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REPORT

TITLE

The Tertiary uplift and subsidence pattern of Fennoscandia and the adjacent offshore areas (Literature survey report)

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SUMMARY

Literature on the Tertiary uplift of Fennoscandia and related subsidence of the neighbouring offshore areas is listed and reviewed.

A major problem is that the age of the uplift has not been determined directly (the only exception being some apatite fission track analyses), but either by correlation of constructed onshore planation surfaces with offshore unconformities or by inference of uplift phases from the presence of thick clastic wedges offshore. Accordingly, dispute on the age of one or several uplift phases goes on.

Similarly, there is no agreement on the mechanism responsible for the uplift.

A last chapter presents the state of age determinations for the Utsira Formation.

KEYWORDS ENGLISH	KEYWORDS NORWEGIAN
Tertiary	tertiær
Tectonics	tektonikk
Uplift, subsidence	landhevning, innsynkning
Fennoscandia	Fennoskandia
North Sea, Norwegian-Greenland Sea	Nordsjøen, Norskehavet

Table of Contents

1. Scope of the report

The pattern of uplift and subsidence areas influences the distribution of sedimentary deposits. Temporal changes of this pattern affect the evolution of sedimentary basis and of their infill. Scandinavia is well known for its uplift history in the Cenozoic (e.g., Stuevold & Eldholm 1996) and the surrounding oceanic areas document both, Cenozoic phases of uplift and subsidence. In spite of a general agreement on the occurrence of uplift and subsidence in that area, opinions diverge on the number and time of individual phases (especially concerning uplift of onshore areas) and on the mechanism(s) responsible for these vertical movements.

The Utsira Formation serves for CO_2 storage in the Sleipner field and is under investigation concerning its suitability for storage in other areas of the northern North Sea. This formation is different from the sediments below and above, due to its lithology (sand vs. shales), its restricted depositional area and its contemporaneity with hiatuses in neighbouring areas. It seems thus to have been deposited under special circumstances which might be linked to regional uplift and subsidence events.

This report aims to summarize the present state of knowledge on the spatial and temporal distribution of, and proposed mechanisms for, uplift and subsidence in southern Scandinavia and the adjacent oceans. Additionally, it provides an updated list of recent literature covering topics of relevance for the understanding of the Miocene to recent evolution of the northern North Sea.

2. Tertiary uplift and subsidence pattern

2.1 Uplift indicated by elevated peneplains

Mesozoic and/or Cenozoic uplift of Scandinavia is a phenomenon known from at least the beginnings of our century (e.g. Reusch 1901). Its occurrence and its areal extent were initially deduced from surface morphology, i.e. the presence of rugged, rather high mountains was interpreted to signify relatively recent uplift. In the meantime, several other methods were employed to define the areal extent and the time of uplift (Tab. 1 & 2).

Determinations of the extent and the amount of uplifted areas in Scandinavia relied mainly on the reconstruction of paleosurfaces, i.e. surfaces that are considered to represent former peneplains. These peneplains were interpreted to have formed during times of intensive weathering in warm climate and to have been situated roughly at sea level.

Reusch (1901) interpreted a major topographic surface which he termed **'Paleic surface'** (see also Gjessing 1967). However, this postulated surface may consist of several planation levels (Riis 1996, Lidmar-Bergstroem et al. 2000) and several other former planation surfaces have been interpreted, ranging from the sub-Cambrian peneplain to the post-glacial 'Strandflat' (e.g., Reusch 1901, Holtedahl 1960b, 1998, Lidmar-Bergstroem 1999, Lidmar-Bergstroem et al. 2000). Some of these surfaces include segments of older surfaces, and there are sometimes disagreements concerning the assignment (i.e. correlation) of local planation surfaces to one of the postulated regional surfaces (e.g. Holtedahl 1960b). This is due to the general problem of dating of these surfaces.

Table 1: Methods to determine the position (and areal extent) of an uplifted region.

Onshore data:	
❒	Area of high (+/- rugged) surface morphology
❒	Area of uplifted paleosurfaces (peneplains)
❒	Area of young cooling ages (esp. apatite fission track)
Offshore data:	
❒	Area from which initially horizontal strata dip away
❒	Source area of (coarse) clastic sediments
❒	Area of erosion (e.g. erosional discordances in seismics)
❒	Area of abnormal compaction or maturity (e.g. seismic velocity, vitrinite reflectance)

Since Scandinavia possesses only very few post-Caledonian sediments, the age of any erosional surface is difficult to establish (for examples of the indirect ways of reasoning refer to Riis 1996 or Lidmar-Bergstroem 1999) with the exception of the very rough statement that uplift is of post-Caledonian age. The age of most local planation surfaces in Scandinavia can not be directly determined at all, but is usually assigned according to the age of the regional surface to which they are correlated. The age of the regional surfaces, however, is usually also not directly determined, but is being interpreted from their general shape and its extrapolation to the offshore area or from the mutual relationships between regional surfaces (altitude, cross-cutting). These characteristics depend in turn on the selection of local surfaces that were used to construct the regional one.

Table 2: Methods to determine the age of uplift.

❐	Age of uplifted paleosurfaces (peneplains) gives maximum age
❐	Radiometric dating of cooling (esp. apatite fission track)
❐	Intervals of coarse clastic sedimentation and/or high sediment input rates (esp. intervals of formation of thick clastic wedges)
❐	Age of erosional discordances
❐	Age of youngest sediments recording abnormal compaction/maturity (maximum age)
❐	Age of initially horizontal sediments that dip away from uplift area (maximum age)

The main paleosurface employed in recent uplift reconstructions is a part of the 'paleic surface' called 'summit height envelope' (Doré 1992), which is defined as a surface touching the highest mountain tops (see, e.g. the profiles of Torske 1972). One effect of the uncertainties outlined above, are differing geometries of the interpreted planes, e.g., of the summit height envelope: (a) one or several domes (Gjessing 1967, Peulvast 1985, Riis & Fjeldskaar 1992, Lidmar-Bergstroem 1999) or (b) a tilted surface with a general dip towards SE (Holtedahl 1953, 1960a). Anyhow, even those arguing for a dome-shape agree that it is asymmetric, having a steeper slope towards the NW than towards SE. It should be emphasized, though, that almost no basic work (topographic analysis, geomorphologic field sudies) has been done on the paleic surface or summit height envelope since the times of Holtedahl (1953, 1960a&b). Gjessing (1967), Peulvast (1985, 1988) and Lidmar-Bergstroem et al. (2000) seem to be the only exceptions.

Further discussions here will be largely confined to the summit height envelope, because this is at present the only paleosurface on which most authors agree. However, opinions diverge concerning its age. Since no direct age evidence (e.g. by pre- and post-planation sediments) exists, several authors correlate the summit height envelope with dated major offshore unconformities (Figure 1): (a) Base Tertiary (Doré 1992), (b) Late Jurassic (Riis 1996; Figure 2), (c) Late Oligocene (Stuevold & Eldholm 1996). Torske (1972) derives an Early Tertiary age by attributing uplift to dated tectonic processes (uplift linked to early rifting of the Norwegian-Greenland Sea).

Lidmar-Bergstroem et al. (2000), in contrast, interpret the paleic surface to consist of several surfaces, and being dissected by valleys. They correlate each of six surfaces and three valley/relief-generations with offshore events (e.g. unconformities) ranging from Late Jurassic to the Quaternary (Figure 1).

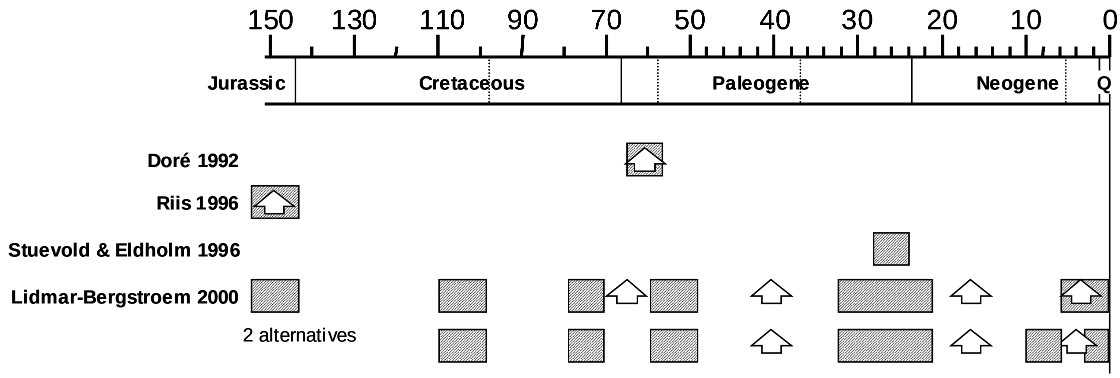

Figure 1 *Uplift phases of Fennoscandia indicated by the paleic surface(s), derived by correlation to offshore events (mainly unconformities). Note change of age scale at 50 Ma. Hatched boxes are ages of offshore surfaces (predominantly unconformities). Arrows are postulated uplift periods.*

Each of the correlations mentioned in the previous two paragraphs implies a different maximum age for regional uplift. The problem is that these correlations are not direct, i.e. by tracing the summit height envelope directly into a regional offshore discordance. They are usually based on the age of post-peneplain uplift, which in turn is interpreted from intervals of major clastic sedimentary input. The authors of these correlations claim a fit of the summit height envelope with the unconformity to which they correlate it. This fit, however, is rather rough because the summit height envelope is only weakly defined in the coastal area, all mentioned unconformities crop out (or subcrop beneath the Pliocene or Quaternary) close to each other parallel to the coast, and all reconstructions propose a steepening of the correlated surface in the coast area (e.g. reconstruction of Riis (1996) in Figure 2).

In spite of the problems mentioned above, most authors of recent publications agree that there are two areas of uplift in Scandinavia (northern and southern Scandinavia) and that both, though to differing amounts, were generated by one or two main uplift phases, one of Paleocene-Eocene age and the other of Neogene age (for recent summaries of ideas see Stuevold & Eldholm 1996 and Japsen & Chalmers 2000). A Neogene age for uplift is in accordance with apatite fission-track data for the southern dome (van der Beek 1995) and apatite and zircon fission track data from the northern dome (Løseth 1999; reports uplift post 10 Ma).

Note, however, that Huuse et al. (2001) regard only a single, Paleogene uplift phase as necessary to explain the observations on- and offshore southern Norway. They point to a possible delay of up to several tens of Myr between uplift and denudation and that timing and intensity of denudation may be strongly controlled by eustatics and climate. It is denudation that will be recorded both by apatite-fission tracks and by increased sediment input into adjacent basins.

Both, the elevation of the summit height envelope and fission track data, point to a maximum uplift of ca. 2000 m for the southern dome. Lidmar-Bergstroem et al. (2000) attribute approx. 1000 m uplift to a Cretaceous-Paleogene initial doming and maximum 1200 m uplift to Middle-Late Cenozoic processes.

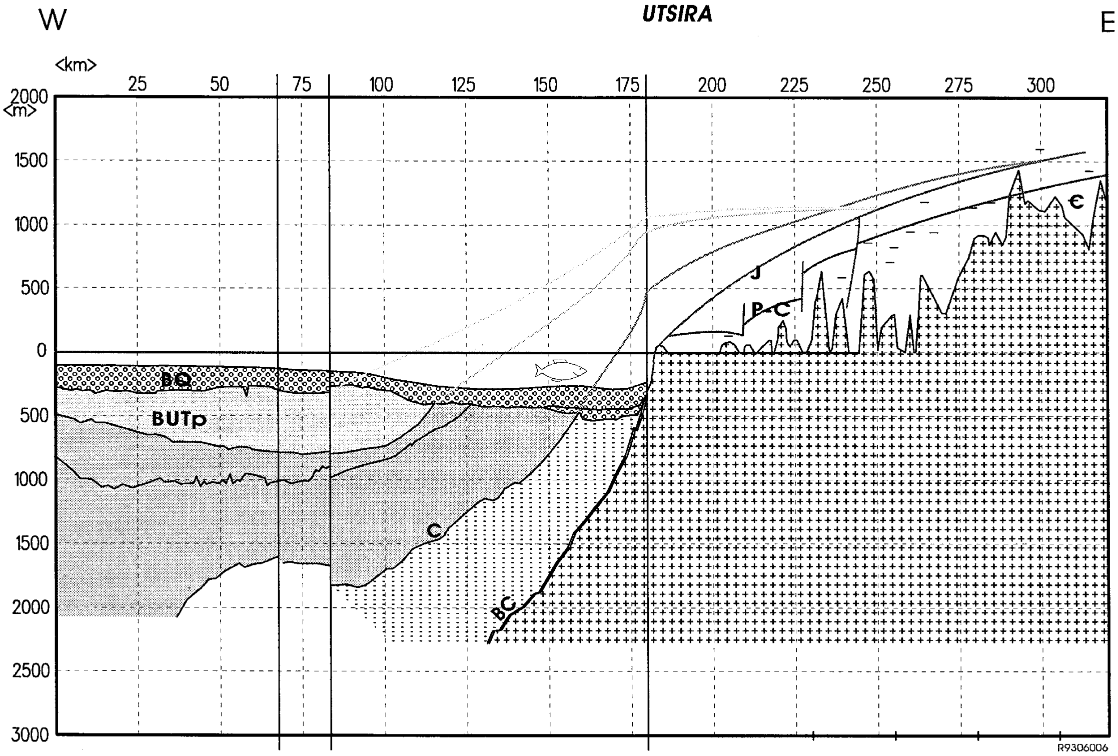

Figure 2 *Correlation of onshore mountain summit envelope with offshore unconformity at Base Cretaceous and extrapolation of offshore formation boundaries towards Scandinavia according to Riis (1996). Note that a correlation of the summit envelope could be done to virtually all sequence boundaries / unconformities offshore.*

Recent biostratigraphic dating of offshore sediments showed the presence of a major hiatus of Middle Miocene age (Eidvin et al. 2000). Following the reasoning of previous publications, this hiatus might then alternatively be correlated to the peneplains surface.

Since uplift ages are only weakly constrained, there is some discussion on the regional extent of individual uplift events. Some authors postulate large-scale uplift of the whole region surrounding the North Atlantic (e.g. Rohrmann & van der Beek 1996, Japsen & Chalmers, 2000), whereas e.g. Stuevold & Eldholm (1996) question the possibility to correlate uplift in Fennoscandia and the northwestern margin of the Norwegian-Greenland Sea.

2.2 Subsidence indicated by sediment accumulations

Neogene offshore subsidence contemporaneously to uplift of Scandinavia is a concept invoked by several authors (e.g., Cloething et al. 1990, Kooi et al. 1991, Doré 1992, Jordt et al. 1995). However, the main data available from the relevant basins (esp. Norwegian Sea and North Sea) is restricted to thicknesses and large-scale geometries of sedimentary deposits. Thus, they provide information on amounts of aggradation and progradation and, consequently, sediment input. Due to rather poor biostratigraphic data, deposition *rates* are more of qualitative character (high, low; but see Chapter 4 below for recent improvements concerning the Utsira Formation).

Only in recent years, Neogene deposits of the Norwegian Sea and the North Sea have become the focus of sedimentological research. Consequently, only very few data and models on their depositional environment and paleobathymetry have been published. This lack of data implies that subsidence reconstructions of the basins for the Neogene are rather speculative (e.g., Kooi & Cloething 1989 and Kooi et al. 1991, who do not include paleobathymetry during construction of their subsidence curves). Periods of increased sediment input are thus interpreted as subsidence intervals, but may in some cases rather reflect glaciation or denudation of the source area. In fact, the age of thick clastic wedges (Table 1) is a major information source used to constrain the age of Scandinavian uplift (see Chapter 2.1).

Table 1 *Age of clastic wedges offshore Norway which are interpreted to document uplift of the source area.*

Location / interpreted age	**Reference**
Offshore Mid Norway:	
Late Pliocene – Pleistocene	Riis & Fjeldskar (1992), Riis (1998)
Mid Pliocene to Pleistocene	Evans et al. (2000)
Mid to Late Pliocene	Henriksen & Vorren (1996),
Early Pliocene	Stuevold & Eldholm (1996)
Late Miocene to Early Pliocene	Henriksen et al. (1999)
Oligocene to Early Miocene	Eidvin pers. comm. 1999, Eidvin et al. (2000)
Northern North Sea:	
Late Pliocene – Pleistocene	Eidvin et al. (1999, 2000), Eidvin & Rundberg (2001a)

Mid-Norwegian margin

Miocene deposits off mid-Norway are relatively thin and were interpreted to record tectonically quiet conditions by Riis & Fjeldskar (1992) and Riis (1998). These authors assign a Late Pliocene to Pleistocene age to thick clastic wedges which they interpret as documents of subsidence. Stuevold & Eldholm (1996) argue for an early Pliocene thick age of the clastic wedge, taken to be caused by high sedimentary input due to glaciation. Henriksen et al. (1999) prefer a Late Miocene to Early Pliocene of the wedge, whereas Eidvin (pers. comm. 1999 in discussion of presentation of Henriksen et al. 1999) stated that biostratigraphic dating of wedge sediments from several wells yielded Oligocene to Early Miocene ages.

However, differences in age assignment may be due to poor biostratigraphic control (Stuevold & Eldholm 1996). Nevertheless, the presence of wedges of Pliocene and/or Pleistocene age is evident (see, e.g., Blystad et al. 1995), and the increase in sediment input is most likely due to source area uplift and/or glaciation. Tilting and erosion of strata up to Plio-Pleistocene in age close to the present shoreline (Riis 1996) evidences Quaternary uplift, which was followed by subsidence and deposition of Quaternary clastic sediments.

Gradstein & Baeckstroem (1996) present biostratigraphic and paleobathymetric data which they interpret to record increased subsidence (i.e. tectonic subsidence) at the Mid-Norwegian margin starting 3-5 Myr ago. Their paleobathymetric reconstruction shows gradually shallowing water depths between 500m and 0m for almost all the Tertiary and a slight deepening since the Late Pliocene. Their subsidence analysis does not indicate a Pliocene or Pleistocene uplift (in fact, the indicate the contrary: rapid subsidence), because the analyzed wells are situated basinward of the uplifted zone.

Northern North Sea

Gradstein & Baeckstroem (1996) present a paleobathymetric reconstruction and a subsidence analysis for a well in the Central North Sea, from which they deduce a Middle Miocene uplift phase followed by fast subsidence from Late Miocene to recent (Figure 3). This mid-Miocene uplift phase could provide an explanation of the so-called 'Mid-Miocene unconformity' (e.g., Isaksen & Tonstad 1989; see also Eidvin et al. 2000) and would be in accordance with the model of Japsen (1997) who argues for a Neogene (most likely Middle Miocene) uplift of eastern UK and the western North Sea. However, Japsen (1997) has no direct evidence for the age of uplift but bases his argumentation for a Middle Miocene uplift age on the mid-Miocene unconformity.

The subsidence reconstruction of Gradstein & Baeckstroem (1996) for the Central North Sea is much less secure than that for the mid-Norwegian margin and depends strongly on an interpreted drastic reduction of water depth (ca. 500m) in the Middle Miocene which results in calculated tectonic uplift (see also Gradstein 1998). The need to create accommodation space for deposition of the thick Pliocene sediments forces them to deduce fast (i.e. tectonic) subsidence (Figure 3). If the reduction of water depth would have occurred later (e.g. during, and as a result of, the outbuilding of Late Miocene and Pliocene thick clastic wedges; see below), both, the Middle Miocene uplift and the fast Late Miocene subsidence events in the reconstruction would disappear. This alternative reconstruction does not exclude Pliocene to recent rapid subsidence like that known from the Haltenbanken area. Note, that Gradstein et al. (1994) show a more gradual decrease in water depth through time for seven northern North Sea wells, of which only two (those with the most sudden decrease) yielded a moderate Miocene uplift phase.

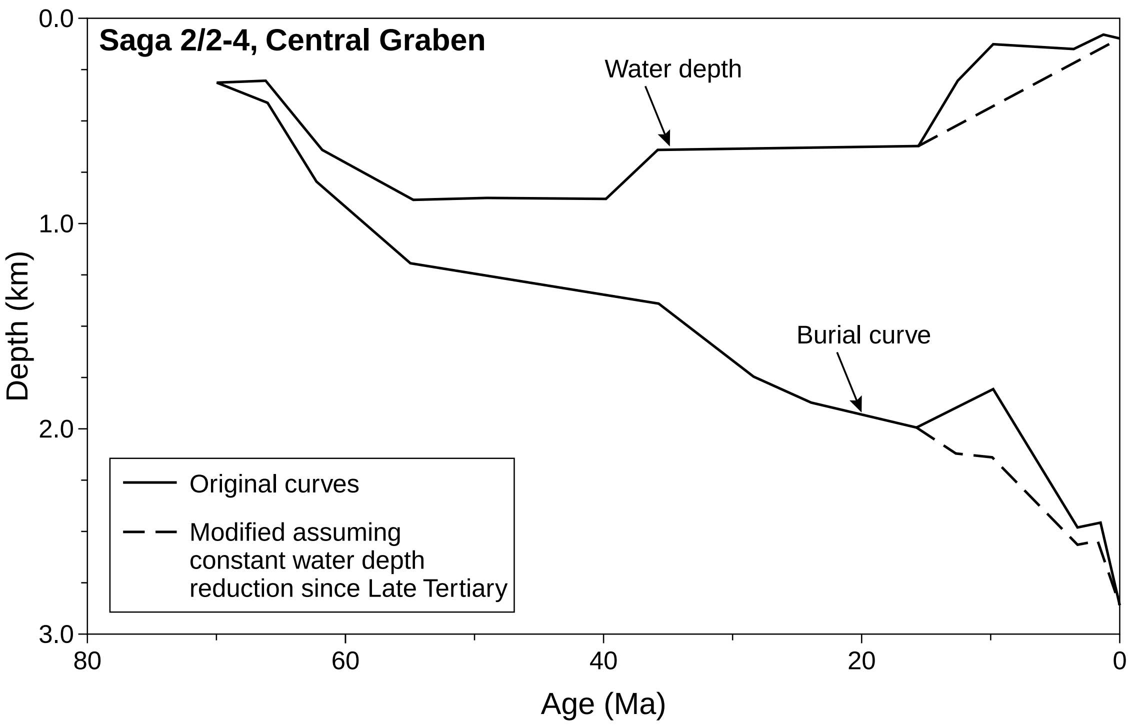

Figure 3 *Subsidence curve for Norwegian well 2/2-4 (Ekofisk area) after Gradstein & Baeckstrøm (1996). The authors deduce an uplift phase in the Miocene followed by a phase of rapid subsidence. Note that the uplift phase would disappear if a constant water depth reduction from the Miocene to recent would be assumed (stippled lines).*

Kjennerud et al. (2001) and Kyrkjebø et al. (2001) carried out paleobathymetric analyses based on micropaleontological data and on structural reconstructions from the northern North Sea. They yield for the majority of wells a substantial deepening during the upper Miocene to create accommodation space for the Pliocene prograding wedges. Most wells are, however, from 100 to 300 km north of the Sleipner area. For the well closest to the Sleipner area, 15/5-3, no such deepening phase has been interpreted. Related paleobathymetric maps documented in Kjennerud (2001) indicate a water depth between 200 and 500 m for the Sleipner area in the Early Pliocene.

Miocene deposits of the northern North Sea can reach several 100 m in thickness in the Sleipner area but are much thinner than those in the Central North Sea. Eidvin et al. (1999) report approx. 400 m thick Miocene sediments in well 15/12-3 as compared to almost 1100 m in well 2/4-C-11 in the Ekofisk area. Further to the north (block 34), Miocene deposits are either absent or very thin (up to approx. 100 m; Eidvin & Rundberg, 2001a).

The Utsira Formation itself reaches up to approx. 300 m in thickness in the Sleipner area but is much thinner elsewhere (Chadwick et al. 2000; Gregersen et al. 2000). Its depositional environment and, accordingly, its depth of deposition, are disputed. Isaksen & Tonstad (1989) argue for shallower, Galloway et al. (1993) for a larger depth. Galloway (2001) postulates a depth between 200 and 250 m, based on the geometry of correlative prograding wedges from the NW. Eidvin et al. (1999) interpret a middle to outer neritic depositional environment for the Sleipner area, i.e. shallower conditions than in the Central North Sea at that time, and Eidvin & Rundberg (2001a) propose for the northernmost North Sea (block 34) a water depth between 100 and 200 m based on somewhat inconclusive data (Figure 4).

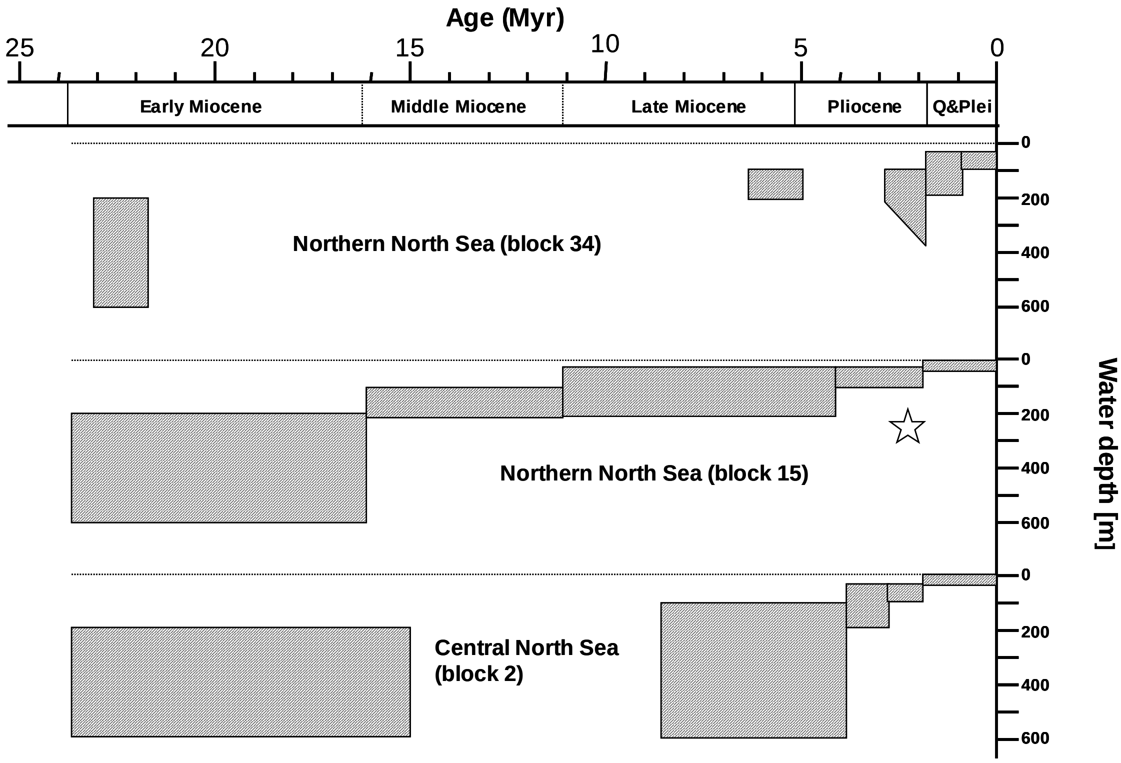

Figure 4 *Water depth ranges according to Eidvin et al. (1999) and Eidvin & Rundberg (2001a) and own interpretations of depositional geometries on seismic data (star symbol).*

The thickness of the overlying Pliocene deposits in the northern North Sea is rather high: several 100 meters, reaching at least 700 m (Fig. 20 in Jordt et al. 1995). They consist mainly of prograding clastic wedges (Gregersen et al. 1997) whose sedimentary architecture points to changing paleowaterdepths from sea level at the margin to at least 250 m at the toe of the wedges. It is not yet clear if this paleotopography was inherited from the Miocene, when it was not filled up due to a low sedimentary input, or if it reflects post-Miocene rapid subsidence (see above).

Deposition of the Pliocene clastic wedges was followed by tilting of the marginal parts of the sediments and substantial erosion, and subsequent deposition of Pleistocene to recent sediments. The present water depth in the central parts of the northern North Sea is around 300 - 400 m, indicating substantial Pleistocene to recent (tectonic) subsidence. In conclusion, data from the northern North Sea provide clear evidence for young (late Pliocene, Pleistocene) uplift and for subrecent tectonic subsidence. Postulated Miocene tectonic uplift and/or subsidence, however, require still to be supported by data.

3. Causes for uplift and subsidence

The occurrence of phases of uplift and subsidence in the North Sea and its surroundings during the Cenozoic is generally accepted (see previous chapter for quotations). As evident from the previous chapter, there is quite good agreement on the uplift amounts of southern Fennoscandia. Most authors agree on approx. 1000 m uplift during the Paleogene and additional uplift of similar magnitude during the Neogene. There is also not much disagreement concerning total subsidence amounts and the ages of major sediment packages are reasonably well constrained. Further, authors agree that there seems not to exist any major faults that could accommodate differential vertical movements between the areas of uplift and subsidence.

There is a consensus that the uplift and subsidence phases constitute deviations from the expected long-term subsidence pattern for the post-rift phase of Jurassic rifting (e.g., Kooi & Cloething 1989, Joy 1993, van der Beek (1995), Kyrkjebø 1999). Several authors have presented potential explanations for such deviations, and some of them will be discussed below. They are generally of a speculative character, applying known or assumed physical (usually: tectonic) processes to the region. Some of them present the links between potential causes and observed consequences on a purely argumentative (qualitative) base, while others quantitatively simulate theoretical consequences and compare them with the observed uplift and subsidence pattern in time and/or space.

The suggested mechanisms (Table 2; see van der Beek 1995, Stuevold & Eldholm 1996 and Jaspen & Chalmers 2000 for recent summaries) differ in the predicted wavelength (i.e. area of uplift or subsidence) and in the predicted uplift/subsidence amounts. Critical parameters to rate the plausibility of the different models are therefore the areal extent of uplifted or subsided areas (and the possible contemporaneity of uplift and subsidence in neighbouring areas) and the uplift and subsidence amounts.

The mechanisms can roughly be grouped into three main classes (Table 2) and will be presented accordingly below.

Thermal mechanisms

These mechanisms are causally related to the opening (rifting) of the Norwegian-Greenland Sea as a part of the North Atlantic or to the hotspot-plume, which is presently beneath Iceland.

Torske (1972), Sales (1992), and Eyles (1996) (and several others, see Stuevold & Eldholm 1996) attribute Fennoscandian uplift to processes related to Paleogene rifting of the Norwegian-Greenland Sea (see e.g. Ziegler 1988). In essence, the uplifted area constituted part of the initial, pre-rifting dome and became the graben shoulder afterwards. This mechanism can explain the earlier, Paleogene uplift phase. The second, Neogene phase that is accompanied by deposition of large sediment volumes offshore, is however separated from the rifting stage by several tens of Myr.

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Table 2 Suggested mechanisms for uplift of Fennoscandia linked to subsidence in the neighboured offshore areas.

Process, Cause	**Reference**
Thermal mechanisms	
Opening of Atlantic (rifting)	Torske 1972, (Huuse et al. 2001)
Rifting-related magmatic underplating	Eyles 1996
Peripheral bulge, related to rifting	Sales 1992
Thermal origin (small-scale convection)	Stuevold & Eldholm 1996
Asthenospheric diapirs related to Island plume	Rohrman & van der Beek 1996
Related to glaciation/deglaciation/isostasy	
Phase transition in lithosphere due to pressure reduction	Riis 1998
Change in glaciation cyclicity	Riis & Fjeldskaar 1992
Tectonic stress	
Compression (tectonic; applied mainly to UK)	Hillis 1995
Intra-plate compression/extension	Kooi & Cloething 1989, Cloething et al. 1990 & 1992, Kooi et al. 1991, Reemst 1995

Japsen & Chalmers (2000) argue that the elevation generated in the Paleogene could have persisted until the Neogene when changing eustatic and climatic conditions could have triggered pronounced denudation and transport of eroded material into the adjacent basins. Similarly, Eyles (1996, 1997) argues that the elevated plateaus existed since the Paleocene-Eocene transition and provided high-standing high-latitude areas sensitive to global cooling during the Neogene.

Stuevold & Eldholm (1996), and Rohrman & van der Beek (1996) attribute Neogene circum-North Atlantic or Fennoscandian uplift to effects of the Iceland plume (see also Clift et al. 1998). Stuevold & Eldholm (1996) suggest two models. One of them is a variation in heat flux through time, including an increased heat flux near the Oligocene-Miocene transition. The other model assumes shallow convection cells initiated in the mid-Tertiary that travel with the lithosphere. Rohrman & van der Beek (1996) suggest that asthenospheric diapirs developed close to the margin of the Iceland plume. The generation of these diapirs would be time-delayed relatively to the arrival of the Iceland plume (Lawver & Müller, 1994) in the neighbourhood of Fennoscandia. The explanation of uplift by a plume is in contrast to modellings of van der Beek (1995) who concluded that thermal erosion of the lithosphere should have related other surface expressions (e.g. volcanism) which are not observed. Rohrman & van der Beek (1996) argue at such effects would be expected to occur with a time-delay, and the lack of volcanism would consequently attest to the young age of the diapiric processes.

Related to glaciation/deglaciation/isostasy

Some isostatic rebound after melting of the glacial ice cover on Fennoscandia is generally accepted to have contributed to recent uplift (see, e.g. the most recent determinations of the present-day uplift rate and its modelling by isostasy in Fjeldskaar et al. 2000 and Dehls et al. 2000). Riis (1996) interprets that the youngest uplift phase started earlier than the deglaciation and he vaguely suggests a change in the glacial cyclicity to have ‘initiated or enhanced crustal processes leading to uplift’.

Earlier, Riis & Fjeldskaar (1992) calculated the mass of glacially eroded sediments from the volume of sediments deposited in clastic wedges around Fennoscandia. They showed that the observed magnitude of uplift is larger than what could be expected from isostatic compensation and they suggested phase transitions in the lithosphere which would be induced by uplift-induced pressure decline, as a possible mechanism.

A general problem is, what was first, Neogene uplift or glaciation? (See for example the general discussion of Molnar & England 1990.) Cloething et al. (1990), Doré (1992) and Eyles (1996, 1997) are among those who argue that the presence of an uplifted area was a pre-requisite for the glaciation. Consequently, a complex model that includes glacial processes seems to be most likely.

Tectonic stress

Tectonic stresses of varying type and origin have been invoked to explain uplift and subsidence (anomalies) in Fennoscandia and its surrounding. Doré (1992), for example, suggested that variations in the NW-European stress field could account for otherwise unexplained uplift and subsidence components. He saw plate tectonic reorganisations in the North Atlantic and Tethyan closure in the southeast as possible causes for such stress variations. Note, that Vågnes et al. (1998) speculatively use stresses transferred from the Alpine area to the Norwegian shelf to explain Late Cenozoic deformation there.

Hillis (1995) interprets Tertiary regional exhumation of the British Isles to be of thick-skinned origin, where lithospheric compression generates a pattern of uplift and subsidence. Similar processes might be postulated for contemporaneous vertical movements in Fennoscandia.

Liu et al. (1992) suggest and model three processes to account for Cenozoic Barents Sea uplift and erosion: subcrustal mantle lithospheric extension, crustal thickening, and magmatic intrusion into the crust

Cloething et al. (1990) and related publications (see Table 2) model the effect of increased compressional intraplate stress on basin subsidence and conclude that it can account for the observed short-term deviations from the expected post-rift subsidence pattern in several areas around the North Atlantic, including the North Sea and the Vøring basin offshore mid-Norway. Van der Beek (1995) however, concludes that the effect of intraplate stresses is too small to explain the uplift of southern Norway.

Conclusion

There seems to be wide consensus that (most of) Paleogene uplift of Fennoscandia can be explained by processes related to rifting of the Norwegian-Greenland Sea. In contrast, explanations for the Neogene uplift phase are not fully conclusive. There is unanimity that Late Cenozoic glaciations played an important role but also that these glaciations and directly related processes such as erosion and isostatic uplift can only account for parts of the observed onshore uplift and offshore subsidence. Some of the suggested models have been ruled out, at least to be the single additional contributor. Many of the remaining models are highly speculative and far from any possibility to quantify – and thus test – their predictions.

In consequence, we can still follow van der Beek (1995) when he states that 'the conclusion must be that the origin of (at least part of) the Neogene uplift of western Fennoscandia remains enigmatic.'

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4. The age of the Utsira Formation

The age of the Utsira Formation has been a matter of dispute as evident from Figure 5 which summarizes the major existing age determinations. Initially, the Utsira Formation was defined by Deegan & Scull (1977) as the section ranging from 644.5 m to 1064 m (MD-RKB) in the type well 16/1-1 (NO). They noted that 'the formation is usually the first thick sand development below the Pliocene and Recent argillaceous sediments' which was widely used to assign sand units of presumably Miocene to Pliocene age to the Utsira Formation. Deegan & Scull (1977) listed a Middle to Late Miocene age for the formation.

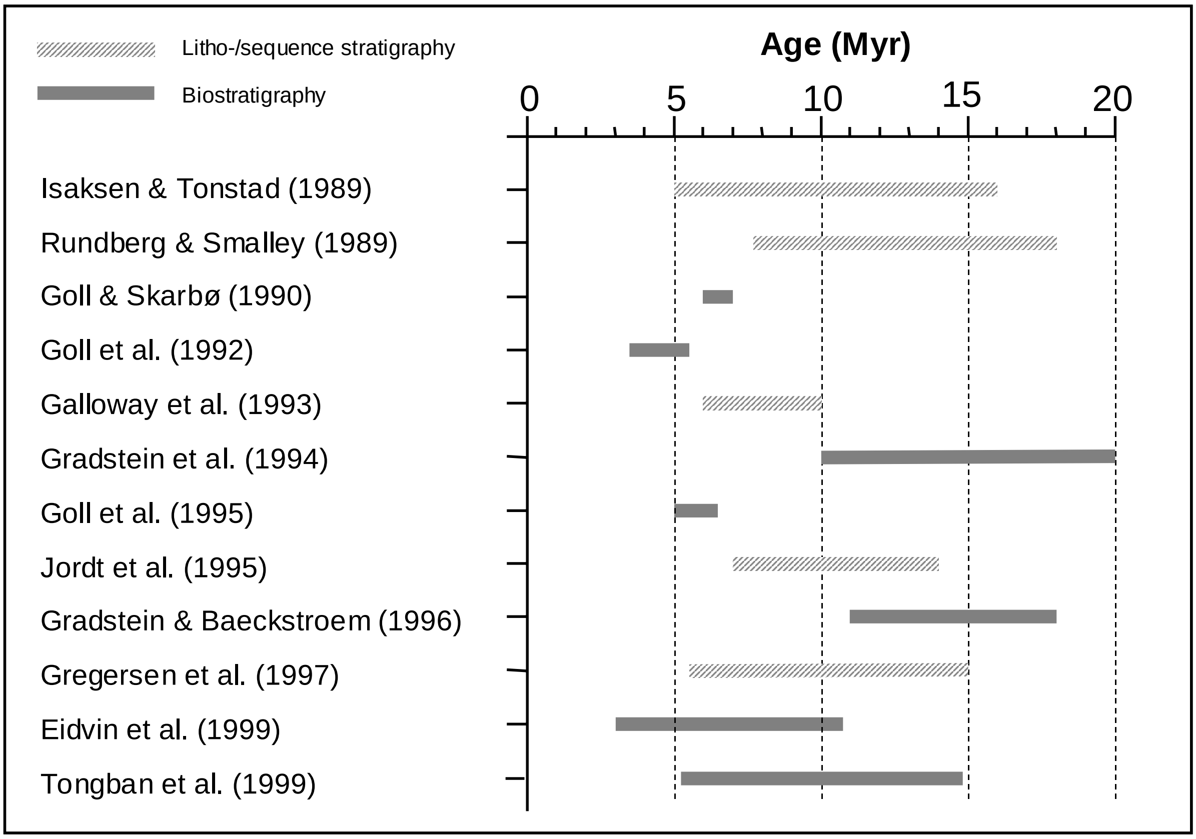


Figure 5 Age determinations for the Utsira Formation. Note that Rundberg & Smalley (1989) used Sr-isotopic age determinations in addition to lithostratigraphic/sequence-stratigraphic correlations.

The large discrepancies between different age determinations for sediments that were classified as Utsira Formation have three major reasons:

- Following the note of Deegan & Scull (1977), more or less all sand packages of more than a few m thickness occurring at the base or directly below the thick Pliocene argillaceous sequences were classified as Utsira Formation by purely lithological arguments, irrespective of the (im-)possibility to correlate these units with confidence from one well to the other (esp. by seismics). Consequently, sand bodies of different age and origin were interpreted to be as the same 'Utsira Formation' and age determinations had accordingly a wide spread.

- The Utsira Formation contains only few fossils, and many of them are probably reworked (see, e.g., Eidvin et al. 1999 and Eidvin & Rundberg 2001a).
- Most biostratigraphic and the few Sr-isotope age determinations prior to the late 1990's were carried out using ditch cuttings, and contamination by sampling of younger formations was therefore a source of error. Only the recent age determinations of Eidvin et al. (1999), Eidvin et al. (2000) and Eidvin & Rundberg (2001a,b) use proven *in situ* material, i.e. core and sidewall core samples.

The correlation of Eidvin et al (2000) shows that the interval of deposition of Utsira Formation sands is towards North restricted by a hiatus (Figure 6). The most complete sequence exists in the Sleipner area. The age determination from well 15/12-3 yielded an age range from latest Middle Miocene to earliest Late Pliocene (Eidvin et al. 1999).

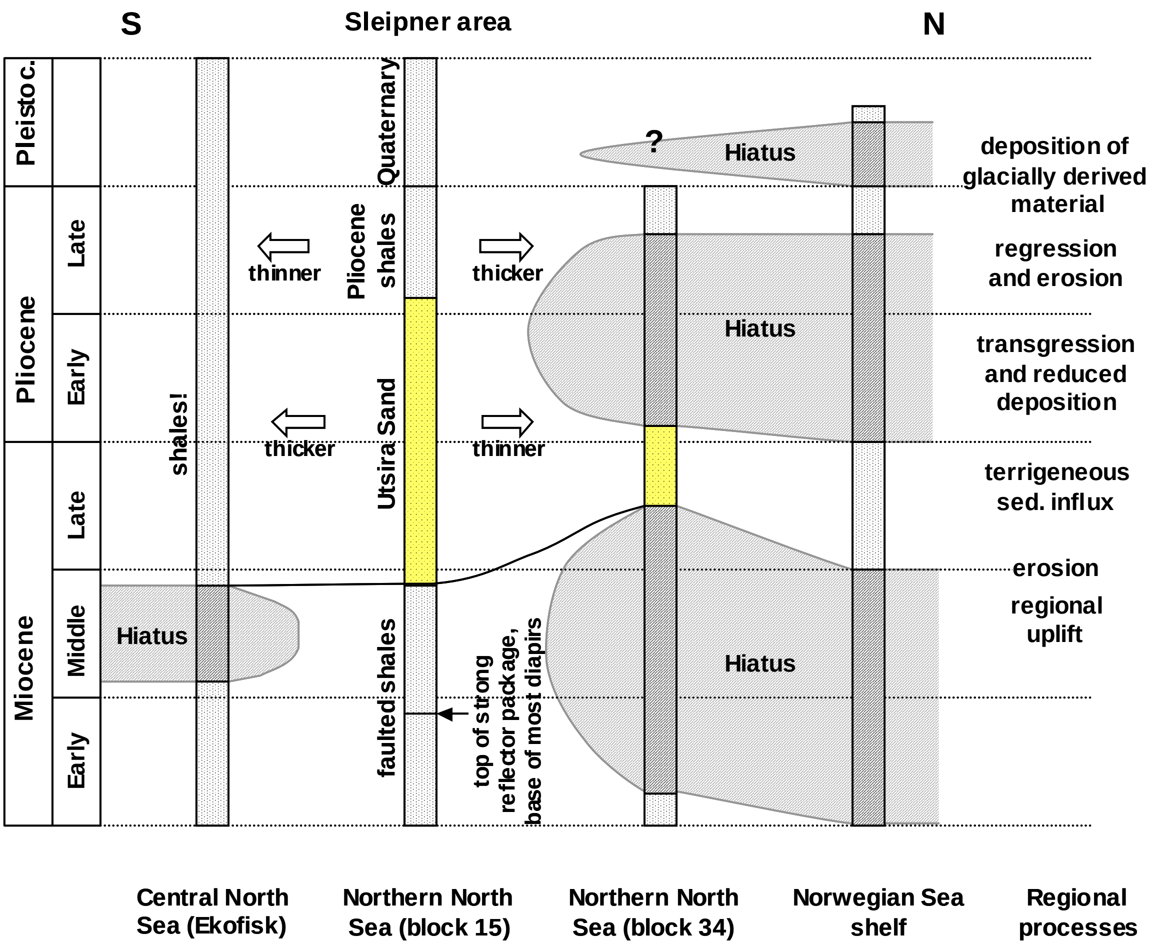


Figure 6 *Schematic correlation scheme for the Miocene to Pleistocene of the Central and Northern North Sea and the Norwegian Sea shelf. Data from Eidvin et al. (2000).*

Analysis of the type well 16/1-1 (NO), which is in close neighbourhood to the Sleipner area (Eidvin & Rundberg 2001b), showed that the lower part of the type section is of the same age (Early Miocene) as parts of the Skade Formation, as defined in its type well 24/12-1 (NO). Eidvin & Rundberg (2001b) propose accordingly to redefine the Utsira Formation and its type section.

Since Eidvin & Rundberg (2001b) do not document the data for their reasoning (the paper is an abstract only), relevant accessible data was examined in this study. Well 16/1-1 is in close neighbourhood of well 24/12-1, the latter being approx. 10.5 km NW of the former. Wire-line log data in Isaksen & Tonstad (1989) show in well 16/1-1 a sand-dominated lower part with low gamma-ray and sonic velocity values and a blocky pattern in both logs (Figure 7a). This is similar to the interval used to define the Skade Formation in well 24/12-1 (Isaksen & Tonstad 1989, Figure 7b). The top of this interval is approx. 50 m deeper in well 16/1-1, which is in accordance with the general trend as evident on seismic (e.g. line VGST98-112, which connects the two wells).

In well 24/12-1, an approx. 330 m thick sand unit occurs above the Skade Formation, which has been interpreted to be the Utsira Formation (Oljedirektoratet 1984). The upper 2/3 of the Utsira Formation in well 16/1-1 (i.e. that part which is not the Skade Formation according to Eidvin & Rundberg 2001b) has dominantly higher gamma-ray values and only approx. half of the thickness consists of sand. It is approx. 260 m thick. NW-ward formation thickening in this area is in accordance with seismic data in line VGST-89-112.

Thickness data from BGS and GEUS derived in the SACS project (Chadwick et al. 2000) show a reduced thickness of the Utsira Sand in the area where wells 16/1-1and 24/12-1 are located, when compared to the Sleipner area. This is in apparent contrast to larger thickness of the Utsira Formation in wells 16/1-1 (without the Skade Formation) and 24/12-1 than in the Sleipner area. Note, however, that the interpreted units are not the same. Whereas the published well interpretations of 16/1-1 and 24/12-1 refer to the Utsira *Formation* (containing substantial shale proportions), mapped Chadwick et al. (2000) the thickness of the sand-dominated part of the same formation (the Utsira *Sand*).

Eidvin et al. (1999) show that the sandy Utsira Formation as it is known from the Sleipner area and further north, is replaced towards south by correlative shaly units. Applying their age determinations to thickness data for the two wells used in their study, yields sedimentation rates for the Ekofisk and the Sleipner area shown in Figure 8. This figure illustrates primarily two trends:

- Very low sedimentation rates for the sandy Utsira Formation followed by much higher rates for the shaly Pliocene deposits.
- Lower rates for the sandy Utsira Formation in the Sleipner area than for the shaly correlative deposits in the Ekofisk area.

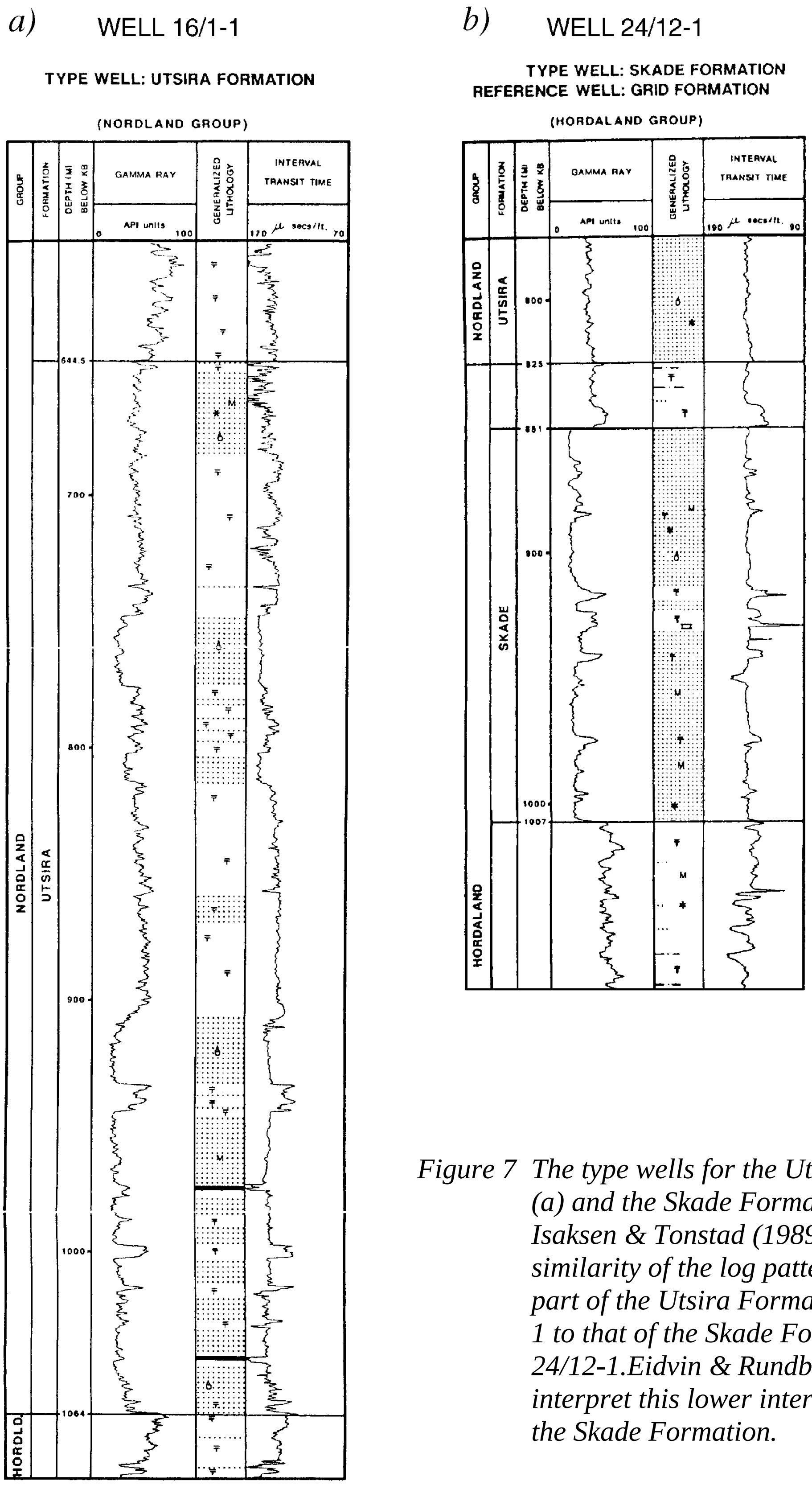
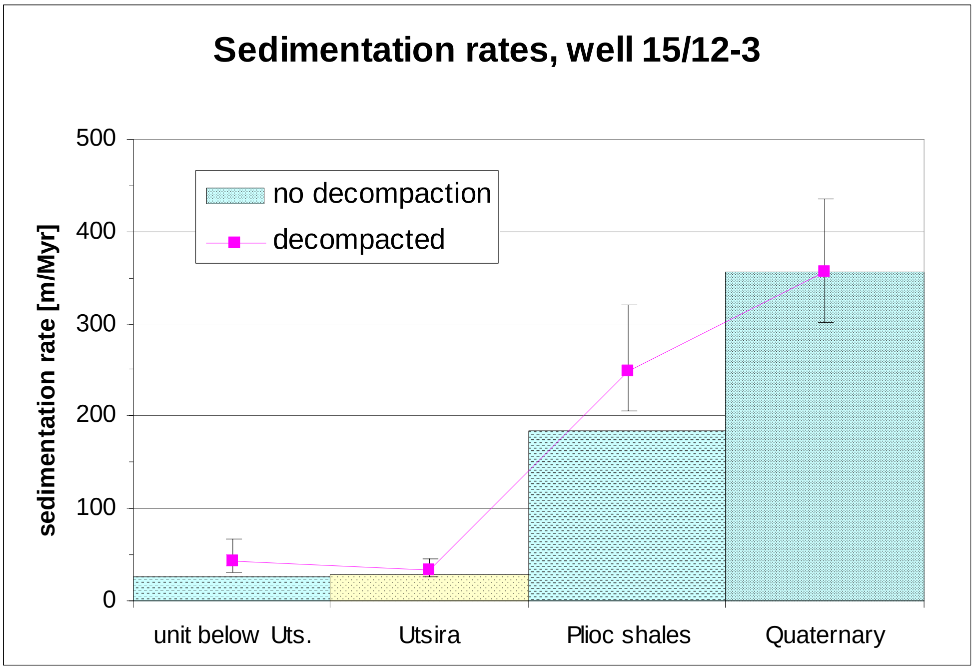


Figure 7 The type wells for the Utsira Formation (a) and the Skade Formation (b) after Isaksen & Tonstad (1989). Note the similarity of the log pattern of the lower part of the Utsira Formation in well 16/1-1 to that of the Skade Formation in well 24/12-1.Eidvin & Rundberg (2001b) interpret this lower interval to belong to the Skade Formation.



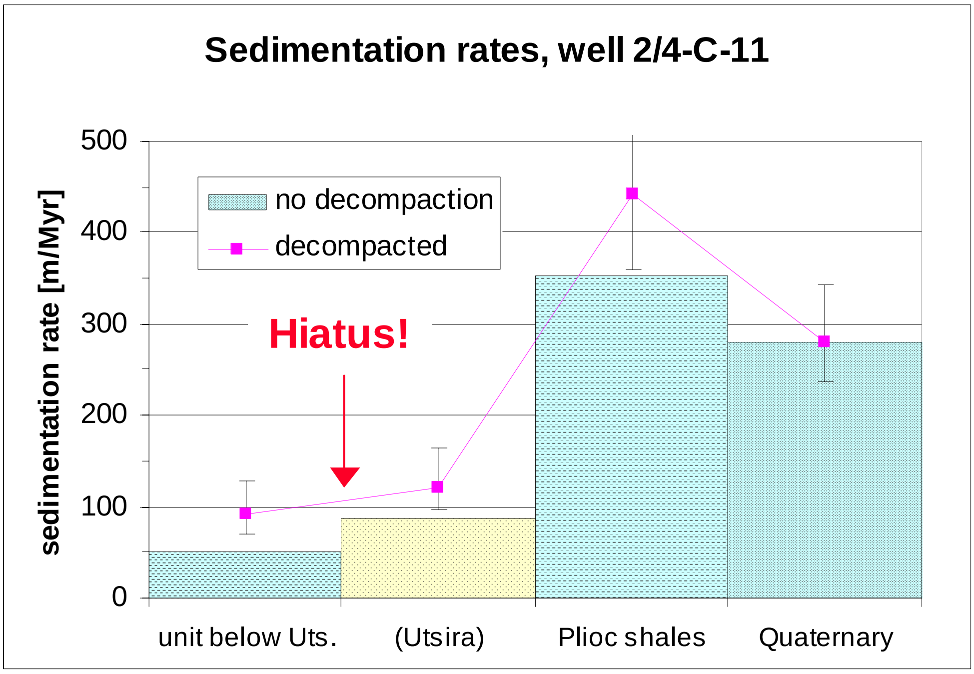


Figure 8 *Sedimentation rates for Miocene to Quaternary formations in the Sleipner and Ekofisk area. Age and thickness data from Eidvin et al. (1999). Decompaction procedure according to Allen & Allen (1990). Note that the unit in well 2/4-C-11 that corresponds to the Utsira Formation further north consists predominantly of shales and is separated from the underlying unit by a hiatus (cf. Figure 6).*

5. Relevant publications

This chapter lists publications referred to in the text and new publications with relevance for the understanding of the Miocene to recent evolution of the northern North Sea. A selection of recent publications (mainly from the late (1990's) of special interest for the topics of this literature survey have summaries attached in the list.

Abreu, V.S. & Anderson, J.B., 1998: Glacial eustasy during the Cenozoic: sequence stratigraphic implications. *Am. Ass. Petrol. Geol. Bulletin*, 82, 1385-1400.

Allen & Allen (1990): *Basin Analysis*. Blackwell Scientific Publications. Oxford (UK), 451 pp.

Bakkelid, S., 1992: Mapping the rate of crustal uplift in Norway: parameters, methods and results. *Norsk Geologisk Tidsskrift*, 72, 239-246.

Bertram, G.T. & Milton, N.J., 1989: Reconstructing basin evolution from sedimentary thickness; the importance of paleobathymetric control, with reference to the North Sea. *Basin Research*, 1, 247-257.

Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J., & Tørudbakken, B., 1995: Structural elements of the Norwegian continental shelf. Part II: The Norwegian Sea Region. *NPD-Bulletin*, 8, 45pp.

Boldreel, L.O. & Andersen, M.S., 1993: Late Paleocene to Miocene compression in the Faeroe-Rockall area. *From Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference* (edited by J.R. Parker). The Geological Society, London, pp. 1025-1034.

Recognize at least three Eocene to Miocene compressional phases based on seismic data: late Paleocene-early Eocene, Oligocene, middle or late Miocene. Note that well control, and thus dating, is poor; this is especially valid in the Neogene.

Brekke, H., 2000: The tectonic evolution of the Norwegian sea continental margin with emphasis on the Vøring and Møre Basins. In: Nøttvedt, A. (ed.): *Dynamics of the Norwegian Margin*. Geol. Soc. Spec. Publ., 167, 327-278

Bungum, H., Alsaker, A., Kvamme, L.B., & Hansen, R.A., 1991: Seismicity and seismotectonics of Norway and nearby continental shelf areas. *Journal of Geophysical Research*, 96, 2249-2265.

Byrkjeland, U., Bungum, H., & Eldholm, O., 2000: Seismotectonics of the Norwegian continental margin. *Journal of Geophysical Research*, 105, 6221-6236.

Norwegian continental margin has lower seismic activity than some comparable areas worldwide. Some seismic activity seems to be related to the position of thick glacial sediments. Large gradients of postglacial rebound in the coastal area are suggested to contribute to locally increased seismic activity. Local stress sources are of importance, as evidenced by the occurrence of shortening axes with up to 90º deviation from the shortening axis caused by the dominating ridge push mechanism.

Chadwick, R.A., Holloway, S., Kirby, G.A., Gregersen, U., & Johannessen, P.N. 2000: The Utsira Sand, Central North Sea - An assessment of its potential for regional CO2 disposal. In: Williams, D. et al. (eds.): *Greenhouse Gas Control Technologies. Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies*. CSIRO Publishing, Collingwood, Australia. pp. 349-354.

Clausen, J.A., Gabrielsen, R.H., Reksnes, P.A., & Nysæther, E., 1999: Development of intraformational (Oligocene-Miocene) faults in the northern North Sea: influence of remote stresses and doming of Fennoscandia. *J. Struct. Geol.*, 21, 1457-1475.

Intra-Oligocene unconformity formed due to uplift of Fennoscandia and sea-level fall. (Further?) tilting of Horda Platform (until?) in Late Mocene due to continued uplift of south-central Norway.

Clift, P.D., Carter, A., & Hurford, A.J., 1998: The erosional and uplift history of NE Atlantic passive margins; constraints on a passing plume. Journal of the Geological Society, 155, 787-800.

Interpret uplift of parts of Greenland and of the Hebrides shelf in the earliest Tertiary as being caused by a frontal tongue of the Iceland plume. Crossing of the plume by the east Greenland coast in mid-late Eocene would account for uplift there but not for the European side of the North Atlantic basin.

Cloething, S. 1986: Intraplate stresses: A new tectonic mechanism for fluctuations of relative sea level. *Geology*, 14, 617-620.

Cloething, 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? *J. Geol. Soc.*, 147, 495-506.

Cloething, S., Reemst, P., Kooi, H., & Fanavoll, S., 1992: Intraplate stresses and the post-Cretaceous uplift and subsidence in northern Atlantic basins. *Norsk Geologisk Tidsskrift*, vol. 72, pp. 229-235.

Chadwick, R.A., Holloway, S., Kirby, G.A., Gregersen, U., & Johannessen, P.N. 2000: The Utsira Sand, Central North Sea - An assessment of its potential for regional CO2 disposal. *5th International Conference on Greenhouse Gas Control Technologies*, Cairns (Australia), August 2000, 6p.

Deegan, C.E. & Scull, B. J., 1977: A standard lithostratigraphic nomenclature for the Central and Northern North Sea. *Institute of Geological Sciences, Report*, 77/25. *Oljedirektoratet, Bulletin*, 1. 36 p.

Dehls, J.F., Olesen, O., Bungum, H., Hicks, E.C., Lindholm, C.D., & Riis, F., 2000: *Neotectonic map: Norway and adjacent areas*. Geological Survey of Norway

Doré, A.G., 1992: The Base Tertiary surface of southern Norway and the northern North Sea. *Norsk Geologisk Tidsskrift*,, 72, 259-265.

Correlates the summit-height envelope of southern Norway with the Base Tertiary horizon offshore. Warping of the surface (i.e. uplift onshore and subsidence offshore) is ascribed to variations in the Cenozoic regional stress field. Warping was enhanced by isostatic compensation for onshore erosion and offshore sediment deposition.

Doré, A.G. & Lundin, E.R., 1996: Cenozoic compressional structures on the NE Atlantic margin: nature, origin and potential significance for hydrocarbon exploration. *Petroleum Geosicence*, 2, pp. 299-311.

Doré, A.G. & Jensen, L.N., 1996: The impact of late Cenozoic uplift and erosion on hydrocarbon exploration: offshore Norway and some other uplifted basins. *Global and Planetary Change*, 12, 415-436.

Regional part deals mainly with Barents Sea for which up to 3000 m overburden removal are reported. Discuss effects of uplift on hydrocarbon potential, based on examples from offshore Norway and other areas.

Eidvin, T. & Rundberg, Y., 1999: A new chronology for the ”Utsira Formation” in the Northern North Sea (Snorre and Visund Fields). *Norsk Geologisk Forening Vintermøte 1999, Stavanger, Abstract Volume* (Geonytt), 43.

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.

Date Utsira Formation in Sleipner area (well 15/12-3) to late Middle Miocene - early Late Pliocene (ca. 11 Ma - ca. 3 Ma). Benthic deep water indicators occur in Utsira Sands, which are interpreted as middle to outer neritic (30 to 200 m water depth). Units corresponding to 'lower Pliocene unit' and 'upper Pliocene unit' of Lothe & Zweigel (1999) dated as middle Late Pliocene and late Late Pliocene, respectively, and interpreted as middle neritic (30 to 100m water depth).

Eidvin, T., Jansen, E., Rundberg, Y., Brekke, H., & Grogan, P., 2000: The upper Cainozoic of the Norwegian continental shelf correlated with the deep sea record of the Norwegian Sea and the North Atlantic. *Marine and Petroleum Geology,* 17, 579-600.

Correlate Central (CNS) and Northern North Sea (NNS) and Norwegian Sea (NWS). Discriminate between several sandy units in NNS that previously all were called 'Utsira Sand'. Period of erosion in late Middle to early Late Miocene in NNS and NWS. Increased terrigeneous influx in Late Miocene. Transgression in Early Pliocene causes reduced deposition rates; sediments of this age mainly in CNS. Regression in earliest Late Pliocene with deep erosion. Rapid deposition of glacially derived material in Late Pliocene. Pleistocene continues like Late Pliocene but has more extensive erosion of inner shelf.

Eidvin, T. & Rundberg, Y., 2001a: Late Cainozoic stratigraphy of the Tampen area (Snorre and Visund fields) in the northern North Sea, with emphasis on the chronology of early Neogene sands. *Norsk Geologisk Tidsskrift,* 81, 119-160.

Present biostratigraphy and Sr-isotope age determinations for the Late Cenozoic in selected wells in Norwegian blocks 31/3, 34/2, 34/4, 34/7, and 34/8. Distinguish several sand units which previously all have been assigned to the Utsira Formation. The Utsira Formation in their restricted definition consists of a lower, quartzose sand and a thin, upper, glauconitic sand. At its base is a major hiatus.

Eidvin, T. & Rundberg, Y. , 2001b: Proposal for redefinition and new chronology of the Skade and Utsira Formations, Norwegian North Sea. EUG XI conference, Strasbourg, April 8th - 12th 2001.

Date Skade Formation in its type and reference wells as Early Miocene only. The top of the Skade Formation corresponds to a inconformity further east. Show that the lower part of the Utsira Formation in its type well is of same age as Skade Formation, i.e. it is in fact Skade Formation. Propose another type well for the Utsira Formation (wells 16/1-2 or 24/12-1). Utsira Formation is the upper part of a coarsening upward sequence. Shales from the lower part are approx. 14-12 Ma. Overlying sands of the Utsira Formation are latest Middle Miocene to early Pliocene in age. State a western source for the sands.

Evans, D., McGiveron, S., McNeill, A.E., Harison, Z.H., Østmo, S.R., & Wild, J.B.L., 2000: Plio-Pleistocene deposits on the mid-Norwegian margin and their implications for late Cenozoic uplift of the Norwegian mainland. *Global and Planetary Change,* 24, 233-237.

Eyles, N., 1996: Passive margin uplift around the North Atlantic region and its role in Northern Hemisphere late Cenozoic glaciation. *Geology,* 24, 103-106.

Points to possibility that late Cenozoic uplift around the North Atlantic could have amplified climatic effects by providing preferential sites for glaciation. Comment: does not clearly separate between early Tertiary and late Tertiary uplift, and connects therefore early Tertiary tectonic processes with late Tertiary glaciation. Regards rifting-related magmatic underplating as major cause for uplift. See also Discussion and reply in Van der Beek & Rohrman (1997) and Eyles (1997).

Eyles, N. 1997: Passive margin uplift around the North Atlantic region and its role in Northern Hemisphere late Cenozoic glaciation. – Reply. *Geology,* 25, 283.

Reply to Van der Beek & Rohrman (1997) who discuss Eyles (1996). States that Eyles (1997) argued that early Cenozoic rifting caused generation of plateaus which were sensitive to summer temperatures and which accordingly reacted during late Cenozoic cooling by glaciation. States that Eyles (1996) did not favour any uplift mechanism.

Fejerskov, M. & Lindholm, C., 2000: Crustal stress in and around Norway: an evaluation of stress-generating mechanisms. In: Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin*. Geol. Soc. Spec. Publ., 167, 451-467.

Consider ridge push force as the primary source for compressive stresses in and around Norway. The continental margin density contrast, topography and sediment-loading induced flexure modify the pattern. Observed pattern accords with tectonics expected from Fennoscandian uplift.

Fejerskov, M., Lindholm, C., Myrvang, A. & Bungum, H., 2000: Crustal stress in and around Norway: a compilation of *in situ* stress observations. In: Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin*. Geol. Soc. Spec. Publ., 167, 441-449.

Identify four major stress provinces: Barents Sea and northern Norway (N-S sigma-H, high horizontal stresses); Norwegian Sea and mid-Norway (NW-SE sigma-H, high horizontal stresses, compressional regime); northern North Sea and western Norway (sigma-H orientation scatters, WNW-ESE dominates, but also NNE-SSW parallel to major structures appears; primarily compressional, but locally extensional); southern North Sea (very scattered sigma-H but NW-SE trend can be deciphered, near isotropic stress field. Different stress determination techniques yield similar results in spite of different depth range coverage. Differences in stress magnitude between north and south may be due to changes in tectonic stress magnitude or related to changes in angle between continental margin strike and ridge push force orientation.

Fjeldskaar, W., 1994: Viscosity and thickness of the asthenosphere detected from the Fennoscandian uplift. *Earth and Planetary Science Letters*, 126, 399-410.

Interprets a low-viscosity asthenosphere, which he suggests to be less than 150 km thick and having a viscosity of less than $7.0*10^{19}$ Pa*s.

Fjeldskaar, W., 1997: Flexural rigidity of Fennoscandia inferred from the postglacial uplift. *Tectonics*, 16, 596-608.

Calculated flexural rigidity for the central parts of Fennoscandia and for the western coast of Norway. Flexural rigidity (elastic thickness in brackets) of central Fennoscandia ranges between 10^{23} N m (T_e approx. 20 km) and $2.5 * 10^{25}$ N m (T_e approx. 50 km) with a most likely value of 10^{24} N m (T_e approx. 50 km). For the coastal area, flexural rigidity is lower, maximum 10^{23} N m (T_e approx. 20 km) with the most likely value at this upper bound.

Fjeldskaar, W., Lindholm, C., Dehls, J., & Fjeldskaar, I., 2000: Postglacial uplift, neotectonics and seismicity in Fennoscandia. *Quaternary Science Reviews*, 19, 1413-1422.

Misfits between observed uplift and modelled uplift based on isostatic response to deglaciation are interpreted to reflect a tectonic component. Areas with misfits partly correspond to areas with relatively high seismicity. Highest seismicity occurs there where deglaciation-related compressive stresses overprint regional compressive stresses constructively. The misfit suggests a regional tilting, with uplift in the (north)west and subsidence in the (south)east, which may be a result of the Plio-Pleistocene erosion pattern.

Gabrielsen, R. (ed.), 1999: *Tectonic impact on sedimentary processes in the post-rift phase - Improved models*. SINTEF Petroleum Research report 23.2561.00/01/99, 2 vol., restricted.

Gabrielsen, R.H. & Ramberg, I.B., 1979: Fracture patterns in Norway from Landsat imagery: results and potential use. *Proceedings of Norw. Sea Symp., Tromsø, Aug. 1979*, 28pp.

Galloway, W.E, 2001: Stratal architecture of linked, sand-rich shore-zone and shelf depositional systems: Utsira Sequence, North Sea Basin. *American Association of Petroleum Geologists (AAPG) Annual Convention, Denver 2001, Abstract volume*, A68.

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 Gelogy of Northwest Europe: Proceedings of the 4th Conference*, Geological Society of London, 33-43.

Ghazi, S.A., 1992: Cenozoic uplift in the Stord Basin area and its consequences for exploration. *Norsk Geologisk Tidsskrift*, vol. 72, 285-290.

Deduces Fennoscandian uplift phases from presence of clastic wedges in the Stord basin: Late Paleocene, Late Oligocene, Mio-Pliocene. Regards rifting pulses and plate re-arrangements as main causes for uplift and adjacent subsidence.

Gjessing, J., 1967: Norway’s Paleic surface. *Norsk Geografisk Tidsskrift*, 21, 69-123.

Goll, R.M. & Skarbø, O., 1990: High-resolution dating of Cenozoic sediments from Northern North Sea using $^{87}Sr/^{86}Sr$ stratigraphy - Discussion. *American Association of Petroleum Geologists Bulletin*, 74, pp. 1283-1286.

Goll, R.M., Hansen, O., Ringås, J.E., Smelror, M., & Verdenius, J.G., 1992: Cretaceous-Cenozoic sequence stratigraphy of the northern North Sea. IKU Report 23.1577.00/01/92, 94pp & appendices.

Goll, R.M., Ringås, J.E., Smelror, M., & Verdenius, J.G., 1995: Sequence stratigraphy of the Northern North Sea, Part 2: Quads 29-30. IKU Report 23.2441.00/01/95, 19 pp. & appendices.

Gradstein, F., 1998: Stratigraphic resolution on accelerated Neogene subsidence, circum North Atlantic. *Neogene Uplift and Tectonics around the North Atlantic, International Workshop, Copenhagen, May 18-19, 1998, Abstract Volume*, 49-50.

Gradstein, F. & Baeckstroem, S., 1996: Cainozoic biostratigraphy and paleobathymetry, northern North Sea and Haltenbanken. *Norsk Geologisk Tidsskrift*, 76, 3-32.

Correlate Cenozoic sediments, make paleobathymetry interpretations and provide subsidence curves. ‘Major phase of late-stage subsidence and sedimentation under shallow marine conditions took place in the North Sea, starting in the Middle Miocene.’ They link this to uplift of Scandinavia. Show widespread hiatus in Upper Miocene involving erosion.

Gradstein, F.M., Kaminski, M.A., Berggren, W.A., Kristiansen, I.L., & D’Ioro, M.A., 1994: Cenozoic biostratigraphy of the North Sea and Labrador Shelf. *Micropaleontology*, 40, supplement, 1-152.

Gregersen, S., 1992: Crustal, stress regime in Fennoscandia from focal mechanisms. *Journal of Geophysical Research*, 97, NO. B8, 11821-11827.

Gregersen, U., Michelsen, O., & Sørensen, J.C., 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.

Gregersen, U, Johannessen, P.N., Chadwick, R.A., Holloway, S. & Kirby, G.A. 2000: Regional study of the Neogene deposits in the southern Viking Graben area - a site for potential CO2 storage. *62nd EAGE meeting*, Glasgow., 4p.

Grollimund, B. & Zoback, M.D., 2000: Post glacial lithospheric flexure and induced stresses and pore pressure changes in the northern North Sea. *Tectonophysics*, 327, 61-81.

Interpret regional variations in stress data from the North Sea as 'the result of deglaciation, superimposed in a regional stress field dominated by ridge push.'

Gudmundsson, A., 1999: Postglacial crustal doming, stresses and fracture formation with application to Norway. *Tectonophysics*, 307, 407-419.

Estimates postglacial uplift of Fennoscandia to maximum 850 m. Predicts tensile fracturing, especially in the central parts of the uplifted dome. Predicts compressive horizontal stresses in the outer parts of the dome which are large enough to generate earthquakes.

Hall, B.D. & White, N., 1994: Origin of anomalous Tertiary subsidence adjacent to North Atlantic continental margins. *Marine and Petroleum Geology*, 1994, 11, 702-714.

Address early Tertiary uplift and contemporaneous subsidence. Conclude that early Tertiary subsidence is not an artefact. Possible plausible causes for them are trapping of basaltic magma at depths greater than 50 km (difficult to test) or a phase of lithospheric stretching for which, however, only limited evidence exists.

Henriksen, S. & Vorren, T., 1996: Late Cenozoic sedimentation and uplift history on the mid-Norway continental shelf. *Global and Planetary Change*, 12, 171-199.

Henriksen, S., Nygård, K.H., Granberg, E., Ingebrigtsen, A., & Løseth, H., 1999: Deltaisk kystprogradasjon i Norskehavet: tvungen regresjon som respons på tidlig pliocen hevning? [Deltaic coast progradation in the Norwegian Sea: Forced regression as a response to Early Pliocene uplift?]. *Norsk Geologisk Forening Vintermøte 1999, Stavanger, Abstract Volume* (Geonytt), 57.

Hicks, E.C., Bungum, H., & Lindholm, C.D., 2001: Stress inversion of earthquake focal mechanism solutions from onshore and offshore Norway. *Norsk Geologisk Tidsskrift*, 80, 235-250.

Determined primary stress directions from earthquake data. Offshore, oblique-slip reverse faulting dominates, whereas onshore oblique-slip normal faulting dominates. Stress directions comply with a NW-SE oriented regional compression direction. Some shallow earthquakes in mid-Norway coastal areas yielded NE-SW compressive stress; the corresponding coast-perpendicular extension might be linked to deglaciation flexure.

Higgs, W.G. & McClay, K.R., 1993: Analogue sandbox modelling of Miocene extensional faulting in the Outer Moray Firth. In: Williams, G.D. & Dobb, A. (eds.): *Tectonics and Seismic Sequence Stratigraphy*, Geol. Soc. Spec. Publ., 71, 141-162.

Observe W-dipping normal faults in rocks of approx. Oligocene age in outer Morray Firth area. The deformed rock sequence corresponds to the polygonally faulted unit below base Utsira in the Sleipner area. Attribute faulting to Middle Miocene eastward tilting, which is in accordance with onlap on the top of the faulted package ('Mid Miocene unconformity') higher on the shelf slope.

Hillis, R.R., 1995: Regional Tertiary Exhumation in and around the United Kingdom. In: Buchanan, J.G. & Buchanan, P.G. (eds.): *Basin Inversion*, Geol. Soc. Spec. Publ., 88, 167-190.

Uplift deduced from sonic logs. 1 km of exhumation during Tertiary. Considers regional exhumation to be most likely associated with Paleocene or Oligocene/Miocene unconformities. Argues for thick-skinned origin of uplift (lithospheric compression).

Holtedahl, H., 1998: The Norwegian strandflat – a geomorphological puzzle. *Norsk Geologisk Tidsskrift*, 78, 47-66.

Holtedahl, O., 1953: On the oblique uplift of some northern lands. *Norsk Geografisk Tidsskrift*, 14, 132-139.

Holtedahl, O., 1960a: On supposed marginal faults and the oblique uplift of the land mass in Cenozoic time. in Holtedahl, O. (ed.): *Geology of Norway*, Norges Geologiske Undersøkelse, 208, 351-357.

Holtedahl, O., 1960b: Features of the geomorphology. in Holtedahl, O. (ed.): *Geology of Norway*, Norges Geologiske Undersøkelse, 208, 507-531.

Huuse, M. & Clausen, O.R., 2001: Morphology and origin of major Cenozoic sequence boundaries in the eastern North Sea Basin: top Eocene, near-top Oligocene and the mid-Miocene unconformity. Basin Research, 13, 17-41

Follow Huuse et al. (2001) and see no need for direct tectonic cause for mid-Miocene unconformity and for increased sediment input afterwards. Interpret mid-Miocene unconformity to be largely eustatically (+ climatically) controlled. Stress that this unconformity is in large parts defined as a downlap surface which is diachronous, with progressively younger ages towards the basin centre.

Huuse, M., Lykke-Andersen, H., & Michelsen, O., 2001: Cenozoic evolution of the eastern Danish North Sea. *Marine Geology*, 177, 243-269.

Relate increases in sediment supply in late Eocene and post-middle Miocene to global climatic cooling and eustatic fall. Interpret from seismic stratal geometries late Cenozoic uplift and erosion of the eastern Danish North Sea of a few 100 m, which is much less than previous estimates. Suggest that 'the present topography of southern Norway and the denudation pattern on the adjacent shelf may be due to early Paleogene [North Atlantic rift related] uplift of the south Norwegian dome followed by denudation and dissection of the topography, accelerating in the late Cenozoic.' Late Cenozoic acceleration is attributed to long-term eustatic lowering and climatic deterioration. The authors see no need for invoking a (tectonic) Neogene uplift phase.

Isaksen, D. & Tonstad, K. (eds.), 1989: A revised Cretaceous and Tertiary lithostratigraphic nomenclature for the Norwegian North Sea. *NPD-Bulletin*, 5, 59 pp.

Japsen, P., 1997: Regional Neogene exhumation of Britain and the western North Sea. *J. Geol. Soc.*, 154, 239-247.

Japsen, P. 1998: Regional Velocity-Depth Anomalies, North Sea Chalk: A Record of Overpressure and Neogene Uplift and Erosion. *AAPG Bulletin*, 82, 2031-2074.

Japsen, P., Boldreel, L.O., & Chalmers, J.A., 1998: Neogene uplift and tectonics around the North Atlantic: Overview. *Neogene Uplift and Tectonics around the North Atlantic, International Workshop, Copenhagen, May 18-19, 1998, Abstract Volume*, 9-12.

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. *Neogene Uplift and Tectonics around the North Atlantic, International Workshop, Copenhagen, May 18-19, 1998, Abstract Volume*, 75-76.

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 A.M. Spencer (ed.): *Generation, Accumulation and Production of Europe's Hydrocarbons III, Special Publication of the European Association of Petroleum Geoscientists*, 3, 79-88.

1000-1200 m Neogene uplift in the Farsund Basin south of South Norway.

Jordt, H., 1996: *The Cenozoic geological evolution of the Central and Northern North Sea based on seismic sequence stratigraphy*. Unpubl. PhD thesis, Univ. of Oslo.

Jordt, H., 1996: Regional Cenozoic uplift and subsidence events in the southeastern North Sea. In: *The Cenozoic geological evolution of the Central and Northern North Sea based on seismic sequence stratigraphy*. Unpubl. PhD thesis, Univ. of Oslo.

Based on seismic interpretation of area offshore west Denmark. Interprets changes in outbuilding direction as indicators for uplift. Three uplift events from Eocene to Pliocene: (i) Eocene uplift of Mid North Sea high; (ii) uplift north of study area (i.e. uplift of Fennoscandia) at Eocene-Oligocene boundary; (iii) Pliocene uplift east of study area (i. e. mainland Denmark and east of it). Relates phases (ii) and (iii) to movements of or along Tornquist Zone.

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 Petrol. Geol.,* 12, 845-879.

Divide the Cenozoic of the central and northern North Sea into 10 seismic stratigraphic sequences. Utsira Formation is according to their correlation scheme, the basal part of sequence CSS7 which includes also the shales overlying including the layer with abundant high seismic amplitudes. [See Lothe & Zweigel (1999, p. 8) for an evaluation of this correlation.] Argue for uplift of southern Norway during most of CSS7 and CSS8 (i.e. during deposition of upper part of Utsira Fm. and of overlying shales.)

Jordt, H., Thyberg, B.I., & Nøttvedt, A., 2000: Cenozoic evolution of the central and northern North Sea with focus on differential vertical movements of the basin floor and surrounding clastic source areas. In: Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin*. Geol. Soc. Spec. Publ., 167, 219-243.

Sediment source from southern Norway since Oligocene. In mid-Miocene stopped outbuilding from west. Outbuilding pattern and changes in sediment composition are not in phase with eustatic sea level changes in Upper Miocene and Pliocene, which is taken to indicate tectonic subsidence.

Joy, A.M., 1993: Comments on the pattern of post-rift subsidence in the Central and Northern North Sea Basin. In Williams, G.D. & Dobb, A. (eds.): *Tectonics and Seismic Sequence Stratigraphy*. Geol. Soc. Spec. Publ., 71, 123-140.

Sees disagreement between predicted and observed post-rift North Sea subsidence pattern. Acceleration of subsidence in approx. mid-Paleocene possibly linked to opening of Norwegian-Greenland Sea.

Karner, G.D., 1986: Effects of lithospheric in-plane stress on sedimentary basin stratigraphy. *Tectonics*, 5, 573-588.

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 Applications to Petroleum Geology*, Norsk Petroleums Forening Special Publication, 1, 187-195.

Model isostatic deformation of the crust in response to ice sheet changes. Yield downwarping (once or several times) and subsequent uplift of the central North Sea (up to 400 m), Haltenbanken (up to 250 m) and Barents Sea (up to 650 m) during the last 2-3 million years. Differential vertical movements due to differences in ice load are more than 1.0 m/km in the graben areas of the North Sea and parts of Haltenbanken, and about 1.3 m/km in the western parts of the Barents Sea. Differential subsidence and uplift may have affected hydrocarbon reservoirs, including substantial loss of previously trapped volumes.

Kjennerud, T., 2001: *Paleobathymetry and rift basin evolution. With particular reference to the northern North Sea Basin*. PhD thesis Norges teknisk-naturvitenskapelige universitet (NTNU) Trondheim, 2001:17, 320 pp.

Kjennerud, T., Faleide, J.I., Gabrielsen, R.H., Gillmore, G.K., Kyrkjebø, R., Lippard, S.J., & Løseth. H., 2001: Structural reconstruction of Cretaceous-Cenozoic (post-rift) paleobathymetry in the northern North Sea. In: Martinsen, O.J. & Dreyer, T. (eds.): *Sedimentary environments offshore Norway – Palaeozoic to recent*. Norwegian Petroleum Society (NPF) Special Publication, 10, 347-364.

Klemann, V. & Wolf, D., 1998: Modelling stresses in the Fennoscandian lithosphere induced by Pleistocene glaciations. *Tectonophysics*, 294, 291-303.

Calculate isostatically caused stresses, which are typical approx. 2 MPa at the surface at present. Argue for the possible presence of a viscoelastic component which should be taken into account in simulations of isostatic stress due to glacial-isostatic adjustments.

Knott, S.D., Burchell, M.T., Jolley, E.J., & Fraser, A.J., 1993: Mesozoic to Cenozoic plate reconstructions of the North Atlantic and hydrocarbon plays of the Atlantic margins. In: Parker, J.R. (ed.): *From Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. The Geological Society, London, 953-974.

Kooi, H. & Cloething, S., 1989: Intraplate stresses and the tectono-stratigraphic evolution of the Central North Sea. *AAPG Memoir*, 46, 541-558.

Kooi, H., Hettema, M., & Cloething, S., 1991: Lithospheric dynamics and the rapid Pliocene-Quaternary subsidence phase in the southern North Sea basin. *Tectonophysics*, 192, 245-259.

Kyrkjebø,R.,1999: *The Cretaceous-Tertiary of the northern North Sea: Thermal and tectonic influences in a post-rift setting*. Dr. scient. thesis, University of Bergen.

Kyrkjebø, R., Hamborg, M., Faleide, J.I., Jordt, H., & Christiansson, P., 2000: Cenozoic tectonic subsidence from 2D depositional simulations of a regional transect in the northern North Sea basin. In: Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin*. Geol. Soc. Spec. Publ., 167, 273-294.

Simulate deposition on a transect through northern North Sea. Using normal post-rift subsidence curves produces not observed sediment geometries. Using increased subsidence in Miocene and Pliocene (and uplift in East) produces observed geometries.

Kyrkjebø, R., Kjennerud, T., Gillmore, G.K., Faleide, J.I., & Gabrielsen, 2001: Cretaceous-Tertiary paleobathymetry in the northern North Sea; integration of paleo-water depth estimates obtained by structural restoration and micropaleontological analysis. In: Martinsen, O.J. & Dreyer, T. (eds.): *Sedimentary environments offshore Norway – Palaeozoic to recent*. Norwegian Petroleum Society (NPF) Special Publication, 10, 321-345.

Lawver, L.A. & Müller, R.D., 1994: Iceland hotspot track. *Geology*, 22, 311-314.

Lawver, L.A., Müller, R.D., Srivastava, S.P., & Roest, W., 1990: The opening of the Arctic Ocean. In: Bleil, U. & Thiede, J. (eds.): *Geological History of the Polar Oceans: Arctic Versus Antarctic*, 29-62.

Lidmar-Bergstroem, K., 1999: Uplift histories revealed by landforms of the Scandinavian domes. In: Smith, B.J.; Whalley, W.B.; & Warke, P.A. (eds.): *Uplift, Erosion and Stability: Perspectives on Long-term Landscape Development*. Geological Society Special Publications, 162, 85-91.

Lidmar-Bergstroem, K., Ollier, C.D., & Sulebak, J.R., 2000: Landforms and uplift history of southern Norway. *Global and Planetary Change*, 24, 211-231.

Interpret paleic surface as consisting of several planation surfaces, which are tentatively correlated to offshore events ranging from Late Jurassic to Quaternary. Suggest 2 uplift phases: Cretaceous-Paleogene (approx. 1000 m) and Middle-Late Cenozoic (max. 1200 m).

Lindholm, C.D., Bungum, H., Hicks, E., & Villagran, M., 2000: Crustal stress and tectonics in Norwegian regions determined from earthquake focal mechanisms. In: Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin*. Geol. Soc. Spec. Publ., 167, 429-439.

Principal horizontal stress trends in the mean NW-SE, with a clockwise rotation when moving from south to north, which accords to predicted trajectories based on he ridge-push model. Offshore predominantly reverse faulting, and onshore predominantly reverse faulting. Offshore mid-Norway several normal-faulting earthquakes were observed. Northern North Sea earthquakes show a depth dependence: normal faulting in shallow depths and reverse faulting at larger depths; this can be explained by the glacial rebound.

Lippard, S. & Fanavoll, S., 1992: Shallow faulting around the Nordkapp Basin and its possible relation to regional uplift. *Norsk Geologisk Tidsskrift*, 72, 317-320.

Report extensional faults in Cretaceous sediments in the Nordkapp basin area, which document extension by at least 8%. Consider gravity sliding, salt tectonics and plate boundary-related extension during the early Tertiary as mechanisms, but also (favoured) as due to differential stresses during one or more phases of regional uplift in the late Cretaceous or, more likely, Cenozoic time.

Liu, G., Lippard, S., Fanavoll, S., Sylta, Ø., Vassmyr, S., & Doré, A., 1992: Quantitative geodynamic modelling of Barents Sea Cenozoic uplift and erosion. *Norsk Geologisk Tidsskrift*, 72, 313-316.

Model effects of three processes on uplift and erosion of the Barents Sea during the Cenozoic: (i) subcrustal mantle lithospheric extension, (ii) crustal thickening, and (iii) magmatic intrusion into the crust. Case (i) yields a maximum extension factor (beta) for the mantle of 1.7. Case (ii) yields a maximum shortening of 14%, and case (iii) an intrusion thickness of 2.7 km.

Liu, X. & Galloway, W.E., 1997: Quantitative determination of Tertiary sediment supply to the North Sea Basin. *AAPG Bulletin*, 81, 1482-1509.

Løseth, H. 1 999: Paleo-geographical evolution of the Lofoten and Vesterålen onshore and offshore area. *Norsk Geologisk Forening Vintermøte 1999, Stavanger, Abstract Volume* (Geonytt), 71-72.

Martinsen, O.J., Bøen, F., Charnock, M.A., Mangerud, G., & Nøttvedt, A., 1999: Cenozoic development of the Norwegian margin 60-64ºN: sequences and sedimentary response to variable basin physiography and tectonic setting. In: Fleet, A.J. & Boldy, S.A.R. (eds.): *Petroleum Geology of Northwest Europe, Proceedings of the 5th conference*, 293-304. Petroleum Geology ’86 Ltd./Geological Society, London.

Report a break in sedimentation in the northernmost North Sea ranging from latest Oligocene (approx. 25 Myr) to Late Miocene (approx. 8-9 Myr) and in some areas up to Pliocene. Utsira is lateral to (parts of) this break. Note that their definition of Utsira deviates from that of Eidvin & Rundberg (compare Their Fig. 4 and Eidvin & Rundberg’s Fig. 3). Interpret Utsira Formation as transgressive systems tract directly overlying the Miocene unconformity. Report Utsira Fm to be sand-rich but to fine towards west. Lower part is glauconitic (NB! This indicates probably that their Utsira corresponds to basinal coarse grained deposits at toes of Pliocene wedges as described by Eidvin & Rundberg 2001.) Interpret the main Cenozoic unconformities to be related to tectonic uplift of Fennoscandia. Speculatively suggest variations in ridge-push and/or Alpine compression as causes for Miocene unconformity. State that the northern North Sea basin was probably subaerially exposed in early Miocene. Identified megasequence and sequence boundaries do not correspond to published eustatic curves which is interpreted to indicate tectonic control.

Muir Wood, R., 1993: A review of the seismotectonics of Sweden. SKB Technical Report 93-13, 225 pp. Svensk Kärnbränslehantering AB (SKB, Swedish Nuclear Fuel and Waste Management CO), Stockholm.

Muir Wood, R., 1995: Reconstructing the tectonic history of Fennoscandia from its margins: The past 100 million years. SKB Technical Report 95-36, more than 85 pp. Svensk Kärnbränselhantering AB (SKB, Swedish Nuclear Fuel and Waste Management CO), Stockholm.

Molnar, P. & England, P., 1990: Late Cenozoic uplift of mountain ranges and global climate changes: chicken or egg? *Nature*, 346, 29-34.

Nielsen, O.B., Sørensen, S., Thiede, J., & Skarbø, O., 1986: Cenozoic differential subsidence of North Sea. *AAPG Bulletin*, 70, 276-298.

Provide isopach maps for several Cenozoic intervals/formations, based on well data available in mid-eighties.

Nilsen, T.H., 1973: The relation of joint patterns to the formation of fjords in western Norway. *Norsk Geologisk Tidsskrift*, 53, 183-194.

Nilsen, T.H., 1974: A Reply. The relation of joint patterns to the formation of fjords in western Norway. *Norsk Geologisk Tidsskrift*, 54, 217-219.

Nyland, B., Jensen, L.N., Skagen, J., Skarpnes, O., & Vorren, T., 1992: Tertiary uplift and erosion in the Barents Sea: Magnitude, Timing and Consequences. In: Larsen, R.M., Brekke, H., Larsen, B.T., & Talleraas, E. (eds.): *Structural and Tectonic Modelling and its Applications to Petroleum Geology*, Norsk Petroleums Forening Special Publication, 1, 153-162.

Deduce from porosity and density trends uplift in the Barents Sea with regionally different magnitudes ranging from 500-1000 m in the Hammerfest basin to 1700-1800 in the Fingerdjupet Subbasin. Volumetric calculations of the Later tertiary deposits along the western shelf margin give erosion amounts of 1-1.2 km for the southern Barents Sea, increasing to approx. 3 km on Svalbard. Interpret fission track and biostratigraphy data to indicate erosion having largely been happened during the last 2-3 Myr.

Oljedirektoratet, 1984: *Well Data Summary Sheets*, Vol. 9. Norwegian Petroleum Directorate.

Peulvast, J.-P., 1978: Le Bourrelet scandinave et les Calédonides: un essai de reconstitution des modalités de la morphogenèse en Norvège. *Géogr. phys. Quat.*, 32, 295-320.

Peulvast, J.-P., 1985: Post-orogenic morphotectonic evolution of the Scandinavian Caledonides during the Mesozoic and Cenozoic. in: Gee, D.G. & Sturt, B.A. (eds.): *The Caledonide Orogen – Scandinavia and related areas*, Wiley & Sons, 979-995.

Peulvast, J.P., 1988: Pre-glacial landform evolution in two coastal high latitude mountains: Lofoten-Versterålen (Norway) and Scoresby Sund area. *Geografiska Annaler*, 70 A, 351-360.

Poudjom Djomani, Y.H., Fairhead, J.D., & Griffin, W.L., 1999: The flexural rigidity of Fennoscandia: reflection of the tectonothermal age of the lithospheric mantle. *Earth and Planetary Science Letters*, 174, 139-154.

Calculate regional variations of elastic plate thickness ranging from 8 to 70 km, i.e. a flexural rigidity ranging from $0.4*10^{22}$ to $3*10^{24}$ Nm. Lithosphere is weakest in areas of the Caledonian belt.

Ramberg, I.B., Gabrielsen, R.H., Larsen, B.T., & Solli, A., 1977: Analysis of fracture patterns in Southern Norway. *Geol. Mijnb*., 56, 295-310.

Rasmussen, E. & Fjeldskaar, W., 1996: Quantification of the Pliocene-Pleistocene erosion of the Barents Sea from present-day bathymetry. *Global and Planetary Change*, 12, 119-133.

Rathore, J.S. & Hospers, J., 1986: A lineament study of southern Norway and adjacent off-shore areas. *Tectonophysics*, 131, 257-285.

Reemst, P., 1995: *Tectonic modelling of rifted continental margins. Basin evolution and tectono-magmatic development of the Norwegian and NE Australian margin*. PhD Thesis, Vrije Universiteit Amsterdam, 183 pp.

Chapter 4 on Vøring Margin basin evolution includes modelling of intraplate compressive stress which is concluded to have contributed to Late Cenozoic rapid subsidence.

Reemst, P., Cloething, S., & Fanavoll, S., 1994: Tectonostratigraphic modelling of Cenozoic uplift and erosion in the southwestern Barents Sea. *Marine and Petroleum Geology*, 11, 478-490.

Reusch, H., 1901: Nogle bidrag til forstaaelsen af, hvorledes Norges dale og fjelde er blevne til. *Norges geologiske Undersøkelse*, 32, 124-217, 239-263.

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 Tectonic modelling and its applications to Petroleum Geology*, Norwegian Petroleum Society (NPF) Spec. Publ., 1, 163-185.

Suggest close relation between uplift and erosion of Scandinavia and Barents Sea and attribute uplift to Paleocene-Oligocene tectonically-induced mountain building and Late Pliocene-Pleistocene glaciation-related processes. Compare uplift amounts with calculated uplift due to isostatic compensation of erosion and conclude that other processes were involved, too. Suggest phase transition in the lithosphere caused by erosion-induced pressure decline as a possible cause.

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.

Correlates enveloping summit level onshore with Base Cretaceous offshore. Late Cretaceous and Early Tertiary uplift generated an erosional surface, which was transgressed in northern Fennoscandia in the Eocene and uplifted in the Neogene. Paleogene uplift had a maximum of almost 1500 m in northern Scandinavia. The Neogene uplift phase had centres with approx. 1000 m uplift in South Norway and Lofoten. Corresponding Neogene erosion of the coastal areas is estimated to have reached a max. of 800-1000 m along the coast of southern Norway and slightly more to the north. Interprets gravity to indicate deep compensation for crustal movements. Suggest change in glaciation cyclicity as possible cause for uplift.

Riis, F., 1998: Some observations on Neogene tectonic and depositional events offshore Norway and on the Scandinavian uplift. *Neogene Uplift and Tectonics around the North Atlantic*, International Workshop, Copenhagen, May 18-19, 1998, Abstract Volume, 33-36.

Roberts, D., 1974: A Discussion. The relation of joint patterns to the formation of fjords in western Norway. *Norsk Geol. Tidsskr.*, 54, 213-215.

Rohrman, M., 1995: *Thermal evolution of the Fennoscandian region from fission track thermochronology, An integrated approach.* Dr. Thesis, Vrije Universiteit, Amsterdam, 168 pp.

Rohrman, M. & van der Beek, P., 1996: Cenozoic postrift domal uplift of North Atlantic margins: An asthenospheric diapirism model. *Geology*, 24; 901-904.

Rohrman, M., Andriessen, P., & van der Beek, P., 1996: The relationship between basin and margin thermal evolution assessed by fission track thermochronology: an application to offshore southern Norway. *Basin Research*, 8, 45-63.

Apatite fission track (AFT) data from wells offshore south Norway (blocks 25, 31, 35) and from onshore indicate rapid cooling during Late Triassic to early Jurassic. Zircon fission track (ZFT) data from the Cretaceous in offshore wells show that sediment supply from Norwegian basement was barely minor, suggesting that parts of southern Norway were then covered with sediments. The south Norwegian basement became again a clastic source at the end of the Paleogene and during the Neogene. AFT and ZFT data indicate no major (>500 m) erosion event since the Jurassic. Lacking AFT equilibration to present-day temperatures show that the present-day thermal regime has only recently been installed, which may probably be due to rapid subsidence and an increased geothermal gradient during the last 5 Myr.

Rohrman, M., van der Beek, P.A., Andriessen, P.A.M., & Cloething, S., 1995: Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. *Tectonics*, 14, 704-718.

Rowley, D. & Lottes, A.L., 1988: Plate-kinematic reconstructions of the North Atlantic and Arctic: Late Jurassic to Present. *Tectonophysics*, 155, 73-120.

Rundberg, Y. & Nystuen, J.P., 1999: Large scale slumping, sliding and soft sediment deformation of Oligocene strata in the Northern North Sea and Møre Basin; A giant collapse in response to tectonic uplift. *Norsk Geologisk Forening Vintermøte 1999*, Stavanger, Abstract Volume (Geonytt), 88-89.

Rundberg, Y., 1989: *Tertiary sedimentary history and basin evolution of Norwegian North Sea between 60°N - 62°N, An Integrated Approach*. Dr. ing. thesis, Universitetet i Trondheim, Norges Tekniske Høgskole, Institutt for Geologi og Bergteknikk, Norway, 292 pp.

Rundberg, Y. & Eidvin, T., 1999: Neogene evolution of the Northern North Sea and Møre Basin. *Norsk Geologisk Forening Vintermøte 1999*, Stavanger, Abstract Volume (Geonytt), 88.

Rundberg, Y.; & Smalley, P.C. 1989: High-resolution dating of Cenozoic sediments from Northern North Sea using $^{87}Sr/^{86}Sr$ stratigraphy. *American Association of Petroleum Geologists Bulletin*, 73, pp. 298-308.

Sales, J.K. 1992: Uplift and subsidence of northwestern Europe: possible causes and influence on hydrocarbon productivity. *Norsk Geologisk Tidsskrift*, 72, pp. 253-258.

Scherneck, H.-G., Johansson, J.M., Mitrovica, J.X., and David, J.L., 1998: The BIFROST project: GPS determined 3-D displacement rates in Fennoscandia from 80 days of continuous observations in the SWEPOS network. *Tectonophysics*, 294, 305-321.

Show high rates of vertical surface displacement in the centre of the Pleistocene glaciation region, confirming the glacial rebound theory.

Smethurst, M.A., 2000: Land-offshore-tectonic links in western Norway and the northern North Sea. *J. Geol. Soc. London*, 157, 769-781.

Identifies offshore lineaments between 60º30’ and 62º based on aeromagnetic and gravity data and links them to onshore structural lineaments. Defines two major NW-striking offshore lineaments.

Stuevold, L.M., 1989: Den tertiære fenoskandiske landhevning i lys av vertikalbevegelser på midtnorsk kontinentalmargin. En undersøkelse basret på analyse av maringeofysiske data. Cand scient thesis, University of Oslo, 175 pp.

Stuevold, L.M. & Eldholm, O., 1996: Cenozoic uplift of Fennoscandia inferred from a study of the mid-Norwegian margin.- *Global and Planet. Change*, 12, 359-386.

Interpret Fennoscandian uplift to be separated in time and space from syn-rift uplift related to opening of North Atlantic at the Paleocene-Eocene transition. Offshore mid Norway, tectonic uplift occurred from late Oligocene through Pliocene and reached up to 1 km in its northern part. Suggest a thermal origin for intraplate deformation causing uplift.

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Stuevold, L.M., Skogseid, J., & Eldholm, O., 1992: Post-Cretaceous uplift events on the Vøring continental margin. *Geology*, 20, 919-922.

Thyberg, B., Jordt, H., Bjørlykke, K., & Faleide, J.I., 2000: Relationships between sequence stratigraphy, mineralogy and geochemistry in Cenozoic sediments of the northern North Sea. In: Nøttvedt, A. et al. (eds.): *Dynamics of the Norwegian Margin*. Geol. Soc. Spec. Publ., 167, 245-272.

No data from the Sleipner area. No data from the Utsira Formation. Data from the cap rock sequence only from much further N than Sleipner area.

Thorne, J.A. & Watts, A.B., 1989: Quantitative Analysis of North Sea Subsidence. *American Association of Petroleum Geologists Bulletin*, 73, 88-116.

Tongban, H., Courme, B., Jacquin, T. & Dunay, R., 1999: Biostratigraphic calibration of Neogene depositional sequences of the North Viking Graben, In: I.J. Martinsen & T.Dreyer (eds.): *Sedimentary Environments offshore Norway; Palaeozoic to Recent*. Extended abstracts. Norwegian Petroleum Society/NPF, 45-48.

Tongban, H., Jacquin, T., Courme, B., Dunay, R., 1999: Three dimensional seismic sequence stratigraphic architecture of the Neogene depositional systems of the North Viking Graben: Restoration of the missing sections. *AAPG International Conference 1999, Birmingham (UK), Abstract Volume*.

Torske, T., 1972: Tertiary oblique uplift of Western Fennoscandia; Crustal Warping in Connection with Rifting and Break-up of the Laurasian Continent. *Norges Geologisk Undersøkelse*, 273, 43-48.

Emphasises oblique uplift character (steeper flank on NW side), and attributes it to (mid-Eocene) opening of the North Atlantic. Qualifies previous dating of uplift in Miocene as indirect and not compelling.

Vågnes, E., Gabrielsen, R.H., & Haremo, P., 1998: Late Cretaceous-Cenozoic intraplate contractional deformation at the Norwegian continental shelf: timing, magnitude and regional implications. *Tectonophysics*, 300, 29-46.

Van der Beek, P., 1995: *Tectonic evolution of continental rifts – inferences from numerical modelling and fission track thermochronology*. Unpubl. PhD thesis, Vrije Univ. Amsterdam, 232 pp.

Van der Beek, P. & Rohrman, P., 1997: Passive margin uplift around the North Atlantic region and its role in Northern Hemisphere late Cenozoic glaciation. – Comment. *Geology*, 25, 282.

Discuss Eyles (1996), reply to discussion is in Eyles (1997). Point to separation in time between early Tertiary continental break-up in the Norwegian Greenland Sea and related uplift on the one hand and late Tertiary Scandinavian glaciation on the other hand. Point to separation in space between areas of magmatic underplating offshore and uplift onshore.

Wiprut, D. & Zoback, M.D., 2000: Fault reactivation and fluid flow along a previously dormant normal fault in the northern North Sea. *Geology*, 28, 595-598.

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