

# A post mid-Cretaceous North Sea model

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Nielsen, S.B. 2002–12–02: A post mid-Cretaceous North Sea model. *Bulletin of the Geological Society of Denmark*. Vol. 49, pp. 187–204. Copenhagen.

The relative importance and causal relationship between tectonics, eustasy and sediment charge is investigated for the post mid-Cretaceous North Sea. Guided by the predictions of a quantitative model and previously published work it is argued that the geological evolution comprises 1) continued subsidence of the central North Sea and its more marginal basin areas, related to Palaeozoic and Mesozoic lithospheric and deeper processes, 2) Cenozoic uplift of the British Isles (Scotland) and western Fennoscandia initiated by the Iceland plume in Paleocene/Eocene, 3) inversion zone dynamics induced by in-plane stress variations from plate boundary processes (the African-Eurasian collision and Atlantic spreading), and 4) denudation controlled by the availability of topography and erosional base level changes.

The processes are consistent with the general present day sediment structure of the North Sea. Furthermore, they produced the pattern and amplitude of the burial anomalies in the North Sea region: 1) the continued subsidence of the central North Sea ensured maximum burial here at the present day, 2) Cenozoic uplift of the coastal areas of Scotland and western Fennoscandia, including southern Norway, produced over-burial that decreases away from the coast with a gradient that depends on the flexural strength of the lithosphere, 3) inversion zones (in particular the Sole Pit High and the Sorgenfrei-Tornquist Zone) developed a two phase burial anomaly, firstly by erosion of the narrow strip of topography in the central zone of inversion, and secondly by more regional erosion of the post-compressional rebound topography, involving both the central inversion zone and the marginal troughs. The falling eustatic level generated a burial anomaly by erosional unloading and isostatic uplift of the basin margins. Deep Quaternary erosion enhanced the burial anomaly in, for example, the Farsund Basin and the Skagerrak. The post-compressional rebound of the Sorgenfrei-Tornquist Zone is identified as the Neogene tectonic mechanism in the eastern North Sea area.

*Keywords:* modelling, lithosphere, basin inversion, erosion, North Sea basin, Neogene uplift.

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This paper discusses general aspects of North Sea evolution from mid-Cretaceous (~100 Ma) till the present day. The primary focus is the eastern North Sea area, which was the subject of the interdisciplinary project 'Tecforce'. The purpose of the discussion is to elucidate the causal relationship between tectonics, eustasy and sediment charge in the geological evolution. The eastern North Sea area, with its dense coverage of geological and geophysical data, is a fine laboratory for such a study. The approach of the discussion is to formulate a quantitative model guided by ideas about which lithospheric and deeper geodynamic and surface processes have influenced the post mid-Cretaceous North Sea evolution. By identifying discrepancies between model predictions and observations the model becomes a diagnostic tool,

which helps to identify factors and processes that were not properly represented or even omitted from the model in the first place. This approach permits new about the causal relationship between tectonics, eustasy and sediment charge in the eastern North Sea area.

Sclater & Christie (1980), Wood (1981), and Barton & Wood (1984) used the work of McKenzie (1978) to explain the principal observational features of the post mid-Cretaceous North Sea evolution in terms of Late Jurassic extension. This hypothesis of basin evolution by passive rifting invokes localised lithospheric thinning in response to in-plane tensional tectonic stresses originating at plate boundaries, followed by quiet thermal subsidence with a time constant of ~60 Ma. In this understanding the Late Jurassic rifting episode

caused the localised fault controlled subsidence of the Central Graben area, which accommodated the thick but areally restricted Upper Jurassic succession. Rifting activity ceased in Lower Cretaceous (Vejbæk 1986) after which subsidence became dominated by quiet regional thermal subsidence accommodating both the Upper Cretaceous succession (helped by a high eustatic level) and the saucer-shaped and more than 3 km thick Cenozoic succession.

Govers & Sæbøe (1985) noted the inconsistency between the localised area of pre mid-Cretaceous tectonics, the vast region of post mid-Cretaceous regional subsidence and the predictions of the original McKenzie model, which does not allow for the development of regional post-rift sag. Some stretching models (e.g. Rowley & Sahagian 1986) invoke depth dependent stretching to produce a steer's head geometry of the post rift sag basin. However, the depth dependency in these kinematic models is ad hoc, and the resulting deformation patterns do not agree well with results produced by thermo-mechanically based lithospheric models (e.g. Frederiksen 2002), which show localised deformations also in the mantle lithosphere. In fact, Frederiksen et al. (2001), in agreement with Vejbæk (1997), need three tectonic events (Early Triassic and Late Jurassic extension and Late Cretaceous compression) and two deeper seated thermal events (Late Carboniferous – Early Permian and Middle Jurassic) to simulate central North Sea evolution using a more realistic and physically consistent thermo-mechanical model.

The above noted discrepancy, supported by the modelling results of Frederiksen et al. (2001), suggests that Upper Jurassic – Late Cretaceous stretching in the Central Graben area is not the only cause for the post mid-Cretaceous North Sea evolution. This was pointed out by Sørensen (1986) in the eastern North Sea area, where there was only limited Late Jurassic tectonic activity. He interpreted the subsidence of the Danish Basin in terms of Triassic rifting superimposed on cooling subsidence following the Permo-Carboniferous igneous event, for which there is ample evidence in dykes and volcanics in the eastern North Sea area, including the North German basin, Scandia and the Oslo rift. Sørensen (1986) also noted the influence of the Middle Jurassic doming episode in the Danish basin (the mid-Cimmerian unconformity) as a retardation of the overall thermal subsidence history.

The work of Ziegler (1990) on the extent of the mid-Cimmerian unconformity, which was followed by Underhill & Partington (1993) and Ansbjerg et al. (2001), shows that widespread Middle Jurassic thermal doming and erosion occurred in the North Sea area, prior to localised Late Jurassic rifting in the Central Graben and Viking Graben areas. As the mid-

Cimmerian unconformity can be recognised in many places within the area of post mid-Cretaceous regional subsidence (Ziegler 1990, Underhill & Partington 1993, Ansbjerg et al. 2001) the obvious inference is that the North Sea Middle Jurassic doming episode and the post mid-Cretaceous North Sea subsidence signal the rise and demise of a mantle plume under the North Sea area. With a lithospheric thermal time constant of 60 Ma, less than 3% of the Permo-Carboniferous cooling of Sørensen (1986) would be left to accommodate the post mid-Cretaceous North Sea succession. It is therefore likely that the Middle Jurassic mantle plume through its demise renewed the subsidence potential of the North Sea area.

The overall thickness of the entire Cenozoic succession of the North Sea varies only gradually from place to place. Nielsen et al. (1986) used borehole data to map lateral thickness variations within the Cenozoic succession. Their study indicated that there are substantial variations from place to place within individual sedimentary units that indicate marked lateral and temporal variations in sedimentation rate. Extensive studies of the stratigraphy of the Cenozoic of the North Sea using both well and seismic data (Jordt et al. 1995, Michelsen et al. 1998, Huuse et al. 2001) have shown that the variations in sediment thickness are caused mostly by different directions of sediment transport and different source areas. In Paleocene – Eocene times the main source area was the British Isles and the Shetlands Platform area (Ziegler 1990), though there was a contribution from southern Norway (Jordt et al. 1995, Clausen et al. 2000). Southern Norway became the main source area in Oligocene and the main depocentres are found off its southern coast (Jordt et al. 1995, Michelsen et al. 1998). During the Miocene and Pliocene, the source area rotated clockwise to southern Scandinavia and eventually to the Baltic and the Alpine Foreland (during the Plio-Pleistocene; Huuse et al. 2001).

Lateral thickness variations within the North Sea Cenozoic succession can thus be explained by shifting source areas and changing delta lobes (Huuse 2002). It is thus tempting to interpret the evolution of the Cenozoic North Sea as (mainly) filling of a uniformly subsiding depression from its margins. This concept was already present in the work of Barton & Wood (1984), although they postulated Late Jurassic rifting as the cause of the post mid-Cretaceous subsidence and took no account of the earlier Permo-Carboniferous and Middle Jurassic tectono-thermal events.

The marginal areas of the North Sea basin bear witness to yet another deviation from the concept of post mid-Cretaceous basin subsidence induced by Jurassic lithospheric stretching. The pre-Quaternary

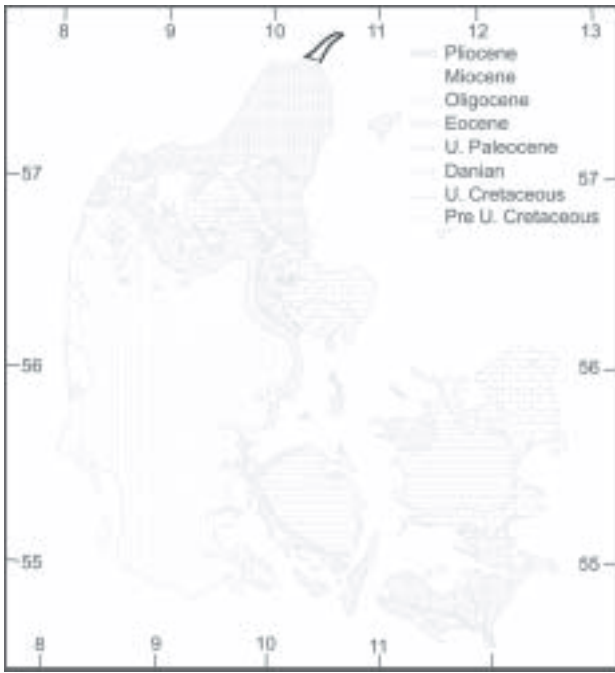


Fig. 1. Pre-Quaternary geological map of onshore Denmark (excl. Bornholm). Redrawn from Sorgenfrei & Berthelsen (1954).

geological map of onshore Denmark (Fig. 1) compiled by T. Sorgenfrei (in Sorgenfrei & Berthelsen 1954) shows a systematic variation in age of the Quaternary subcrop, ranging from Pliocene in SW Jutland to Early Cretaceous in the northeast. This age pattern may be the evidence of a NE–SW tilting of the eastern North Sea area, associated with tectonic uplift of the Fennoscandian shield and continuous subsidence in the central North Sea. This fundamental observation (Jensen & Michelsen 1992, Jensen & Schmidt 1992, Japsen 1993), which also is apparent on seismic profiles perpendicular to the margins all over the North Sea area, has attracted much attention in the last decade.

More recently Japsen (1998) and Japsen & Bidstrup (1999) quantified the thickness of the missing sequence based on sonic velocity anomalies of Jurassic and Cretaceous formations and depth profiles of vitrinite reflectance. They concluded that post mid-Cretaceous subsidence continued uninterrupted in the central North Sea, while the margins of the North Sea basin saw (mainly) Neogene tectonic uplift and erosion, with possibly increasing intensity toward the present day. Although their estimates of the thickness of the missing section have been contested by Huuse et al. (2001), it is generally agreed that the margins of the North Sea basin have been eroded, with the thickness of the missing section increasing towards the

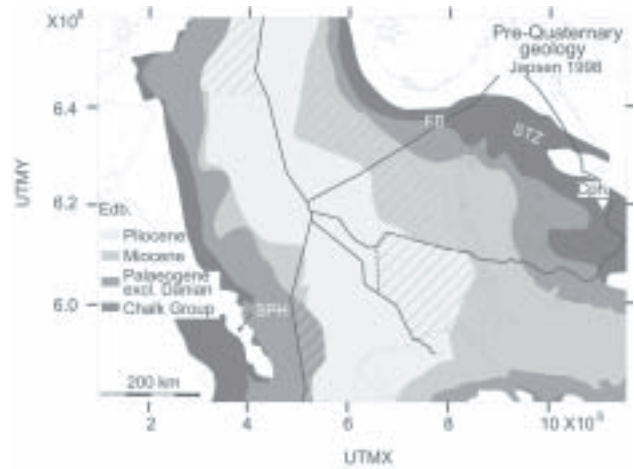


Fig. 2. Pre-Quaternary geological map of the North Sea region. Cph.: Copenhagen; Edb.: Edinburgh; FB: Farsund Basin; STZ: Sorgenfrei-Tornquist Zone; SPH: Sole Pit High. Hatched areas means thin or uncertain presence of units. Redrawn from Japsen (1998).

basin margin. This general pattern of marginal erosion is apparent from Fig. 2, which shows the pre-Quaternary map compiled by Japsen (1998). Fig. 3, which shows the estimated burial anomaly of the Chalk Group of Japsen (1998), illustrates how the Chalk Group previously has been more deeply buried than it is at the present day.

Although there is general agreement about the fundamental observation of erosion of the margins, save for the depth of erosion, there is little consensus regarding the cause and timing of the erosion pattern of the North Sea margins. The agents of geological

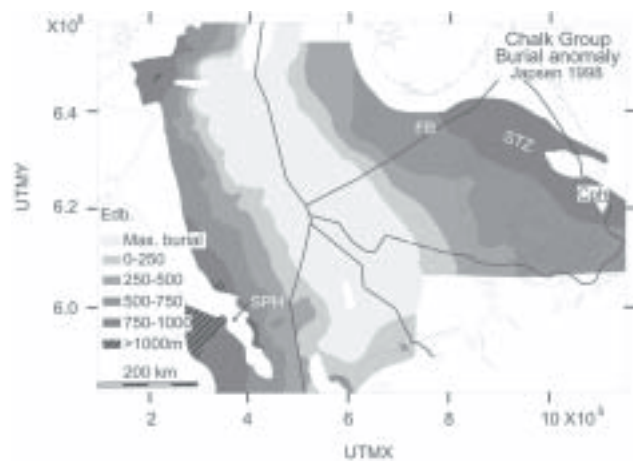


Fig. 3. The Chalk Group burial anomaly derived by Japsen (1998). The map shows the difference between the present day burial depth of the chalk group and the burial depth inferred from measured seismic velocities in the chalk group and a normal depth-trend of chalk velocity. Symbols as in Fig. 2.

evolution are tectonics, eustasy, and climate. Tectonic processes and eustasy create and destroy sediment accommodation space and sediment source areas. Climate provides the primary control on denudation and sediment transport processes. The outstanding question is the relative importance and causal relations of these ingredients of geological evolution in the eastern North Sea area. The present contribution to the discussion, along with others (Huuse et al. 2001, Nielsen et al. 2002, Huuse 2002), is of the opinion that the effects of established tectonic agents, passive isostatic effects and climate must be considered before some of the many proposed active tectonic mechanisms summarized by Japsen & Chalmers (2000) or indicated by Cloetingh et al. (1990) are brought into play. The present paper therefore proceeds by formulating a minimal quantitative post mid-Cretaceous North Sea model, involving only the strictly necessary agents of the post mid-Cretaceous North Sea evolution. Obvious departures between model predictions and observations then may indicate tectonic, eustatic or sediment charge effects not accounted for in the model.

## Model

The model was designed to simulate the last 100 Ma of North Sea evolution. As rifting activity in the North Sea region decayed during Early Cretaceous (Vejbæk 1986) only three tectonic processes affected accommodation space: 1) regional saucer-shaped subsidence in the North Sea area, 2) inversion of structurally weak zones such as the Sorgenfrei-Tornquist Zone, The Farsund Basin, the Weald Basin, and the Sole Pit High, and 3) the uplift of some land areas bordering the North Sea basin during the Cenozoic. Although there is little doubt that uplift occurred (Riis & Fjeldskaar 1992), the timing and distribution of uplift is controversial. In the present context the principal role of the bordering land areas is to produce sediments that fill the North Sea basin. Sediment production is a function of several factors including tectonic activity, climate and base level. In this paper we avoid the choice of a particular uplift history by using 'coastal feeding' to provide for the sediments to fill the North Sea basin. For a discussion of mechanisms, which can produce uplift of land areas adjacent to continuously subsiding basins (see Nielsen et al. 2002). Other mechanisms affecting accommodation space comprise eustatic variations, compaction of previously deposited sediment, and isostatic loading, all of which are part of the model.

The model includes the following processes:

- 1) A Middle Jurassic mantle plume that caused doming and temporarily delayed and even reversed the regional subsidence followed the Permo-Carboniferous tectono-thermal event (Sørensen 1986). Continued thermal decay and isostatic subsidence following the demise of the Middle Jurassic plume, created the accommodation space for Upper Cretaceous and Cenozoic North Sea sediments. The resulting post mid-Cretaceous subsidence caused by this complex of lithospheric and asthenospheric processes is mimicked by the simpler process of conductive cooling and contraction of an initially warmer lithosphere slab. Although the physical reality differs from the model, the resulting subsidence effect is similar: quiet regional post mid-Cretaceous subsidence.
- 2) Eustatic sea level was high (250 m) during the Late Cretaceous. A general long-term fall was initiated in the Paleocene at ~60 Ma.
- 3) Sediments are transported laterally (random walk) from source areas and deposited where marine accommodation space is available.
- 4) The temporal changes in sediment source areas are simulated by adding transportable sediments to the system during specific time periods and at specific locations adjacent to the North Sea basin. Chalk sedimentation is simulated by adding sediment (chalk) to the water column.
- 5) Erosion of basin topography is proportional to the elevation above the current sea level. This means that margins are eroded as they become exposed by falling eustatic level.
- 6) Sediment compaction is irreversible and exponential (Slater & Christie 1980), and determined by lithology and the maximum depth of burial.
- 7) The dynamics of selected inversion zones (the Sorgenfrei-Tornquist Zone, the Weald Basin, the Sole Pit High, and the Central Netherlands Basin) are included by kinematic thickening of crust and sediments in the inversion zones.
- 8) The isostatic compensation of inversion zones, sediment, water, and thermal loads is regionally distributed by use of a thin elastic plate.

The above specified rules of the 'post mid-Cretaceous North Sea game' are made quantitative by the following partial differential equations.

The evolution of the thermal structure of the lithosphere is calculated from the transient three-dimensional heat equation (Carslaw & Jaeger 1959):

$$\frac{\partial^2}{\partial x^2} T + \frac{\partial^2}{\partial y^2} T + \frac{\partial^2}{\partial z^2} T - \frac{1}{\kappa} \frac{\partial}{\partial t} T = 0 \quad (1)$$

$T$  is temperature,  $x$ ,  $y$ , and  $z$  are Cartesian co-ordinates,  $\kappa$  is the thermal diffusivity and  $t$  is time. Eq. 1 is solved on a finite difference grid using operator splitting and fully implicit time integration (Press et al. 1992). The sediments are treated as a vanishingly thin layer of finite thermal resistance, heat capacity, and heat production rate, and enter the surface boundary condition of Eq. 1. This approximation results in great computational savings and is valid for long wavelengths of sediment thickness variations, which is suitable for the level of detail of the present study. The thermal parameters of the sediment layer are derived by well-known mixing laws from the actual sediment structure, which consists of layers of finite thickness with exponential porosity decrease. The surface temperature,  $T_s$ , is constant ( $0^\circ\text{C}$ ). This choice is not important as the only rheology involved in this model is an elastic plate. The background heat flow at the base of the lithosphere is initially adjusted by a trial and error process to produce the thermal subsidence necessary to accommodate the present day post mid-Cretaceous sediment succession.

Sediments are redistributed by surface transport processes according to the diffusion equation

$$\frac{\partial^2}{\partial x^2} C + \frac{\partial^2}{\partial y^2} C - \frac{1}{\beta} \frac{\partial}{\partial t} C = -S \quad (2)$$

$C$  is the concentration of sediments in transport ( $\text{kg}/\text{m}^2$ ) and  $b$  is a sediment diffusion constant. The spatially and temporally varying source term,  $S$ , has a positive contribution from the production of transportable sediments by erosion of topography, by marine life (chalk), or by coastal feeding, and a negative contribution from the removal of transportable sediments by sedimentation. Sediment deposition occurs only in water and is proportional to the water depth and the current concentration of transportable sediment (deep water but no sediments available ( $C = 0 \text{ kg}/\text{m}^2$ ) results in no sedimentation).

Sediments compact according to an exponential porosity-depth relationship (Sclater & Christie 1980). The evolving sediment structure is tracked by monitoring the evolution of sediment layers corresponding to geological time periods. This includes the monitoring of maximum burial depth of individual sedimentary layers so that compaction takes only place for deeper burial. Uplift and erosion does not involve decompaction.

The isostatic response to thermal, sediment, and

water loading is redistributed according to the flexure of a thin elastic plate under a vertical load:

$$D \frac{\partial^4}{\partial x^4} w + 2D \frac{\partial^2}{\partial x^2} \frac{\partial^2}{\partial y^2} w + D \frac{\partial^4}{\partial y^4} w + \rho_a g w = q(x, y) \quad (3)$$

$D$  is the flexural rigidity,  $w$  is the vertical deflection,  $\rho_a$  is the density of the asthenosphere,  $g$  is the acceleration due to gravity, and the load term  $q(x, y)$  is caused by thermal loading, redistribution of sediment, changing water depths, and sediment and crustal thickening in inversion zones. Eq. 3 is solved by the Fourier method on the same equidistantly sampled grid as was used to solve Eq. 2.  $q(x, y)$  was determined iteratively  $n$  each time step because coast lines move laterally and because the changing eustatic level changes the land-sea configuration.

As a proxy for lithospheric lateral strength the thin-sheet model of Eq. 3 should be used with caution. Its application here allows for a first order modelling of the regional effect of compressional inversion of weak zones like the Sorgenfrei-Tornquist Zone. As shown by Nielsen & Hansen (2000) and Hansen et al. (2000) compression of structurally weak zones result in the creation of topography in the central inversion zone and marginal troughs, which are deepening towards the zone of intense inversion. Deflection caused by vertical loading is the natural realm of the flexural model of Eq. 3 wherefore it can be used in the present context. However, Eq. 3 does not allow for compressional enhancement of deflection or transient stress relaxation, which means that the post-compressional rebound (Nielsen & Hansen 2000) of the inversion zone and the marginal troughs is underestimated.

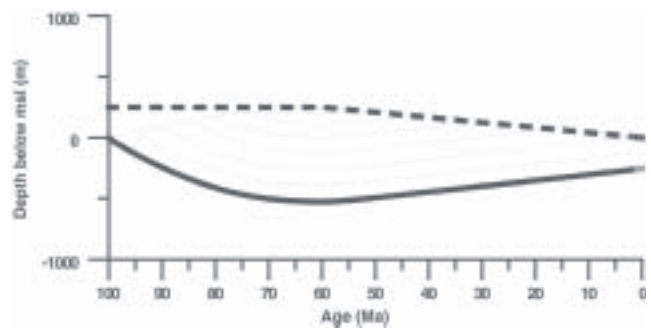


Fig. 4. Illustration of how a falling eustatic level (broken line) exposes sedimentary strata deposited at a higher eustatic level to erosion and causes over-burial. The sediment at the surface today (0 Ma) was buried below 500 m of sediment at the time of maximum burial, and therefore exhibits a burial anomaly of 500 m. The figure applies local isostasy and exponential sediment compaction. Fine lines are 5 Ma isochrones in the sediments.

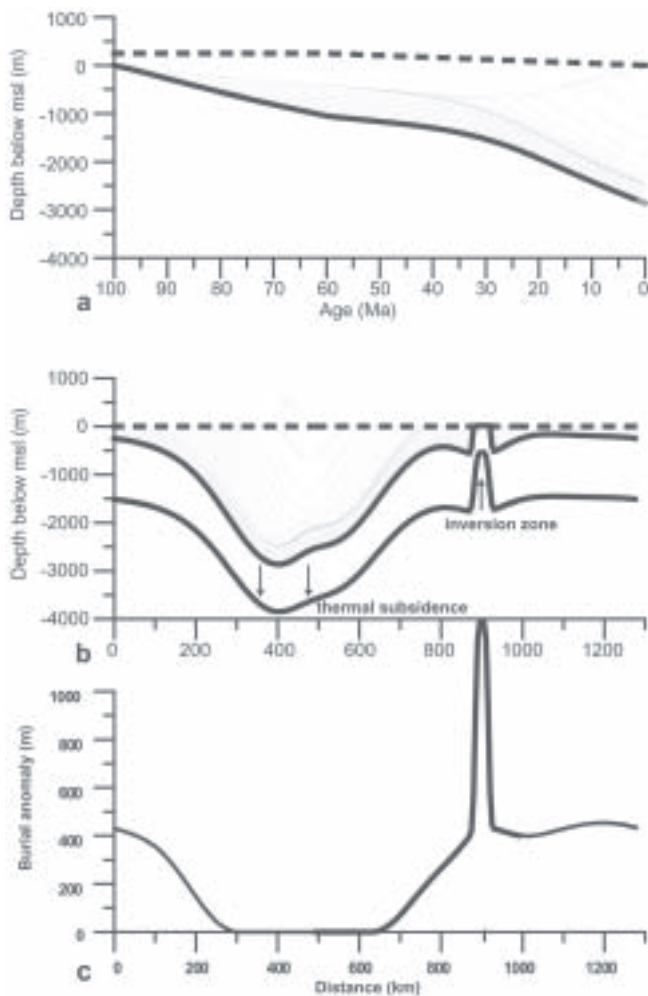


Fig. 5. 100 Ma of evolution along a profile (b) through an intra-cratonic basin like the North Sea basin, subjected to thermal subsidence in the central region, the eustatic history of Fig. 4, sediment infilling by chalk production in the water column from 100–60 Ma, clino-form migration from the sides from 60–0 Ma, and structural inversion in a narrow zone at 65 Ma. The subsidence history (a) shows the infilling history near the basin centre. As the clinoforms finally reach the basin centre at ~35 Ma an apparent increase in subsidence rate occurs. However, this is caused by the rapid filling of existing accommodation space by sediments produced at the now exposed margins. The burial anomaly of the chalk group (c) reflects the depth of erosion. Notice the symmetry of the burial anomaly and of the erosional truncation of the 60–0 Ma clinoforms at distances 120–300 km and 640–760 km. Thin lines are 5 Ma isochrones in the sediments.

The following examples serve to demonstrate the mechanisms of the model. Consider the filling of a sedimentary basin with an initial water depth of 250 m, corresponding to the eustatic level at 100 Ma. Fig. 4 shows the subsidence diagram. Shortly before 60 Ma, the basin was filled to the brim and accommodated a total of 750 m of sediment. The accommoda-

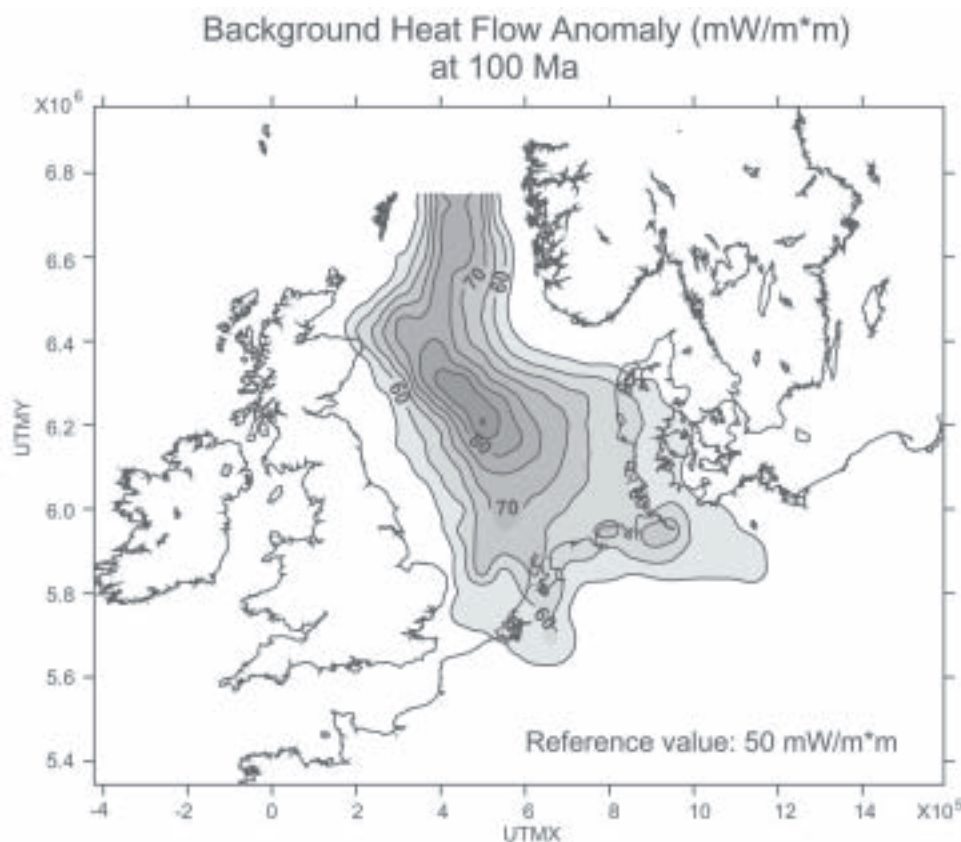
tion space is due to 1) the initial water depth, 2) loading subsidence produced by replacing sediment with water, and 3) compaction of 1000 m of existing sediment. At 60 Ma the eustatic level started to fall at a constant rate to the present day value of 0 m. This resulted in gradual exposure and erosion of the previously deposited sediment so that the sedimentary units at the surface at the present day are those which were previously buried at a depth of 500 m. They therefore show an over-burial of 500 m, which is also the thickness of the missing section.

Fig. 5 shows the evolution along a profile containing all of the elements of the North Sea model to be discussed below. In the central part of the profile the sedimentary succession is complete because thermal subsidence and loading subsidence outpaced basin filling and the falling eustatic level. Towards the margin an inversion zone was active at ~65 Ma and produced a narrow zone of uplift flanked by sedimentary troughs. The subsidence diagram of Fig. 5 is located close to the basin centre and shows initial quiet thermal subsidence outpacing the infilling of the basin and the sea-level fall. Toward the end of the evolution clinoforms have migrated into the basin centre resulting in a high sedimentation rate that outpaces the creation of accommodation space by thermal subsidence. Note how this produces an apparently accelerated basin subsidence toward the present day. The over compaction along the profile shows extreme values in the central inversion zone, where deeply buried (older) strata have been brought to the surface and eroded. At the margins, the effect shown in Fig. 4 produces over-burial as the exposed margins are gradually eroded. In the centre of the basin the sediments are presently at deepest burial ever, and show no over-compaction. Had fluid flow been included in the model, the sediments in the centre of the basin would show under-compaction (be over-pressured) because of the recent high rates of sedimentation.

## Model initiation

Evolution of the model starts at 100 Ma at the beginning of the Late Cretaceous. The initial topography, the initial thermal structure and the thickness of pre-Upper Cretaceous sediments must be specified at that time. The initial sediment is determined as the decompacted pre-Upper Cretaceous sedimentary column treated as a homogeneous sedimentary layer. The applied thickness distribution is from the compilations of Ziegler (1990). The initial topography is chosen to be relatively flat with a water depth almost everywhere of 200 m. Another initial topography

Fig. 6. Initial heat flow anomaly required to produce the thermal subsidence, which accommodates the post mid-Cretaceous North Sea sedimentary sequence.



could have been selected, but would not change the results presented here as discussed below. The surrounding areas are assigned a low relief. 'Coastal feeding' provides the necessary sediments to fill the North Sea.

The decay of an initial thermal anomaly is used to produce the thermal subsidence,  $DL$ , which, together with the initial water depth and compaction of pre-existing sediment, is required to accommodate the post mid-Cretaceous sediments. As  $DL = aLDT$ , where  $a = 3.28 \cdot 10^{-5} K^{-1}$  is the coefficient of thermal expansion,  $L$  is the lithosphere thickness, and  $DT$  is the average temperature change in a lithosphere column, there is a trade off between the required temperature anomaly and lithospheric thickness. The same  $DL$  can be produced by infinitely many combinations of  $L$  and  $DT$ . In the present model we take  $L$  to be 100 km and determine an initial heat flow anomaly which, for the choice of initial topography, results in a  $DL$  which accommodates the post mid-Cretaceous sediment distribution for our particular choice of eustatic sea level variation and sediment compaction parameters. The initial heat flow anomaly is determined in a trial and error process and appears in Fig. 6. At the onset of the evolution, the heat flow is reduced to a constant value of  $50 \text{ mW/m}^2$ . It is very likely that the initial water depth in the central North Sea was larger than 200 m. Allowing for this would result in a smaller

initial thermal anomaly in the central North Sea, as less accommodation space would have to come from thermal subsidence, and the water depth and heat flow evolution would become different, but in terms of sediment distribution and over-burial the end result would be very similar to the results presented here.

## Model predictions

### General predictions

The present model reproduces the post mid-Cretaceous sediment distribution in the North Sea region in general terms. Fig. 7 shows the predicted post Danian isopach. Comparing with the compilation of Ziegler (1990) there are obvious similarities such as the occurrence of more than 3500 m of sediment in the central North Sea. Also the distribution of the Cenozoic deposits and in particular the shape of the erosional truncation in the eastern North Sea area bears similarities with observations. For example, the predicted curvature of the erosional truncation in the eastern North Sea resembles although slightly displaced from observations to an extent that suggests that the mechanisms of the model capture some of

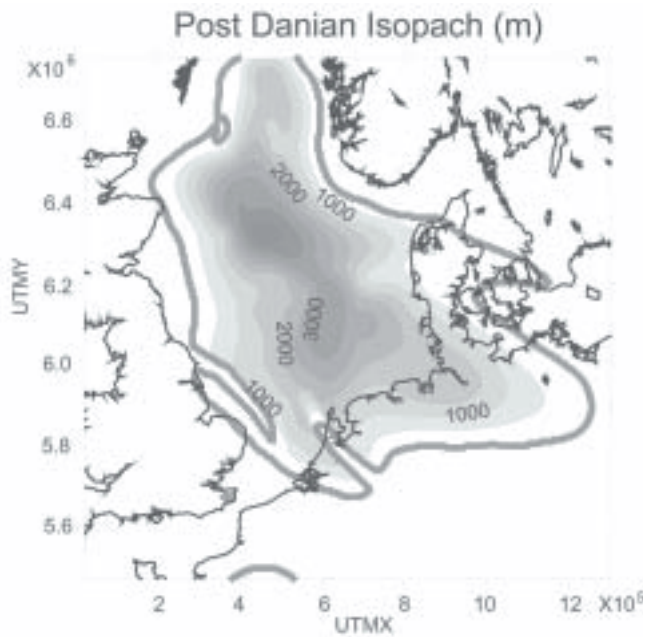


Fig. 7. Modelled post-Danian isopach.

the essence of reality. In the model, the curvature arises mainly from erosional truncation of the topography produced in the inversion of the Sorgenfrei-Tornquist Zone, and because the smaller thickness of pre mid-

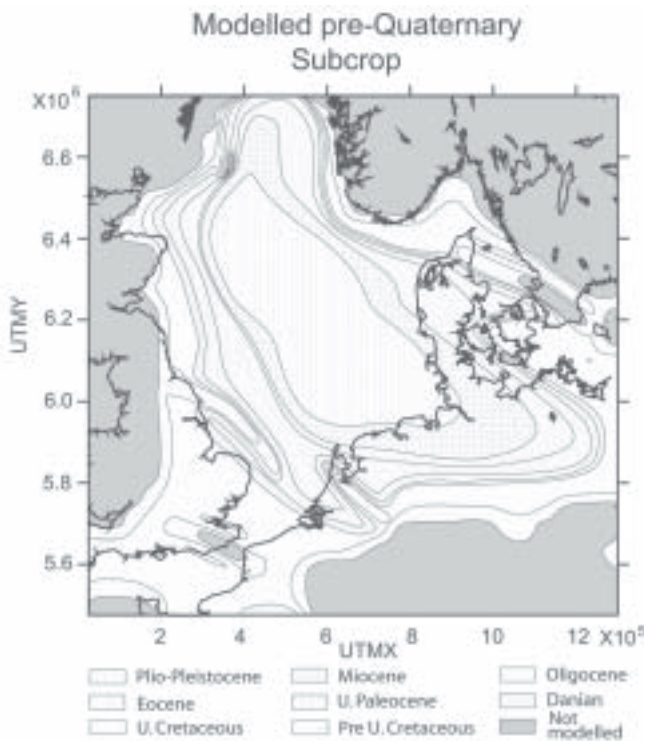


Fig. 8. Modelled pre-Quaternary geological map of the North Sea area.

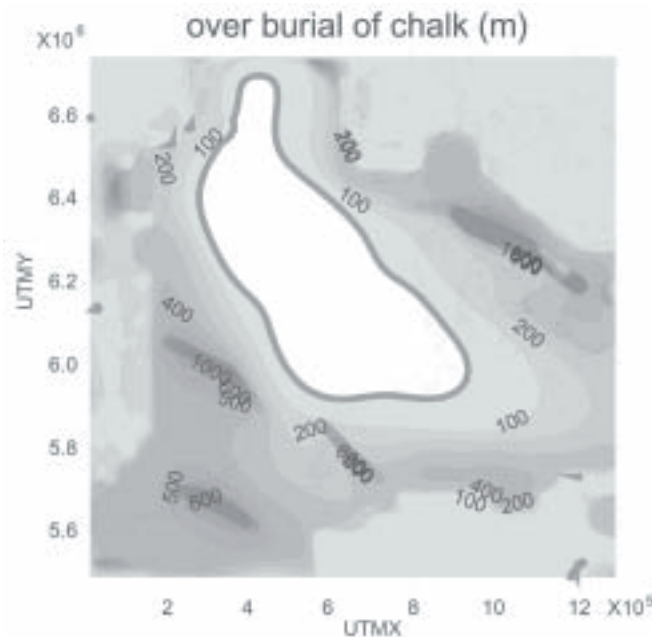


Fig. 9. Modelled Chalk Group burial anomaly in the North Sea area.

Cretaceous sediments on the Ringkøbing-Fyn High yields less compaction-related accommodation space. The S-shape of the erosional truncation is the result of the interaction of the different model mechanisms. It was not explicitly put into the model.

Fig. 8 shows the modelled fine structure of the erosional truncation of the Cenozoic deposits in the form of a pre-Quaternary geological map. It can be compared to the compilation of Japsen (1998) for the North Sea area (Fig. 2), and with the map of Sorgenfrei & Berthelsen (1954) onshore Denmark (Fig. 1). It is apparent that the model shows a systematic age variation at the base of the Quaternary, which compares well with observations. Some differences, such as the extent of the Oligocene deposits in the eastern North Sea area, are caused by the erosion in the model being to the present day sea level. No topography is left to stand within the basin, which unfortunately removes the abundant Miocene deposits in Jutland and exposes older strata.

The over-burial of the Chalk Group (Upper Cretaceous and Danian) is the last general model prediction to be considered. In case the Chalk Group was partly or fully eroded, the over-burial estimate refers to the remaining chalk succession, or to what lies below. The predicted map (Fig. 9) is the difference between the maximum burial of the chalk surface, which is registered during model evolution, and the present day position of the surface. The mechanisms responsible for the generation of the over-burial pattern can be seen in Figs. 4 and 5. The predicted over-burial

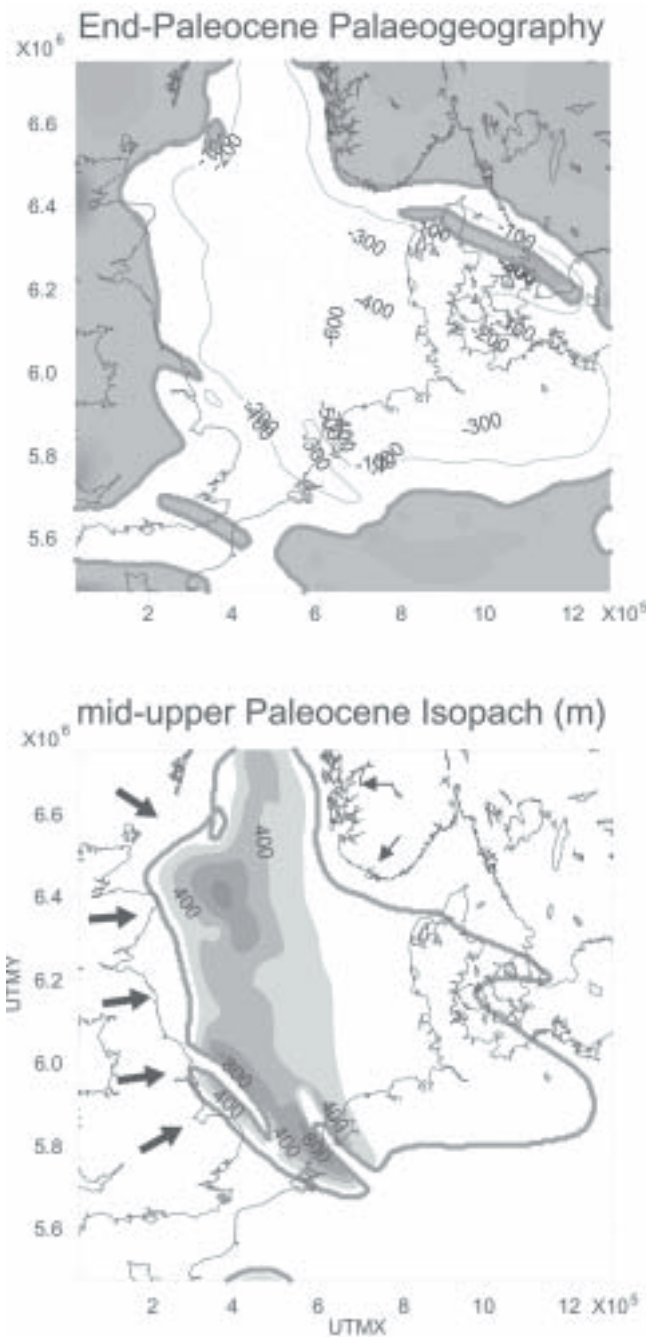


Fig. 10. Modelled end-Paleocene palaeogeography and the mid-upper Paleocene isopach. Arrows indicate that sediment supply is mainly from the British Isles. Contours are water depth (negative) and topography or sediment thickness (positive).

pattern is another example of a model outcome that was not specifically put into the model, but which results from interactions between the quantitative rules of the post mid-Cretaceous North Sea game.

The over-burial prediction can be compared with the findings of Japsen (1998) shown in Fig. 3. We no-

tice the elongated area in the central North Sea where chalk is presently at its maximum burial. Symmetrically flanking this zone are increasing values of over-burial toward the basin margins on both sides of the North Sea basin. The included inversion structures show extreme values of over-burial because here deeply buried rocks have been brought to the surface by localised vertical movements. Allowing for the finite model resolution (e.g. the few inversion zones actually included), and for the finite resolution of data it appears that the only real difference between predictions and observations are the amplitude of over-burial in some marginal areas of the North Sea basin. This very interesting discrepancy between model predictions and observations can be understood as evidence of active Neogene uplift of southern Scandinavia, which is not explicitly included in the present model.

### Palaeogeography predictions

Underlying the general model predictions of above is the palaeogeographic evolution shown in Figs. 10–15. The general picture, which in the central North Sea area is similar to the results from Barton & Wood (1984), emerges as the evolving North Sea depression is filled from the sides with sediments from different source areas. In general, the modelled evolution shows a striking similarity with the results of Huuse (2002) and Clausen & Huuse (2002).

During Late Cretaceous and Danian sediment supply is by chalk production in the water column and by chalk erosion from the inversion zones. Later the different land areas become more active. In Late Paleocene and Eocene sediments in the eastern North Sea area are utterly fine-grained clays. At that time sediment supply is mainly from the British Isles, and a deep depression develops in the central North Sea because thermal subsidence outpaces the supply of sediments (compare Fig. 5). Notice the occurrence of an Eocene depocentre in the marginal trough southwest of the Sorgenfrei-Tornquist Zone in Fig. 11. This is a known Paleocene – Eocene depocenter (Michelsen et al. 1998), where also the Eocene – Oligocene Viborg formation is developed. In Oligocene Southern Norway becomes an active sediment source, resulting in a proven depocentre off the coast of Northwest Jutland. Through Miocene to recent, the coast line finally bypasses onshore Denmark.

The inversion zones of the model were activated in Late Cretaceous and Early Paleocene, although some (Sole Pit high and the Weald Basin) in reality were active mainly in Oligocene (Ziegler 1990; Vejbaek and Andersen, 2002). Structural inversion results in

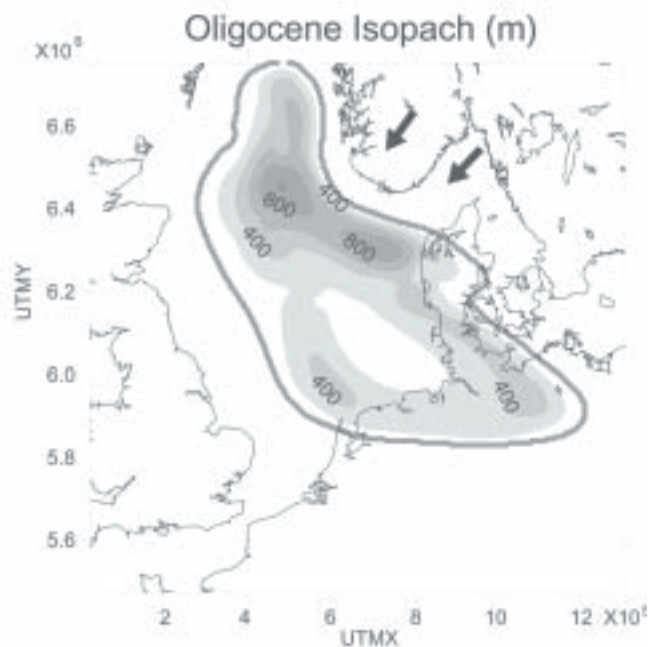
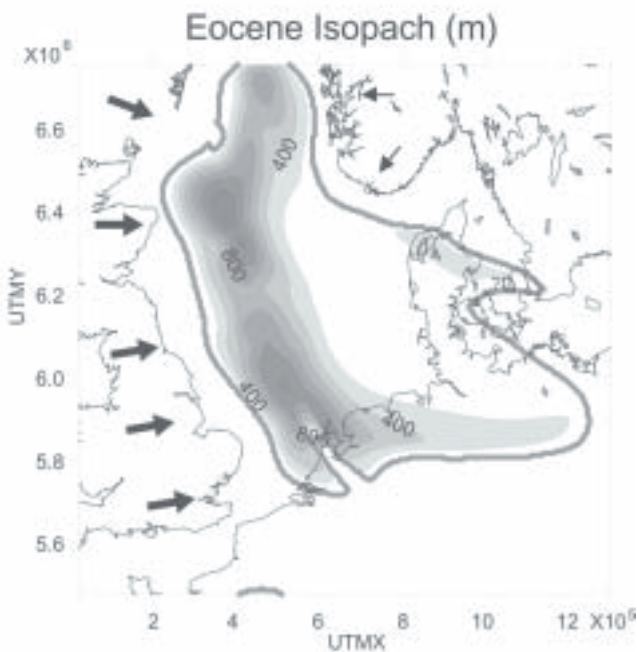
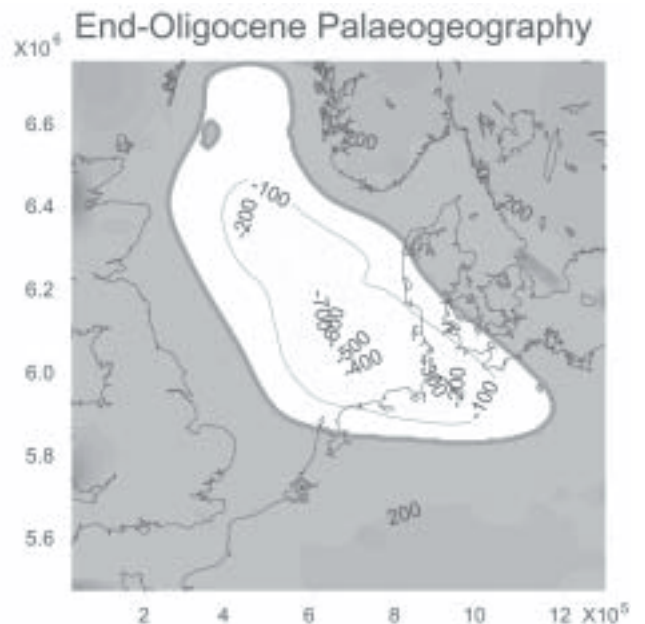
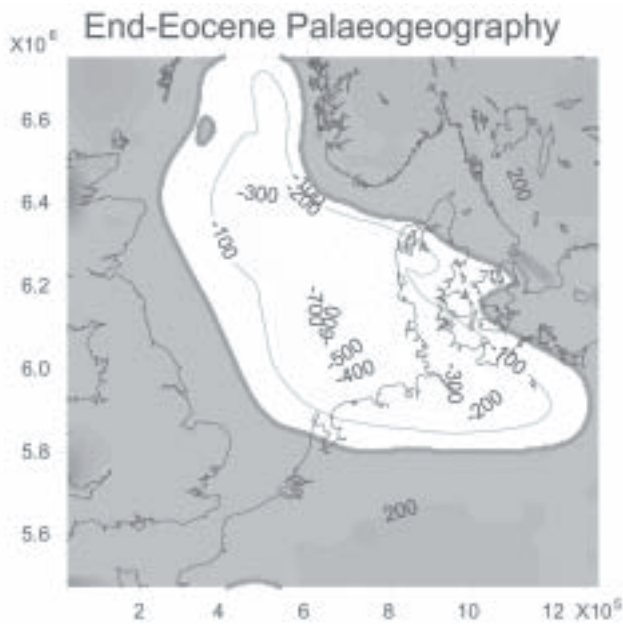


Fig. 11. Modelled end-Eocene palaeogeography and the Eocene isopach. Sediment supply is mainly from the west. Notice the depocentre south west of the Sorgenfrei-Tornquist Zone in the Danish area.

Fig. 12. Modelled end-Oligocene palaeogeography and the Oligocene isopach. Southern Norway is now assumed to be a major source of sediments.

the formation of narrow strips of topography flanked by marginal depressions, which act as sediment traps. The Sorgenfrei-Tornquist Zone shows a positive relief through Paleocene into Eocene. If indeed the creation of relief in the central inversion zone outpaced the processes of denudation, the Sorgenfrei-Tornquist Zone may have acted as a barrier against coarse clas-

tic influx from Fennoscandia during that time (Huuse 2002, Clausen & Huuse 2002).

The present model invokes a linear decrease of the eustatic level from 250 m at 60 Ma to 0 m at the present day. This is a crude generalisation of the changes in erosional base level, which excludes the detailed modelling of the regressions and transgressions in the

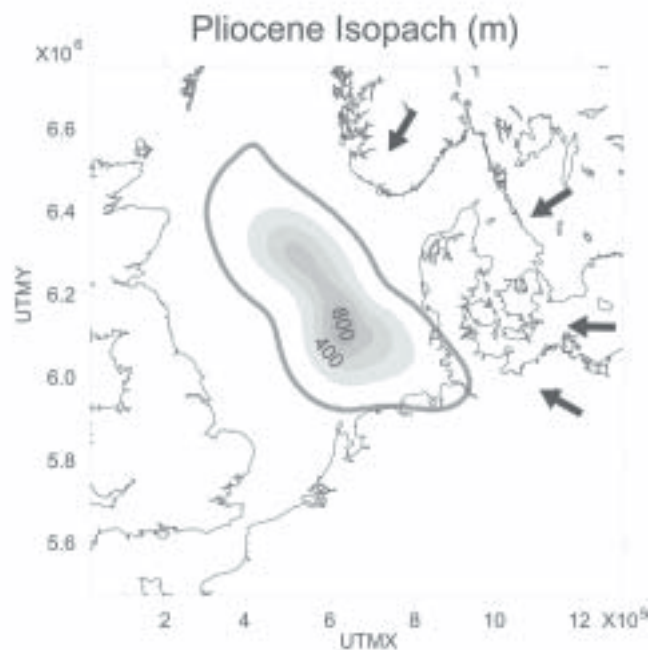
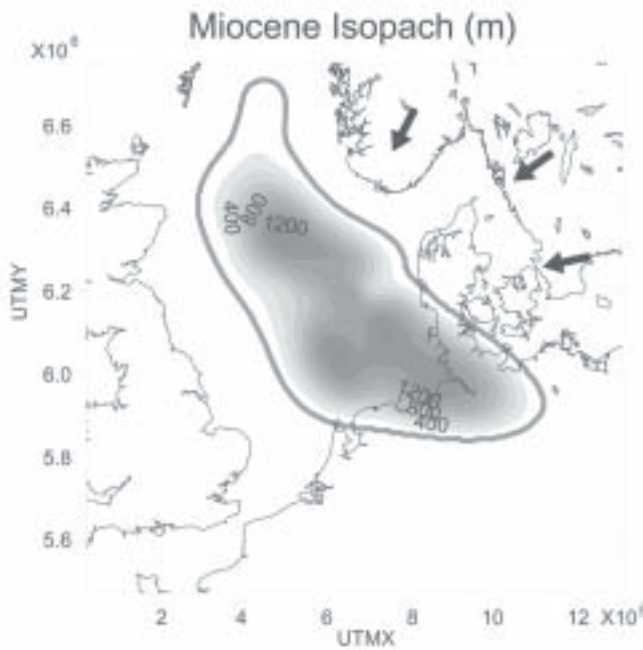
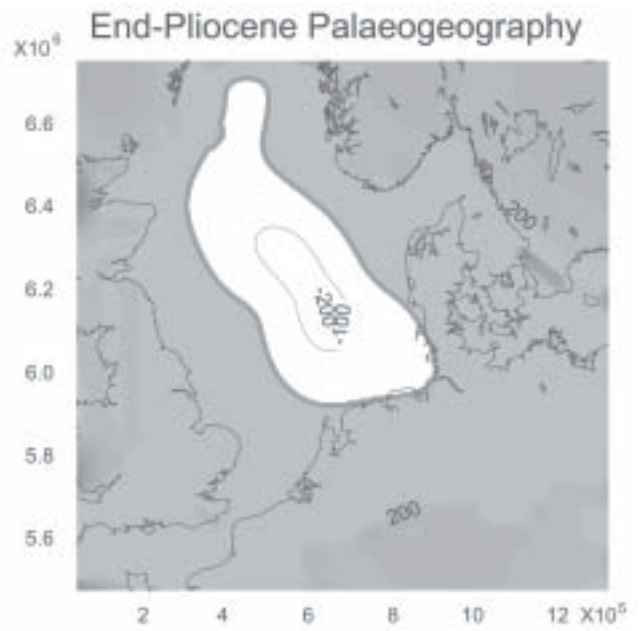
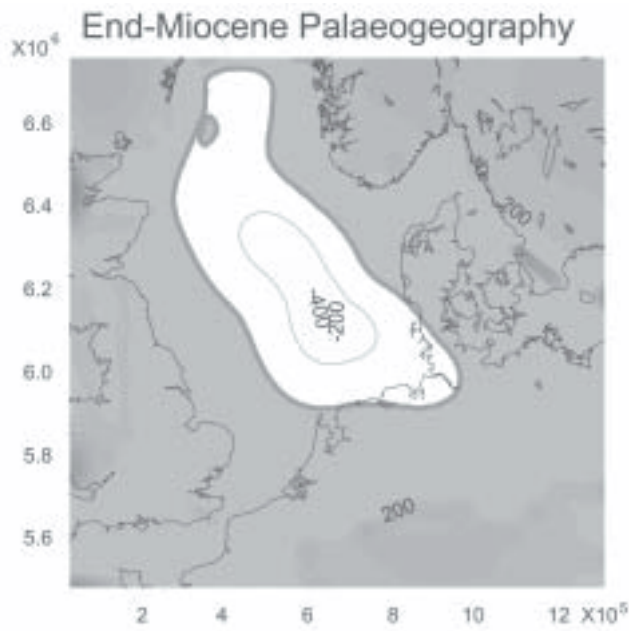


Fig. 13. End-Miocene palaeogeography and the Miocene isopach. Arrows indicate the main sediment supply directions.

Fig. 14. End-Pliocene palaeogeography and the Pliocene isopach. Arrows indicate the main sediment supply directions.

eastern North Sea area that are visible in the interchanging coarse clastic and marine deposits in Jutland. The position of the coast line in Figs. 10–15 should therefore be considered as average position.

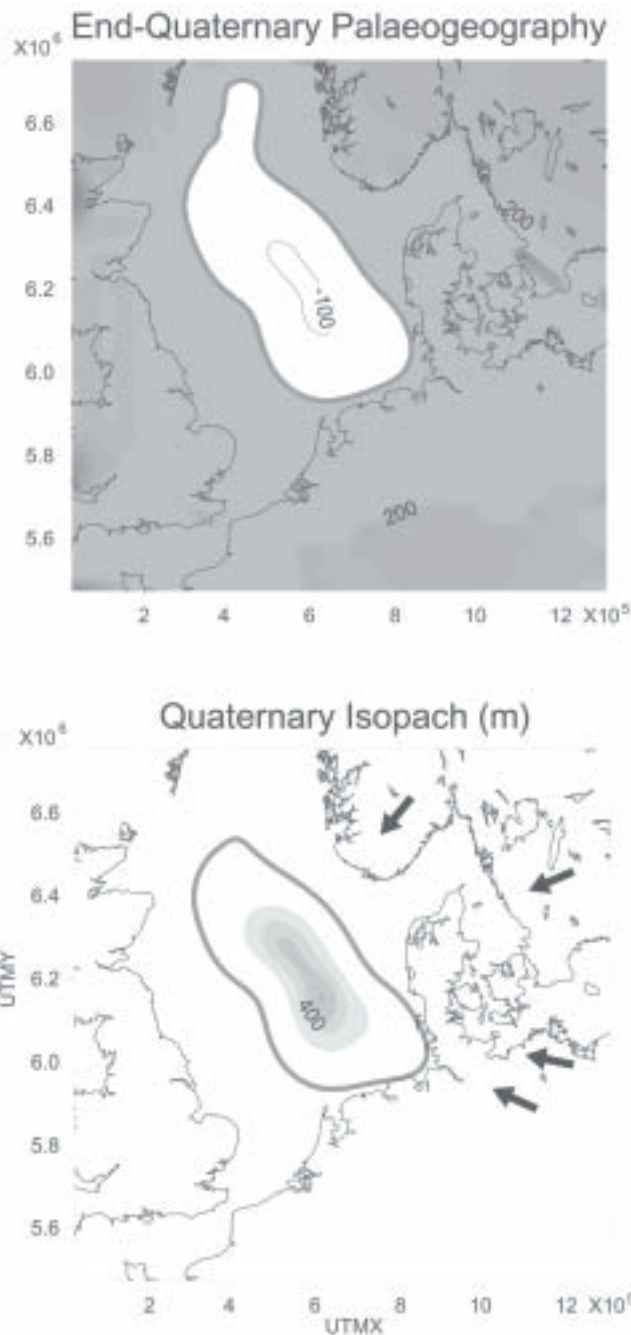


Fig. 15. End-Quaternary palaeogeography and the Quaternary isopach. Arrows indicate the main sediment supply directions. Glacial processes are not considered, resulting in major differences between the present-day topography and the modelled topography.

## Discussion

The amplitude of chalk over-burial and the burial anomalies derived by others (Jensen & Schmidt 1992, Hansen 1996) toward the coast of the British Isles, Scotland and southern Norway, and in the vicinity of inversion zones probably represent the most significant discrepancy between observations and predictions. This discrepancy can be caused by an incomplete model, errors in observations, or both.

The observation of chalk over-burial is derived from measured compressional velocities in chalk in North Sea boreholes and an assumption about the normal velocity-depth relationship for chalk. Japsen (1998) has exercised great care in deriving the best possible normal velocity-depth relationship. However, even with the inclusion of more data in the normal trend, the possibility remains that it after all could have been slightly different. The particular choice of normal compaction model introduces bias. Furthermore, it can be argued that a normal compaction trend parameterised by only one parameter – the burial depth – may not exist, as chalk compaction is also a function of other laterally varying factors such as facies, clay content, and temperature. The latter problem would induce both random scatter and bias in the derived burial map, reflecting random and systematic lateral variations of chalk compaction properties. The use of many wells in a large area, as done by Japsen (1998), reduces this problem. Bias is by its nature impossible to get rid of. If better information were indeed available it would have been used to improve the normal velocity-depth model, and a less biased over-burial map would have resulted. The conclusion here is that the burial anomaly map (Japsen 1998; Fig. 3), and any other burial anomaly map, may contain an error of unknown amplitude and sign. However, as I am tempted by the challenge of explaining the burial anomaly, hoping to learn more about tectonics, eustasy and sediment charge, I am happy to agree that probably the bias is not very large and that it certainly does not significantly distort the general regional pattern of over-burial. The point of departure for the discussion below is therefore that the model prediction of over-burial in some areas is lower than observations, and that the model therefore is incomplete regarding this aspect, and that additional geological processes that generate over-burial are called for.

The model invokes two geological mechanisms to generate over-burial: 1) falling erosional base level by means of a falling sea level (Fig. 4), and 2) tectonic uplift in zones of inversion (Fig. 5). A maximum of ~500 m of over-burial can be produced by erosional unloading of basin margins for a eustatic fall of 250

m. For a smaller eustatic fall, or if the basin was not filled to the brim, the over-burial is reduced accordingly. The over-burial along the axis of inversion zones may potentially be large, in the kilometre range, depending on the intensity of inversion and thereby the depth of erosion.

### Over-burial associated with inversion zones

The representation of inversion zone dynamics is not complete as a thin elastic plate rather than a full scale rheological model is used (e.g. Frederiksen 2002, Gemmer et al. 2002, Hansen et al. 2002). Following Nielsen & Hansen (2000), the compression-induced topography of an inversion zone can be understood as the superposition of two opposite topographic effects: the high frequency short wavelength topography caused by shortening and thickening of sediments and crust in the central inversion zone, and the long wavelength downward flexure of the upper mantle caused by the load of the central inversion zone on the upper mantle. The first phase of vertical movements during inversion involves uplift, possibly extensive, in the central inversion zone, simultaneous with subsidence of the marginal troughs. The depth of the marginal troughs gives an indication to the intensity of the inversion: shallow marginal troughs reflect minor shortening and uplift and erosion in the axial inversion zone, and vice versa. The Sorgenfrei-Tornquist Zone exhibits a very deep marginal trough at its south west border, in places with more than 2000 m of mainly chalk along a line from northern Sealand and Scania in the southeast to the central part of the Norwegian-Danish basin in the northwest. Comparison with the marginal troughs of other inversion zones in the Alpine foreland (Ziegler 1990, Nielsen & Hansen 2000) makes it clear that the inversion of the Sorgenfrei-Tornquist Zone represents a major tectonic event that generated significant differential vertical movements.

The first phase of axial inversion and marginal trough formation is well modelled by static loading of a thin elastic plate. However, rheological modelling shows (Nielsen & Hansen 2000, Hansen et al. 2000) that, as the compressional forces cease, the system inverts a second time, now regionally, involving both the central inversion zone and the marginal troughs. The secondary inversion attains its maximum value along the axis of the inversion zone and decays smoothly away from the inversion axes. This aspect of inversion zone dynamics, which involves transient stress relaxation and a minor component of thermal expansion of a slightly thickened lithosphere, is not represented properly by the elastic plate model.

This is problematic as the amplitude of secondary inversion, which becomes enhanced by erosional unloading, easily amounts to more than 500 m in the central inversion zone and becomes insignificant at the far boundaries of the marginal troughs. As the post-compressional rebound is not part of the present model, the generation of topography, and therefore the depth of erosion, associated with the second phase of inversion of the Sorgenfrei-Tornquist Zone is underestimated in a strip of width 50–75 km on either side of the inversion axis. Certainly the marginal trough chalk depocenter southwest of the Sorgenfrei-Tornquist Zone lies well within the zone affected by post-compressional rebound.

### Over-burial in the coastal areas of Southern Norway and Scotland

The present model does not explicitly include the uplift of southern Norway and Scotland, which is known to have occurred during the Cenozoic, following the volcanic opening of the North Atlantic. Nielsen et al. (2002) argued that the uplift of western Fennoscandia and Scotland was initiated in Paleocene/Eocene by destabilisation and drop off of a deep lithospheric root, triggered by the arrival of the Iceland mantle plume. This mechanism caused several phases of uplift: 1) a minor transient uplift at the time of plume emplacement, which decayed as the plume material cooled, 2) some uplift at the time of the actual drop off of the lithospheric root, which may have been later than plume emplacement as the Rayleigh-Taylor instability may take time to develop, followed by 3) a significant transient uplift at a decreasing rate throughout the Cenozoic as the remaining lithosphere heated to accommodate the higher thermal gradient following the elevation of the lower temperature boundary condition of the lithosphere. Delamination yields only a minor increase in the surface heat flow with a time constant of ~60 Ma and would not show in the present day heat flow pattern. The uplift is further enhanced by erosional unloading, which is strongly influenced by climate and base level changes.

In the present context this means that as the topography of Southern Norway and Scotland evolved through early humps followed by a gradual rise and erosional unloading, the coastal regions became uplifted and exposed to erosion. The uplift is at its maximum at the centre of delamination and decreases away from it, becoming insignificant at a distance of 75–100 km perpendicular to the coast. The eastern North Sea area thus is beyond the reach of this uplift as the distance between southern Norway and the

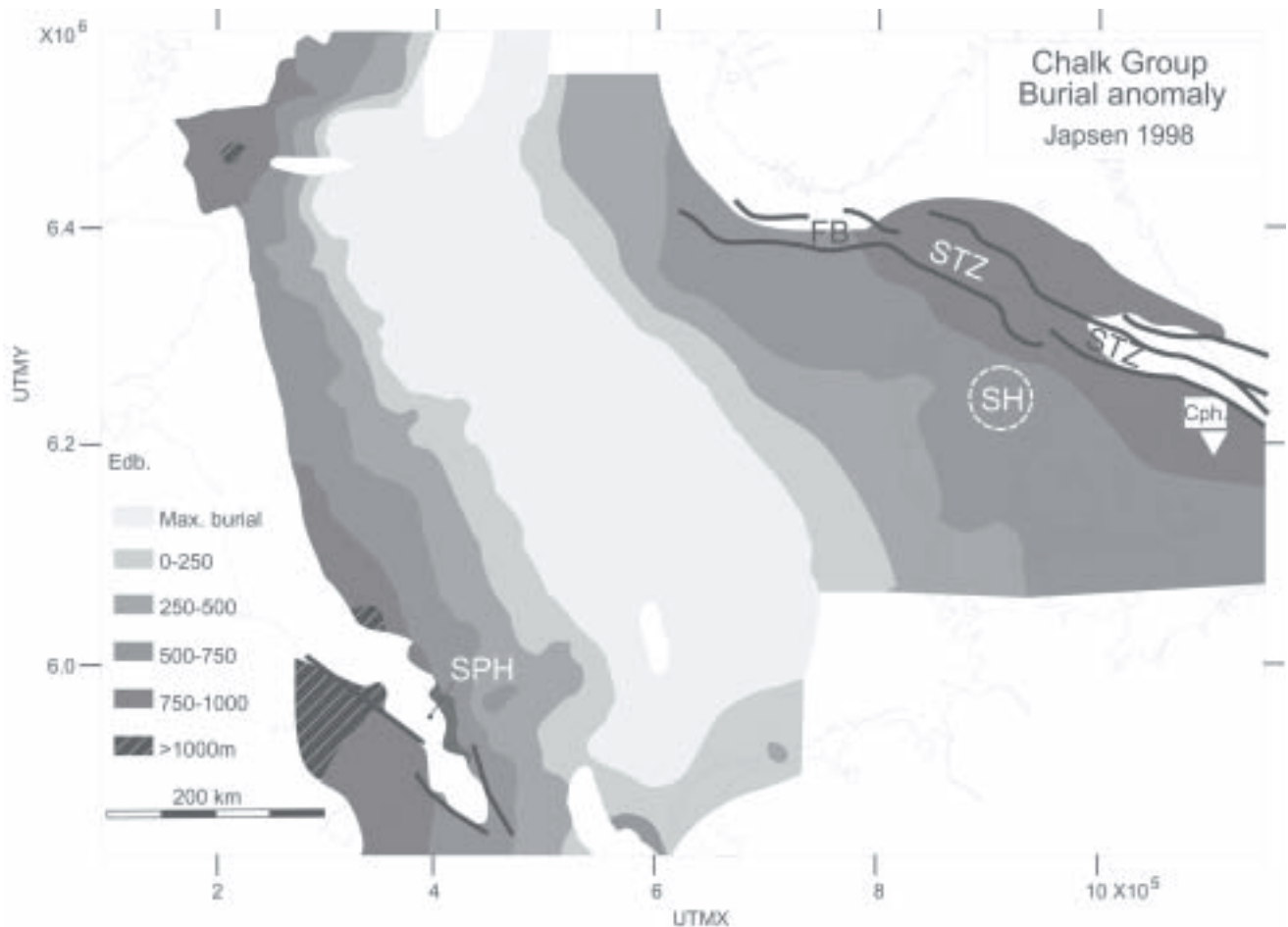


Fig. 16. The burial anomaly map of Japsen (1998) with superimposed structural elements of the Sorgenfrei-Tornquist Zone (STZ), the Farsund Basin (FB), and the Sole Pit High (SPH). SH is the Søhøjland area of central Jutland.

eastern North Sea area is beyond the flexural wave length of even a very strong lithospheric plate. The delamination induced uplift of western Fennoscandia, supplemented with deep Quaternary erosion and unloading, is sufficient to explain the over-burial pattern and amplitudes (Jensen & Schmidt 1992, Hansen 1996) observed on the Norwegian shelf and in the Skagerrak.

### Over-burial caused by Quaternary processes

The present model does not allow for erosion below the present base level and therefore does not include Quaternary erosion by glaciers. For example, the Norwegian channel is believed to have been carved by glaciers and demonstrates the potential of glacial erosion (Longva & Thorsnes 1997). A restoration of the eastern North Sea area prior to the onset of Quaternary erosion, which is beyond the scope of this

paper and therefore is not shown, indicates that well above 1000 m of sediments has been removed from the Norwegian Channel and the Skagerrak-Oslo fjord area, which was also noted by Riis & Fjeldskaar (1992). Depending on the height of the pre-Quaternary topography, Quaternary erosion could augment over-burial generated by the uplift of southern Norway by more than 500 m in the Skagerrak-Oslo Fjord area. Here there is no well control on the amplitude of over-burial and the map of Fig. 3 does not extend into this area.

### Over-burial of the North Sea Chalk Group has different causes

It is apparent from Fig. 16 that the burial anomaly estimates of Japsen (1998) are at a maximum in the axial zones and the marginal troughs of the two most prominent inversion zones of the North Sea region: The Sole Pit High to the west and the Sorgenfrei-Torn-

quist Zone to the east. Based on our knowledge about inversion zone dynamics, it is therefore reasonable to associate the large values of over-burial derived here with the occurrence of deep erosional truncation of sedimentary strata made available to denudation processes during the first phase of compressional inversion of the axial zone, and during the second phase of post-compressional rebound, which is smaller in amplitude but includes the marginal troughs. Also the Farsund Basin off the coast of southern Norway has experienced Late Cretaceous inversion (Jensen & Schmidt 1993), setting the scene for the later post-compressional uplift of a broader area. However, the Farsund Basin area was also under the influence of deep glacial erosion, which has augmented the values of over-burial. Toward the Norwegian coast the delamination-induced uplift of southern Norway becomes dominating. The gradual reduction of the over-burial estimates toward the central North Sea area is explained well by erosion caused by a falling base level, or by Quaternary erosion. The central area of zero over-burial represents the area where basin subsidence and sediment loading has kept up with falling base level and sediment infilling.

### Timing of post-compressional rebound

The prerequisite for post compressional rebound of inversion zones to occur is a modification of the inversion inducing regional stress field in the form of a reduction in strength or a rotation. The inversion inducing compressions of northwest Europe are believed to have been caused by the Atlantic opening and the African-European convergence, which produced inversions of structurally weak zones (rifts) in (mainly) Late Cretaceous through Palaeogene (Ziegler 1990, Vejbæk & Andersen 2002). With progressive Atlantic opening, ridge push became more important until the present day, when the general principal tectonic stress direction of North West Europe is NW-SE, largely perpendicular to the North Atlantic spreading axis (Zoback 1989). The North Sea area therefore has seen a marked change of the regional stress field during Cenozoic time, and therefore satisfies the primary prerequisite for the occurrence of post-compressional rebound of inversion zones. The timing of the rebound is linked to the regional stress field evolution, but depends also on the extent of erosional unloading, i.e. base level fall and climate. 100 m of tectonically produce rebound topography transforms to ~500 m of erosion once the topography again is level.

It is possible that a more detailed consideration of stress inducing processes at the boundaries of the

Eurasian plate can constrain the paleo stress evolution in the North Sea region and thereby bracket the occurrence of the post compressional movements. Another avenue to rebound timing is based on sediment stratigraphy. In general, a regional change of the stress field induces differential vertical movements of laterally heterogeneous lithospheric plates. As demonstrated by Gemmer et al. (2002) the central Jutland area (Fig. 16, Søhøjlandet) can be linked to a lithospheric strength anomaly consistent with the occurrence of Carboniferous-Permian intrusions (Abrahamsen & Madirazza 1986, Thybo & Schönharting 1991) in the lower crust. During the intense compressions, which inverted the Sorgenfrei-Tornquist Zone, the lithospheric 'strong spot' associated with Søhøjlandet subsided more than the neighbouring areas of the marginal trough and locally enhanced the depocentre. Later, as the regional stress field changed, the area of the 'strong spot' emerged with positive topography relative to the surroundings. The distribution and age of marine deposits in central Jutland therefore provide a sensitive timing of the onset of differential vertical movements in the eastern North Sea area. Along these lines the results of Huuse et al. (2001) and Huuse (2002) show how the Early to Middle Miocene north-eastern clastic influx from the Fennoscandian Shield through the eastern North Sea area during Middle to Late Miocene became cut off and deviated to the north along the Norwegian coast and to the south through the Baltic region. This observation may represent the evidence for the timing of the creation of a topographic barrier against north-eastern clastic influx by post-compressional rebound along the Sorgenfrei-Tornquist trend.

### Conclusions

In summary I find that the pattern and amplitude of sediment over burial, and in particular chalk over-burial, in the North Sea region are explained by four different processes, which are 1) continued subsidence of the central North Sea enhanced by sediment loading, compensating for the reduction in accommodation space caused by sediment filling and falling sea level, 2) Cenozoic uplift of the coastal areas of Scotland and southern Norway induced by plume initiated uplift of these land areas, enhanced by erosional unloading, 3) inversion zone dynamics in the form of two different phases of vertical movements caused by intra-plate stress variations from plate boundary processes, enhanced by erosional unloading, and 4) general denudation of the basin margins

and bordering land areas controlled by erosional base level changes.

I find that it is not necessary to invoke new Neogene tectonic events for the understanding of the evolution of the North Sea margins. However, as the mechanism of post-compressional rebound of inversion zones only recently has been realised, and because the tectonic rebound of the Sorgenfrei-Tornquist Zone is likely to stretch into Neogene time - perhaps even with major intensity in Middle to Late Miocene, it is fair to say that the rebound mechanism is the new and long missing Neogene tectonic mechanism in the eastern North Sea area.

I furthermore find that there is no causal relationship between the mechanisms responsible for the uplift of western Fennoscandia and Scotland, the accelerated Neogene subsidence of the central North Sea area and the occurrence of inversion zone dynamics. The spatial and temporal coherence of the associated sediment production and deposition, as well as the uplift related over-burial patterns, is enforced by regional synchronicity of climate and base level changes.

## Dansk sammendrag

En integreret kvantitativ model er anvendt på de seneste 100 mill. år af Nordsøområdet udvikling. Baseret på modellens forudsigelser, herunder visse modelforudsigelsers afvigelser fra observationer samt på resultaterne af tidligere arbejder, kan det konkluderes, at den geologiske udvikling af området indeholder følgende elementer: 1) fortsat indsynkning i det centrale Nordsø område som følge af palæozoiske og mesozoiske lithosfære- og kappeprocesser, 2) kænozoisk hævnning af Skotland og Sydnorge, begyndende i Paleocæn/Eocæn som følge af den islandske kappediapirs destabilisering af den dybe lithosfære under disse områder, 3) inversionszonedynamik som en funktion af ændringer af lithosfærens spændingsfelterne hidrørende fra pladerandsprocesser, samt 4) erosion og sedimenttransport kontrolleret af det faldende havspejl og klimavariationer. Disse processer er konsistente med den nutidige sedimentfordeling i Nordsøområdet, og er ydermere tilstrækkelige til at forklare mønsteret og amplituderne af sedimentoverbegravelse observeret i området. 1) den fortsatte indsynkning i den centrale Nordsø sikrer at sedimenterne her i dag antager den maksimale begravelsesdybde, 2) hævnning og erosionsaflastning af Skotland og Sydnorge har medført en sedimentoverbegravelse, der aftager væk fra kystområderne med en gradient, der afspejler lithosfærens fleksurelle egenskaber, 3) inversionszonerne (i særdeleshed Sole Pit High og

Sorgenfrei-Tornquist Zonen) har udviklet en to-faset begravelsesanomali, først i forbindelse med hævnning og erosion af den centrale inversionszone på tidspunktet for den primære kompression, senere ved den sekundære og mere udbredte post-kompressionelle hævnning og erosion af både den centrale inversionszone og de marginale trug. De nævnte tektoniske processer er grundlæggende uafhængige af hinanden. Den sammenhæng mellem de tektoniske processer, som alderen og fordelingen af sediment i Nordsøområdet antyder eksistensen af, er baseret på det forhold at regionale klimavariationer og havspejlsændringer nødvendigvis virker samtidig på den topografi som de tektoniske processer skaber. Den post-kompressionelle hævnning af Sorgenfrei-Tornquist Zonen foreslås at være den manglende Neogene tektoniske mekanisme i den østlige Nordsø.

## Acknowledgements

My colleagues in the 'TECFORCE' and 'CENMOVE' working groups are gratefully acknowledged for many discussions. The Danish Natural Science Research Council gave economical support to the project 'Tecforce'. James A. Chalmers and Ole V. Vejbæk are thanked for thorough and very useful reviews. Svend Stouge and Ole Rønø Clausen are thanked for the final editorial handling.

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