England 1990).

While the effect of the Plio-Pleistocene climatic deterioration has been widely recognized, the effects of the earlier major episodes of climatic deterioration have largely been neglected or rendered of minor importance by North Sea researchers. Jordt et al. (1995) thus stated that tectonic events overprinted the effects of eustasy in the North Sea Cenozoic, even during the most marked episodes of climatic cooling and eustatic lowering at the Eocene/Oligocene transition and in the middle Miocene. Their view of an overall tectonic control on the Cenozoic development of the North Sea Basin is supported by Galloway et al. (1993) and Liu & Galloway (1997). A great number of tectonic mechanisms have been proposed, but the exact cause of the inferred tectonic uplift remains conjectural (Doré 1992, Jensen & Schmidt 1993, Stuevold & Eldholm 1996, Jensen & Doré 1998, Japsen & Chalmers 2000). Hence, the objective of the following section is to discuss the possibility of an overall climatic and eustatic control on the late Cenozoic evolution of the North Sea Basin, i.e. whether late Cenozoic tectonic uplift of source areas is required in order to explain the development of the North Sea Basin.

Early Palaeogene tectonic uplift

Late Cretaceous-Danian basin inversion caused significant uplift of the Sorgenfrei-Tornquist Zone bordering the North Sea Basin to the east-northeast (Liboriussen et al. 1987). Late Paleocene-early Eocene magmatic activity related to the opening of the North Atlantic caused uplift of the land surface in Norway and Scotland (Toske 1972, Ziegler 1990, Doré 1992, Riis & Fjeldskaar 1992, Jensen & Schmidt 1993). Palaeogene uplift of source areas thus occurred in at least two separate regions: along the Sorgenfrei-Tornquist Zone and along the Atlantic margin of northwest Europe. The exact magnitude of uplift is, however, uncertain (e.g. Riis & Fjeldskaar 1992, Lidmar-Bergström et al. 2000).

Sediment supply and climate

The occurrence of upper Paleocene and Eocene deltaic wedges southwest of Norway (units 1–3, Fig. 3, Jordt et al. 1995, Michelsen et al. 1998) indicates that southern Norway experienced substantial erosion in the early-middle Palaeogene. The substantially greater thickness of the Oligocene (unit 4, Fig. 3) and Neogene depocentres (units 5–7) indicates that sediment supply to the basin increased dramatically at the Eocene/Oligocene transition and in the post-Middle Miocene (cf. Fig. 3). Such abrupt increases in sediment supply may be produced by either of three factors: tectonic uplift of the hinterland, by climatic deterioration, or by a eustatic fall (Galloway 1989, England & Molnar 1990, Molnar & England 1990, Schumm 1993).

Oxygen-isotope records have become a widely used proxy for gauging glacioeustatic and climatic changes (e.g. Miller et al. 1987, 1998). Sequence boundaries on the New Jersey Sea Level Transect have been correlated with $\delta^{18}O$ increases, leading to the inference that ice-volume changes has been the primary control on the formation of sequence boundaries since middle Eocene time (c. 42 Ma, Miller et al. 1998). The increase in sediment supply at the Eocene/Oligocene transition is coeval with a period of rapid climatic cooling and eustatic fall indicated by $\delta^{18}O$ records (Fig. 2). A contemporaneous increase in the sediment supply to many continental shelves at terminal Eocene time, termed the 'siliciclastic switch', has been attributed to global climatic cooling (Molnar & England 1990, Miller et al. 1998, Séranne 1999, Steckler et al. 1999). Great care should obviously be taken when correlating a given stratigraphic record with global climatic and eustatic events (cf. Miall 1992). However, the correlations presented here are of first-order events, and are based on detailed biostratigraphic correlations with oxygen-isotope curves (Huuse & Clausen 2001).

The large supply of sediments of Scandinavian provenance in the early Neogene (units 5 and 6, Fig. 3) and the increase in sediment supply in post-Middle Miocene time (unit 7, Fig. 3, Jordt et al. 1995, Michelsen et al. 1995, 1998) shows that southern Fennoscandia was exposed to weathering and erosion throughout the middle and late Cenozoic. The marked increase in sediment supply in post-Middle Miocene time coincides with a period of global climatic cooling and eustatic fall (Fig. 2, cf. Buchardt 1978, Molnar & England 1990, Jordt et al. 1995, Miller et al. 1998, Huuse & Clausen 2001).

The clinoform development in the upper Miocene to lower Pleistocene of the southern North Sea and in the Pliocene of the northern North Sea is remarkably

similar to the general stratigraphic architecture of the Neogene along many of the world's continental shelves (cf. Bartek et al. 1991: fig. 2 and Cameron et al. 1993a: fig. 2). This stratigraphic pattern has been attributed to glacioeustasy (Bartek et al. 1991) and global climatic cooling (Donnelly 1982, Molnar & England 1990). Glacioeustasy and climate are, of course, inter-related phenomena, and they should leave as clear a signature in the North Sea as in other shelf settings, unless special factors (e.g. tectonics) were at play. The similarity between North Sea depositional geometries and the generalized 'global Neogene stratigraphic signature' of Bartek et al. (1991) could imply that tectonics were of relatively minor importance in the creation of the North Sea stratigraphic signature.

The 'self-perpetuating' passive model

In the 'self-perpetuating' passive model, regional isostatic uplift is driven by erosional unloading of a relief caused by early Palaeogene tectonic uplift (Toske 1972, Doré 1992). The main appeal of the passive model is its simplicity and the conjectural nature of the tectonic mechanisms invoked to explain late Cenozoic uplift. In practice, the sedimentation/erosion effects produced by climatic and eustatic changes may often be indistinguishable from those induced by tectonic events (cf. Molnar & England 1990, Schumm 1993). Thus, as argued above, variations in the intensity of the late Cenozoic erosion, previously ascribed to tectonic uplift, could also be caused by long-term changes in climate and eustasy. The changes to consider here are the major cooling events at terminal Eocene and middle Miocene time, the Plio-Pleistocene glaciations, and the long-term eustatic fall of c. 200 m since the middle Eocene (cf. Miller et al. 1998). While regional climatic changes may cause accelerated erosion of an existing relief, such changes may not be capable of sustaining erosional unloading over a period of 50 Myr, since at some point erosion will have lowered the relief to an equilibrium level. However, new relief was made available by the overall eustatic lowering since the middle Eocene, thus providing a lowering of erosional base level of c. 200 m.

Arguments against the 'self-perpetuating' passive model

The 'self-perpetuating' passive model was originally proposed and partly rejected by Doré (1992), who, among others, concluded that an additional tectonic uplift component was required to explain the present elevation of southern Norway. Several arguments have been made against the passive model. The most important arguments against the model are analysed in the following four paragraphs:

1. Late Cenozoic uplift appears separated in time from the early Cenozoic rift-related uplift, and the sediment supply to the basin areas surrounding Norway appears to have been episodic, suggesting discrete periods of uplift (Doré 1992, Stuevold & Eldholm 1996).

These arguments are mainly based on the mapping and dating of the erosional products in the basin. The map of Cenozoic depocentres (Fig. 3, Michelsen et al. 1998) shows that sediments have been supplied from southern Norway more or less continuously since the Late Paleocene, with a marked increase at the Eocene/Oligocene transition. It thus appears that the land surface of southern Norway was elevated sufficiently to enable the generation of substantial amounts of clastic sediments throughout the Palaeogene.

Variations in the rate of sediment supply may be related to climate and eustasy as well as tectonics (e.g. Schumm 1993). Such variations are thus not diagnostic of uplift. The three-dimensional variability of the deltaic outbuilding indicated by the migration of depocentres shown in Fig. 3 may further contribute to an episodic appearance of the sedimentation. For example, the first occurrence of sandy deposits onshore Denmark has been used to date the uplift as being mainly Neogene (Spjeldnæs 1975, Jensen & Schmidt 1993). The post-Middle Miocene increase in sedimentation rate in the central North Sea has also been used as evidence of uplift (Jordt et al. 1995, Riis 1996). The occurrence of an almost 1000 m thick Oligocene wedge of deltaic sediments south of Norway (unit 4, Figs 3, 6) led Michelsen et al. (1995, 1998) to suggest that uplift of southern Norway commenced in the late Eocene/early Oligocene. A late Palaeogene onset of uplift was supported by Clausen et al. (2000), based on similar considerations and on clay mineralogy data, indicating that reworking of early Palaeogene sediments occurred from the late Palaeogene onwards. Hence, the timing estimated by a particular study may be biased by the age of the first proximal sediments in the study area, thus introducing apparently abrupt variations in the rate of sediment supply. Moreover, even if the sediment supply really was episodic, this could be an effect of changes in climate and eustasy as well as tectonics.

2. Rift-related uplift cannot explain the uplift observed south of Norway and in the Danish area (e.g. Doré 1992, Riis 1996)

When discussing the lateral extent of uplift in Scan-

dinavia it is important to distinguish between (a) rift-related uplift along the Norwegian margin, and (b) uplift due to inversion of the Sorgenfrei-Tornquist Zone in southern Sweden, Denmark and in Skagerrak. If the effect of inversion is not taken into account, it does appear as if the pattern of uplift and erosion cannot be explained by rift-related uplift (cf. Riis 1996: fig. 15).

However, recent results of numerical basin modelling (Hansen et al. 2000, Gemmer et al. 2002, Nielsen 2002) indicate that the pattern of uplift and erosion ('burial anomaly') of the Danish area, inferred from studies of shale and chalk compaction (cf. Jensen & Schmidt 1992, 1993, Japsen 1998), can be accounted for by inversion of the Sorgenfrei-Tornquist Zone in the late Cretaceous-Paleocene combined with a long term eustatic lowering of 200–250 m since the mid-Cretaceous. The modelling results indicate that uplift resulting from inversion and eustatic lowering is concentrated in a rather narrow zone along the inverted area, and thus fail to reproduce the regional uplift (and erosion), which has been estimated based on compaction methods.

The modelling results thus suggest: 1) that additional tectonic uplift (not modelled) has taken place over a wide area, or 2) that compaction methods have overestimated the amount of uplift by several hundred metres (Nielsen 2002).

Additional information may be gathered from depositional geometries observed on high-resolution multichannel seismic data (Fig. 8). Neogene differential uplift and erosion from north to south along the profile in Fig. 8 has been estimated at c. 650 m based on chalk compaction (Japsen 1998) and c. 1000 m based on shale compaction trends and vitrinite reflectance of Jurassic shales (Jensen & Michelsen 1992, Jensen & Schmidt 1992, 1993). A recent study integrating chalk compaction and basin modelling (Japsen & Bidstrup 1999) yielded values slightly lower than those of Japsen (1998). The c. 600-m thick Oligocene succession (unit 4) is complete at the location of the Inez-1 well (Fig. 8). The lower Miocene deposits (unit 5) onlap the Oligocene deltaic wedge (unit 4) to the north and prograde towards the south. The middle and upper Miocene strata (lower part of unit 7) onlap the mid-Miocene unconformity. Pliocene deposits are virtually absent due to sedimentary bypass (cf. Fig. 12a), and c. 300 m of lower-middle Pleistocene deposits are present to the south (Fig. 8).

Consequently, there are two scenarios possible for producing an apparent differential uplift and erosion (i.e. burial anomaly) of 500–1000 m along this profile. (a) A 1100–1600 m thick wedge of Paleocene-Eocene sediments was deposited to the north and subsequently removed prior to the Oligocene, or (b) 500–1000 m of Neogene sediments were deposited on top of the Oligocene deltaic sequence and subsequently removed during the Plio-Pleistocene. (a) The condensed character of the upper Paleocene and Eocene succession indicates that a sediment-starved environment prevailed during this period. This is incompatible with the massive sedimentation rates required by the first scenario. (b) The second scenario would require that more than 500 m of middle and upper Miocene sediments had been deposited in a location where the available accommodation had previously been filled during the Oligocene and early Miocene. This is incompatible with seismic geometries (Fig. 8) and with the palaeogeographic reconstructions (cf. Figs 10a, 10b, 12a), which indicate that sedimentation shifted towards the south, with sediments accumulating basinward of the Oligocene depocentre (and not on top of it).

Seismic geometries, palaeogeographic reconstructions and basin modelling thus indicate that studies based on shale- and chalk compaction trends may have overestimated the uplift of the northeastern Danish North Sea by several hundred metres.

3. Late Early Eocene marine diatoms have been found at present elevations of c. 200 m in Swedish and Finnish Lapland (Tynni 1982, Fenner 1988).

The occurrence of lower Eocene marine deposits at present elevations of c. 200 m in Lapland is probably the best indication that the surface of Fennoscandia has moved upwards with respect to sea level since early Eocene time. It should be borne in mind, however, that global sea level has fallen by c. 200 m since the middle Eocene (cf. Haq et al. 1987, Miller et al. 1998). Moreover, erosional unloading of an adjacent highland may cause the land surface of adjacent non-eroded areas to be uplifted due to regional isostatic compensation (cf. Molnar & England 1990). The latter effect may also apply to the seaward dipping wedges off the Norwegian coast.

4. Modelling studies require a tectonic component in order to reproduce the observed elevation of the land surface (Riis & Fjeldskaar 1992, Stuevold & Eldholm 1996).

Modelling studies, which have failed to reproduce the pattern of Cenozoic uplift without invoking late Cenozoic tectonic events, have neglected the effects of eustatic changes (e.g. Stuevold & Eldholm 1996). Furthermore, these studies are critically dependent on assumptions regarding the initial elevation (due to rift-related uplift) of the Fennoscandian landmass (Riis & Fjeldskaar 1992, Stuevold & Eldholm 1996). The post-Middle Eocene long-term lowering in sea level has been estimated at 150–200 m (Miller et al.

1998), or even 200–250 m (Haq et al. 1987). The effect of neglecting a long-term eustatic lowering of 200 m in basin modelling is similar to introducing mean surface uplift of the same magnitude. A late Cenozoic surface uplift of similar magnitude to the long-term eustatic fall was modelled by Riis & Fjeldskaar (1992), who suggested that phase transitions in the upper mantle could be responsible for such an event. All in all it appears that the modelled late Cenozoic 'tectonic uplift' may be an effect of the late Cenozoic eustatic lowering, i.e. that there is no need to invoke tectonic mechanisms in order to explain the observed uplift.

Uplift due to erosional unloading: simple calculations

When calculating the isostatic effect of erosional unloading it is the effect onto the mean elevation of a given region, which is relevant (England & Molnar 1990). The effect of erosion of a layer of a given height depends on the density of the eroded material and the density of the mantle (Molnar & England 1990, Stuevold & Eldholm 1996).

The distinction between uplift of rocks and uplift of the Earth's surface with respect to the geoid (or sea level) is important as uplift of rocks may be entirely due to erosional unloading of the lithosphere, whereas regional uplift of the Earth's surface requires a tectonic driving mechanism of substantial force (England & Molnar 1990). In addition, if calculations are referred to sea level then eustatic variations need to be accounted for.

The density of the mantle may be considered relatively uniform ($\rho_m \approx 3.3$ kg/m^3), but the density of the eroded material may be more variable depending on whether sediments ($\rho_c \approx 2.4$ kg/m^3) or crystalline rock ($\rho_c \approx 2.75$ kg/m^3) is removed. If the removal of a layer of the Earth's crust of thickness h and density ρ_c is compensated isostatically by a crustal root in a mantle of density ρ_m the erosion would cause a lowering of the mean surface elevation of $\Delta H = h(\rho_m - \rho_c)/\rho_m \approx h/6$ to $h/4$ depending on the density of the removed material (cf. Molnar & England 1990: fig. 2).

If a rock layer of average thickness h≈1 km has been removed from Fennoscandia due to Cenozoic uplift and erosion (cf. Riis & Fjeldskaar 1992: fig. 13), it follows that the mean surface would be lowered by ΔH=170–250 m. This value is comparable with the long-term eustatic lowering during the Cenozoic (c. 200 m). Hence, it appears that surface lowering due to erosion could have been balanced by the relative uplift caused by long-term eustatic lowering, i.e. that the mean surface elevation of Scandinavia has remained at roughly the same level since early Palaeogene uplift. This is compatible with estimates of the early Palaeogene uplift of c. 1000 m (cf. Lidmar-Bergström et al. 2000).

Climatic *vs* tectonic forcing: future directions

Obviously, quantitative basin models are needed to test whether a passive model merely involving early Palaeogene rift-related uplift followed by erosional unloading due to climatic cooling and eustatic lowering through the middle-late Cenozoic is in fact feasible. An ideal test would be to perform mass-balanced palaeogeographic reconstructions of the entire basin and surrounding source areas. Such a study was carried out for the Cenozoic in the northwestern Gulf of Mexico and its western-central North American source area (Hay et al. 1989). The situation in the North Sea is probably more complex due to several potential source regions, but it seems like such a study is required to quantify the relative contributions of climate, eustasy and tectonics on the Cenozoic evolution of the North Sea Basin and surrounding areas.

Conclusion

The late Cenozoic development of the eastern North Sea Basin has been described in a series of generalized palaeogeographic maps, illustrating the basin configuration at late Eocene, late Oligocene, middle Miocene, late Miocene, late Pliocene, and at middle Pleistocene time.

From the Oligocene onwards, the eastern North Sea Basin was progressively filled by sediments supplied by ancient rivers which fed large deltas along the eastern basin margin. These vast deltas prograded towards the basin centre from southern Norway (late Paleocene-Oligocene and Pliocene), southern Norway and Sweden (early Miocene), the Baltic region (middle Miocene to early Pleistocene), and finally from the Rhine area (early and middle Pleistocene).

The sediments first filled the available accommodation adjacent to the basin margins, before filling in the deep basin which had developed in the Central Trough area. The post-Middle Miocene increase in the rate of sediment supply to the previously sediment starved central parts of the basin probably resulted in rapid load-induced subsidence. It is uncertain whether an additional tectonic subsidence component is needed to explain the rapid post-Middle Miocene subsidence of the central North Sea.

Periods of rapid deltaic progradation in the early Oligocene and in the post-Middle Miocene seem to correlate with periods of global climatic cooling and eustatic lowering, and are contemporaneous with increases in sediment supply to continental shelves world wide.

It is suggested that basin-centred (thermal and load-induced) subsidence and post-rift isostatic uplift of Fennoscandia (due to erosional unloading), interacted with episodes of climatic cooling and long-term eustatic lowering to produce the Cenozoic sedimentary record of the North Sea Basin. The main requirement for such a model is that the early Palaeogene mean surface elevation of the source areas (after inversion and rift-related uplift) was comparable to today's mean elevation. It is concluded that while the possibility of Neogene tectonic uplift and subsidence events in the North Sea region cannot be excluded, such events may not be needed in order to explain the observed (or inferred) patterns of erosion and deposition.

The previously inferred Neogene uplift and erosion of 500–1000 m in the northeastern Danish North Sea is not compatible with seismic geometries nor with the palaeogeographic development described here. This could indicate that previous estimates of Neogene uplift and erosion of the Danish area outside the Sorgenfrei-Tornquist Zone are several hundred metres too high.

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Dansk sammendrag

Den sen-eocæne til mellem pleistocæne udvikling af det østlige Nordsø-bassin er beskrevet ved en serie palæogeografiske kort. Kortlægningen er baseret på publicerede data integreret med undersøgelser af et stort antal højopløselige og konventionelle seismiske profiler samt brønddata fra den østlige Nordsø. Kortene viser geometrien af Nordsø-bassinet i sen Eocæn, sen Oligocæn, mellem Miocæn, sen Miocæn, sen Pliocæn og mellem Pleistocæn tid. I post-Eocæn tid blev det østlige og centrale Nordø-bassin gradvist udfyldt af pro-deltaiske og deltaiske aflejringer, som primært blev tilført fra den østlige bassin-margin. Deltaerne blev forsynet af floder, der løb ud i bassinet fra det sydlige Norge (sen Paleocæn-Oligocæn og Pliocæn), sydlige Norge og Sverige (tidlig Miocæn), det Baltiske område (sen Miocæn-tidlig Pliocæn) og Holland (mellem Pleistocæn).

Der argumenteres for at den sen-kænozoiske udvikling af det østlige Nordsø-bassin kan forklares ved en passiv model, der involverer isostatisk opløft af kildeområder på grund af gradvis erosion af et relief skabt ved tektonisk opløft i tidlig Palæogen. Erosionsintensiteten accelererede ved Eocæn/Oligocæn-overgangen, i mellem Miocæn og i Plio-Pleistocæn, svarende til perioder med global klimatisk afkøling og faldende globalt havniveau, som indikeret af iltisotop ($\delta^{18}O$) målinger. Den passive model behøver ikke neogene tektoniske begivenheder for at forklare udviklingen af Nordsø-bassinet, men sådanne begivenheder kan på den anden side heller ikke udelukkes.

Tidligere estimater af neogen opløft og erosion af den nordsøstlige danske Nordsø er i størrelsesordenen 500–1000 m. Disse estimater kan vanskeligt forenes med seismiske geometrier eller med den regionale palæogeografiske udvikling. Dette indikerer at tidligere estimater af den neogene opløft og erosion af den nordøstlige danske Nordsø kan være flere hundrede meter for høje.

References

Abreu, V.S. & Anderson, J.B. 1998: Glacial eustasy during the Cenozoic: sequence stratigraphic implications. American Association of Petroleum Geologists Bulletin 82, 1385–1400.

Bartek, L.R., Vail, P.R., Anderson, J.B., Emmet, P.A. & Wu, S. 1991: Effect of Cenozoic ice sheet fluctuations in Antarctica on the stratigraphic signature of the Neogene. Journal of Geophysical Research 96 B4, 6753–6778.

Bidstrup, T. 1995: Seismic sequence stratigraphy of the Tertiary in the Danish North Sea; incl. 7 structural maps of the main sequences, and 35 isochore maps of main sequences and smaller units. EFP-92 project: Basin development of the Tertiary of the Central Trough with emphasis on possible hydrocarbon reservoirs 5. 25 pp. Danish Energy Agency.

Bijlsma, S. 1981: Fluvial sedimentation from the Fennoscandian area into the north-west European Basin during the Late Cenozoic. Geologie en Mijnbouw 60, 337–345.

Bowman, M.B.J. 1998: Cenozoic. In Glennie, K.W. (ed.) Petroleum Geology of the North Sea, 350–375. Oxford: Blackwell Science.

Breiner, M. 1999: A sequence stratigraphic study of the Dutch

offshore sector blocks E, F, G, K, L and M of Neogene and younger sediments I, II. 93 pp., 103 pp. M.Sc.-thesis, University of Aarhus, Denmark.
Browning, J.V., Miller, K.G. & Pak, D.K. 1996: Global implications of lower to middle Eocene sequence boundaries on the New Jersey coastal plain: The icehouse cometh. Geology 24, 639–642.
Buchardt, B. 1978: Oxygen isotope palaeotemperatures from the Tertiary period in the North Sea area. Nature 275, 121–123.
Buchardt-Larsen, B. & Heilmann-Clausen, C. 1988: The Danish Subbasin, Southern Jutland. In Vinken, R. (ed.) The Northwest European Tertiary Basin. Geologisches Jahrbuch A 100, 83–90.
Cameron, T.D.J., Bulat, J. & Mesdag, C. S. 1993a: High resolution seismic profile through a Late Cenozoic delta complex in the southern North Sea. Marine and Petroleum Geology 10, 591–599.
Cameron, D., van Doorn, D., Laban, C. & Streif, H.J. 1993b: Geology of the Southern North Sea Basin. In Hillen, R. & Verhagen, H. J. (eds) Coastlines of the southern North Sea, 14–26. New York: American Society of Civil Engineers.
Cameron, T.D.J., Laban, C. & Schüttenhelm, R.T.E. 1989a: Upper Pliocene and Lower Pleistocene stratigraphy in the Southern Bight of the North Sea. In Henriet, J. P. & de Moor, G. (eds) The Quaternary and Tertiary Geology of the Southern Bight, North Sea, 97–110. University of Ghent, The Netherlands.
Cameron, T.D.J., Schüttenhelm, R.T.E. & Laban, C. 1989b: Middle and Upper Pleistocene and Holocene stratigraphy in the southern North Sea between 52° and 54°N, 2° to 4°E. In Henriet, J.P. & de Moor, G. (eds) The Quaternary and Tertiary Geology of the Southern Bight, North Sea, 119–135. University of Ghent, The Netherlands.
Cameron, T.D.J., Stoker, M.S. & Long, D. 1987: The history of Quaternary sedimentation in the UK sector of the North Sea Basin. Journal of the Geological Society, London 144, 43–58.
Clausen, O.R., Gregersen, U., Michelsen, O. & Sørensen, J.C. 1999: Factors controlling the Cenozoic sequence development in the eastern parts of the North Sea. Journal of the Geological Society, London 156, 809–816.
Clausen, O.R. & Huuse, M. 1999: Topography of the Top Chalk surface, on- and offshore Denmark. Marine and Petroleum Geology 16, 677–691.
Clausen, O.R. & Huuse, M. 2002: Mid-Paleocene palaeogeography of the Danish area. Bulletin of the Geological Society of Denmark 49, 171–186 (this volume).
Clausen, O.R., Nielsen, O.B., Huuse, M. & Michelsen, O. 2000: Geological indications for Palaeogene uplift in the eastern North Sea Basin. Global and Planetary Change 24, 175–187.
Cloetingh, S., Gradstein, F.M., Kooi, H., Grant, A.C. & Kaminski, M. 1990: Plate reorganization: a cause of rapid late Neogene subsidence and sedimentation around the North Atlantic? Journal of the Geological Society, London 147, 495–506.
Cloetingh, S., Reemst, P., Kooi, H. & Fanavoll, S. 1992: Intraplate stresses and the post-Cretaceous uplift and subsidence in northern Atlantic basins. Norsk Geologisk Tidsskrift 72, 229–235.
Collinson, M.E., Fowler, K. & Boulter, M.C. 1981: Floristic changes indicate a cooling climate in the Eocene of southern England. Nature 291, 315–317.
Danielsen, M. 1997: Sequence stratigraphy of uppermost Oligocene to Lower Miocene deposits within the Danish North Sea Basin, 49 pp. In Danielsen, M. 1997: Sequence stratigraphic interpretation of Danish Cenozoic deposits with special emphasis on log- and lithology interpretations. Ph.D.-thesis, University of Aarhus, Denmark.
Danielsen, M., Michelsen, O. & Clausen, O.R. 1997: Oligocene sequence stratigraphy and basin development in the Danish North Sea sector based on log interpretations. Marine and Petroleum Geology 14, 931–950.
DGU 1975: Dansk Nordsø S-1x, Lithologisk og biostratigrafisk rapport. Geological Survey of Denmark, 4 pp., 8 enclosures.
Donnelly, T. 1982: Worldwide continental denudation and climatic deterioration during the late Tertiary: Evidence from deep-sea sediments. Geology 10, 451–454.
Doré, A.G. 1992: The Base Tertiary Surface of southern Norway and the northern North Sea. Norsk Geologisk Tidsskrift 72, 259–265.
Driscoll, N.W. & Karner, G.D. 1999: Three-dimensional quantitative modelling of clinoform development. Marine Geology 154, 383–398.
Ehlers, J. 1990: Reconstructing the dynamics of the north-west European Pleistocene ice sheets. Quaternary Science Reviews 9, 71–83.
Eidvin, T., Riis, F. & Rundberg, Y. 1999: Upper Cainozoic stratigraphy in the central North Sea (Ekofisk and Sleipner fields). Norsk Geologisk Tidsskrift 79, 97–128.
Einsele, G. 1992. Sedimentary Basins. 628 pp. Heidelberg: Springer-Verlag.
Emery, D. & Myers, K.J. 1996: Sequence Stratigraphy. 297 pp. Oxford: Blackwell Science.
England, P. & Molnar, P. 1990: Surface uplift, uplift of rocks, and exhumation of rocks. Geology 18, 1173–1177.
Fenner, J. 1988: Occurrences of pre-Quaternary diatoms in Scandinavia reconsidered. Meyniana 40, 133–141.
Friis, H. 1995: Neogene aflejringer. In Nielsen, O.B. (ed.) Danmarks geologi fra Kridt til i dag. Aarhus Geokompendier 1, 115–127.
Friis, H., Mikkelsen, J. & Sandersen, P. 1998: Depositional environment of the Vejle Fjord Formation of the Upper Oligocene-Lower Miocene of Denmark: a barrier island/barrier-protected depositional complex. Sedimentary Geology 117, 221–244.
Funnell, B.M. 1996: Plio-Pleistocene palaeogeography of the southern North Sea Basin (3.75–0.60 Ma). Quaternary Science Reviews 15, 391–405.
Galloway, W.E. 1989: Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded units. American Association of Petroleum Geologists Bulletin 73, 125–142.
Galloway, W.E., Garber, J.L., Liu, X. & Sloan, B.J. 1993: Sequence stratigraphic and depositional framework of the Cenozoic fill, Central and Northern North Sea Basin. In Parker, J.R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, 33–43, London: Geological Society.
Gemmer, L., Nielsen, S.B. & Lykke-Andersen, H. 2002: Differential vertical movements in the eastern North Sea area from 3-D thermo-mechanical finite elemental modelling. Bulletin of the Geological Society of Denmark 49, 119–128 (this volume).
Gibbard, P.L. 1988: The history of the great northwest European rivers during the past three million years. Philosophi-

cal Transactions of the Royal Society of London B318, 559–602.
Gramann, F. & Kockel, F. 1988: Palaeogeographical, lithological, palaeoecological and palaeoclimatic development of the Northwest European Tertiary Basin. In Vinken, R. (ed.) The Northwest European Tertiary Basin. Geologisches Jahrbuch A 100, 428–441.
Gregersen, U., Sørensen, J.C. & Michelsen, O. 1997: Stratigraphy and facies distribution of the Utsira Formation and the Pliocene sequences in the northern North Sea. Marine and Petroleum Geology 14, 893–914.
Gripp, K. 1964: Erdgeschichte von Schleswig-Holstein. 411 pp. Neumünster: Karl Wachholtz Verlag.
Hansen, D.L., Nielsen, S.B. & Lykke-Andersen, H. 2000:The post-Triassic evolution of the Sorgenfrei-Tornquist Zone-Results from thermo-mechanical modeling. Tectonophysics 328, 245–267.
Haq, B.U., Hardenbol, J. & Vail, P. 1987: Chronology of fluctuating sea levels since the Triassic. Science 235, 1156–1167.
Hay, W.W., Shaw, C.A. & Wold, C.N. 1989: Mass-balanced paleogeographic reconstructions. Geologische Rundschau 78, 207–242.
Heilmann-Clausen, C. 1995: Palæogene aflejringer. In Nielsen, O.B. (ed.) Danmarks geologi fra Kridt til i dag. Aarhus Geokompendier 1, 69–114.
Heilmann-Clausen, C., Nielsen,O.B. & Gersner, F. 1985: Lithostratigraphy and depositional environments in the Upper Paleocene and Eocene of Denmark. Bulletin of the Geological Society of Denmark 33, 287–323.
Hinsch, W. & Ortlam, D. 1974: Stand und Probleme der Gliederung des Tertiärs in Nordwestdeutschland. Geologisches Jahrbuch A16, 3–25.
Huuse, M. & Clausen, O.R. 2001: Morphology and origin of major Cenozoic sequence boundaries in the eastern Danish North Sea: top Eocene, near top Oligocene and the mid-Miocene unconformity. Basin Research 13(1), 17–41.
Huuse, M. & Lykke-Andersen, H. 2000: Overdeepened Quaternary valleys in the eastern Danish North Sea: morphology and origin. Quaternary Science Reviews 19, 1233–1253.
Jansen, E. & Sjøholm, J. 1991: Reconstruction of glaciation over the past 6 Myr from ice-borne deposits in the Norwegian Sea. Nature 349, 600–603.
Japsen, P. 1998: Regional Velocity-Depth Anomalies, North Sea Chalk: A Record of Overpressure and Neogene Uplift and Erosion. American Association of Petroleum Geologists Bulletin 82, 2031–2074.
Japsen, P. & Bidstrup, T. 1999: Quantification of late Cenozoic erosion in Denmark based on sonic data and basin modelling. Bulletin of the Geological Society of Denmark 46, 79–99.
Japsen, P. & Chalmers, J.A. 2000. Neogene uplift and tectonics around the North Atlantic: Overview. Global and Planetary Change 24, 165–173.
Jensen, L.N. & Doré, T. 1998: Cenozoic uplift in the North Atlantic area: magnitude, timing and mechanisms. In Boldreel, L. & Japsen, P. (eds) Neogene uplift and tectonics around the North Atlantic. International workshop at the Geological Survey of Denmark and Greenland, Copenhagen. Abstract Volume, 75–76.
Jensen, L.N. & Michelsen, O. 1992: Tertiær hævning og erosion i Skagerrak, Nordjylland og Kattegat. Dansk Geologisk Forening, Årsskrift for 1990–1991, 159–168.
Jensen, L.N. & Schmidt, B.J. 1992: Late Tertiary uplift and erosion in the Skagerrak area: magnitude and consequences. Norsk Geologisk Tidsskrift 72, 275–279.
Jensen, L.N. & Schmidt, B.J. 1993: Neogene uplift and erosion offshore south Norway: magnitude and consequences for hydrocarbon exploration in the Farsund Basin. In Spencer, A. M. (ed.) Generation, Accumulation and Production of Europe's hydrocarbons III. European Association of Petroleum Geoscientists Special Publication 3, 79–88.
Jordt, H., Faleide, J.I., Bjørlykke, K. & Ibrahim, M.T. 1995: Cenozoic sequence stratigraphy of the central and northern North Sea Basin: tectonic development, sediment distribution and provenance areas. Marine and Petroleum Geology 12, 845–879.
Jürgens, U. 1996: Mittelmiozäne bis pliozäne Randmeer-Sequenzen aus dem deutschen Sektor der Nordsee. Geologisches Jahrbuch A146, 217-232.
Keigwin Jr, L.D. 1980: Palaeoceanographic change in the Pacific at the Eocene-Oligocene boundary. Nature 287, 722–725.
King, C. 1973: R-1x Stratigraphical/paleontological final report. 29 pp. Paleoservices, England. DGU Report File 3069.
King, C., Allen, L.O. & Meyrick, R.W. 1978: Inez-1 Final stratigraphical / paleontological report. Inez-1 Completion Report, DGU Report File 3186, 11–42.
Kjemperud, A. & Fjeldskaar, W. 1992: Pleistocene glacial isostasy – implications for petroleum geology. In Larsen, R.M., Brekke, H., Larsen, B.T. & Talleraas, E. (eds) Structural and Tectonic Modelling and its Application to Petroleum Geology. Norwegian Petroleum Society Special Publication 1, 187–195.
Koch, B.E. 1989: Geology of the Søby-Fasterholt area (text). Geological Survey of Denmark A22, 171 pp.
Kockel, F. 1988: The palaeogeographical maps. In Vinken, R. (ed.) The Northwest European Tertiary Basin. Geologisches Jahrbuch A100, 423–427, 7 maps.
Kockel, F. 1995: Structural and palaeogeographical development of the German North Sea sector. Beiträge zur regionalen Geologie der Erde 26, 96 pp. Berlin: Gebrüder Borntraeger.
Kristoffersen, F.N. & Bang, I. 1982: Cenozoic excl. Danian limestone. In Michelsen, O. (ed.) Geology of the Danish Central Graben. Geological Survey of Denmark B8, 61–70.
Larsen, G. & Dinesen, A. 1959: Vejle Fjord Formationen ved Brejning. Geological Survey of Denmark II 82, 114 pp.
Laursen, G.V. 1995: Foraminiferal biostratigraphy of Cenozoic sections in five wells from the Danish area. EFP-92 project: Basin development of the Tertiary of the Central Trough with emphasis on possible hydrocarbon reservoirs 20. 33 pp. Danish Energy Agency.
Laursen, G.V., Konradi, P.B. & Bidstrup, T. 1997: Foraminiferal and seismic interpretations of the palaeoenvironment of a profile in the North Sea. Bulletin of the Geological Society of France 168, 187–196.
Letsch, W.J. & Sissingh, W. 1983: Tertiary stratigraphy of the Netherlands. Geologie en Mijnbouw 62, 305–318.
Liboriussen, J., Ashton, P. & Tygesen, T. 1987: The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics 137, 21–29.
Lidmar-Bergström, K., Ollier, C.D. & Sulebak, J.R. 2000: Landforms and uplift history of southern Norway. Global and Planetary Change 24, 211–231.
Liu, X. & Galloway, W.E. 1997: Quantitative Determination of

Tertiary Sediment Supply to the North Sea Basin. American Association of Petroleum Geologists Bulletin 81, 1482–1509.
Miall, A.D. 1992: Exxon global cycle chart: An event for every occasion? Geology 20, 787–790.
Michelsen, O. 1994: Stratigraphic correlation of the Danish onshore and offshore Tertiary successions based on sequence stratigraphy. Bulletin of the Geological Society of Denmark 41, 145–161.
Michelsen, O. 1996: Late Cenozoic basin development of the eastern North Sea Basin. Bulletin of the Geological Society of Denmark 43, 9–21.
Michelsen, O., Danielsen, M., Heilmann-Clausen, C., Jordt, H., Laursen, G.V. & Thomsen, E. 1995: Occurrence of major sequence stratigraphic boundaries in relation to basin development in Cenozoic deposits of the southeastern North Sea. In Steel, R. J., Felt, V.L., Johannessen, E.P. & Mathieu, C. (eds) Sequence Stratigraphy of the Northwest European Margin. Norwegian Petroleum Society Special Publication 5, 415–427.
Michelsen, O., Thomsen, E., Danielsen, M., Heilmann-Clausen, C., Jordt, H. & Laursen, G.V. 1998: Cenozoic sequence stratigraphy in the eastern North Sea. Society for Sedimentary Geology (SEPM) Special Publication 60, 91–118.
Miller, K.G., Fairbanks, R.G. & Mountain, G.S. 1987: Tertiary oxygen isotope synthesis, sea level history, and continental margin erosion. Paleoceanography 2, 1–19.
Miller, K.G., Liu, C & Feigenson, M.D. 1996: Oligocene to middle Miocene Sr-isotopic stratigraphy of the New Jersey continental slope. In Mountain, G.S., Miller, K.G., Blum, P., Poag, C.W. & Twichell, D.C. (eds) Proceedings of the Ocean Drilling Program, Scientific Results, 150, 97–114.
Miller, K.G., Mountain, G.S., Browning, J.V., Kominz, M., Sugarman, P.J., Christie-Blick, N., Katz, M.E. & Wright, J.D. 1998: Cenozoic global sea level, sequences, and the New Jersey Transect: results from coastal plain and continental slope drilling. Reviews of Geophysics 36, 569–601.
Molnar, P. & England, P. 1990: Late Cenozoic uplift of mountain ranges: chicken or egg? Nature 346, 29–34.
Nielsen, O.B. 1995: Den geologiske udvikling af Nordsøbassinet i Kridt og Tertiær. In Nielsen, O.B. (ed.) Danmarks geologi fra Kridt til i dag. Aarhus Geokompendier 1, 3–18.
Nielsen, S.B. 2002: A post mid-Cretaceous North Sea model. Bulletin of the Geological Society of Denmark 49, 187–204 (this volume).
Nielsen, O.B., Sørensen, S., Thiede, J. & Skarbø, O. 1986: Cenozoic differential subsidence of North Sea. American Association of Petroleum Geologists Bulletin 70, 276–298.
Nielsen, S.A.V. & Nielsen, L.H. 1995: Mid-Miocene progradational barrier island and back-barrier deposits, central Jylland, Denmark. Geological Survey of Denmark C12, 21–38.
Quitzow, H.W. 1953: Altersbeziehungen und Flözzusammenhänge in der jüngeren Braunkohlenformation nördlich der Mittelgebirge. Geologisches Jahrbuch 68, 27–132.
Rasmussen, E.S. 1996: Sequence stratigraphic subdivision of the Oligocene and Miocene succession in South Jutland. Bulletin of the Geological Society of Denmark 43, 143–155.
Rasmussen, E.S. 1998: Detached lowstand deposits illustrated through seismic data, lithology and clay mineralogy: an example from the Lower Miocene of Denmark. In Gradstein, F.M., Sandvik, K.O. & Milton, N.J. (eds) Sequence Stratigraphy – Concepts and Applications. Norwegian Petroleum Society Special Publication 8, 413–421.
Rasmussen, L.B. 1961: De miocæne Formationer i Danmark. Geological Survey of Denmark IV 4(5), 45 pp.
Rasmussen, L.B. 1966: Molluscan Faunas and Biostratigraphy of the Marine Younger Miocene Formations in Denmark – Part I: Geology and Biostratigraphy. Geological Survey of Denmark II 88, 358 pp.
Rasmussen, L.B. 1974: Some Geological results from the first five Danish exploration wells in the North Sea. Geological Survey of Denmark III 42, 46 pp.
Rasmussen, L.B. 1978: Geological aspects of the Danish North Sea sector. Geological Survey of Denmark III 44, 85 pp.
Ravn, J.P.J. 1922: Geologisk kort over Danmark. Geological Survey of Denmark III 22, 79 pp.
Riis, F. 1996: Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. Global and Planetary Change 12, 331–357.
Riis, F. & Fjeldskaar, W. 1992: On the magnitude of the Late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents Sea. In Larsen, R.M., Brekke, H., Larsen, B T. & Talleraas, E. (eds) Structural and Tectonic Modelling and its Application to Petroleum Geology. Norwegian Petroleum Society Special Publication 1, 163–185.
Rohrman, M., van der Beek, P., Andriessen, P. & Cloetingh, S. 1995: Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. Tectonics 14, 704–718.
Schumm, S.A. 1993: River response to baselevel change: implications for sequence stratigraphy. Journal of Geology 101, 279–294.
Séranne, M. 1999: Early Oligocene stratigraphic turnover on the west Africa continental margin: a signature of the Tertiary greenhouse-to-icehouse transition? Terra Nova 11, 135–140.
Sorgenfrei, T. & Berthelsen, O. 1954: Geologi og vandboring. Geological Survey of Denmark III 31, 106 pp.
Spjeldnæs. N. 1975: Palaeogeography and Facies distribution in the Tertiary of Denmark and Surrounding Areas. Geological Survey of Norway 316, 289–311.
Steckler, M.S., Mountain, G.S., Miller, K.G. & Christie-Blick, N. 1999: Reconstruction of Tertiary progradation and clinoform development on the New Jersey passive margin by 2-D backstripping. Marine Geology 154, 399–420.
Strass, I.F. (compiler) 1979: Lithology. Well 11/10-1. Norwegian Petroleum Directorate Paper 23, 17 pp.
Stuevold, L.M. & Eldholm, O. 1996: Cenozoic uplift of Fennoscandia inferred from a study of the mid-Norwegian margin. Global and Planetary Change 12, 359–386.
Sørensen, J.C., Gregersen, U., Breiner, M. & Michelsen, O. 1997: High-frequency sequence stratigraphy of Upper Cenozoic deposits in the central and southeastern North Sea areas. Marine and Petroleum Geology 14, 99–123.
Sørensen, J.C. & Michelsen, O. 1995: Upper Cenozoic sequences in the southeastern North Sea Basin. Bulletin of the Geological Society of Denmark 42, 74–95.
Torske, T. 1972: Tertiary oblique uplift of western Fennoscandia; crustal warping in connection with rifting and breakup of the Laurasian continent. Norges Geologiske Undersøgelser 273, 43–48.

Tynni, R. 1982: The reflection of geological evolution in Tertiary and interglacial diatoms and silicoflagellates in Finnish Lapland. Geological Survey of Finland 320. 40 pp.
Ussing, N.V. 1899: Danmarks Geologi i almenfatteligt omrids. Geological Survey of Denmark III 2, 358 pp.
Vail, P.R., Mitchum Jr., R.M. & Thompson III, S. 1977: Seismic stratigraphy and global changes of sea level, Part 3: Relative changes of sea level from coastal onlap. In Payton, C.E. (ed.) Seismic stratigraphy – applications to hydrocarbon exploration. American Association of Petroleum Geologists Memoir 26, 63–81.
Vejbæk, O.V. 1990: The Horn Graben, and its relationship to the Oslo Graben and the Danish Basin. Tectonophysics 178, 29–49.
Vejbæk, O.V. & Andersen, C. 1987: Cretaceous-Early Tertiary inversion tectonism in the Danish Central Trough. Tectonophysics 137, 221–238.
Vejbæk, O.V. & Britze, P. (eds) 1994. Top pre-Zechstein (two-way traveltime and depth). Geological map of Denmark 1:750 000. Geological Survey of Denmark, Map Series 45.
Vinken, R. (ed.) 1988: The Northwest European Tertiary Basin. Geologisches Jahrbuch A 100, 508 pp.
Zagwijn, W.H. 1989: The Netherlands during the Tertiary and Quaternary: A case history of Coastal Lowland evolution. Geologie en Mijnbouw 68, 107–120.
Zagwijn, W.H. & Doppert, J.W.C. 1978: Upper Cenozoic of the southern North Sea Basin: palaeoclimatic and palaeogeographic evolution. Geologie en Mijnbouw 57, 577–588
Zagwijn, W.H. & Hager, H. 1987: Correlation of continental and marine Neogene deposits in the south-eastern Netherlands and the Lower Rhine District. Mededelingen van de Werkgroep voor Tertiaire en Kvartaire Geologie 24, 59–78.
Ziegler, P.A. 1990: Geological Atlas of Western and Central Europe. 239 pp. The Hague: Shell Internationale Petroleum Maatschappij BV.
Ziegler, P. A. 1994: Cenozoic rift system of western and central Europe: an overview. Geologie en Mijnbouw 73, 99–127.