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The Tertiary of Norden

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This chapter provides a lithostratigraphic correlation and the present knowledge of the depositional history of the Tertiary succession of the Scandinavian countries. The succession records an initial phase of carbonate deposition in the early Paleocene. This was succeeded by deposition of deep marine clays with intercalation of sand-rich mass-flow deposits during most of the Paleocene and Eocene. Volcanic activity in the North Atlantic was extensive at the transition from the Paleocene to the Eocene resulting in widespread sedimentation of ash-rich layers in the North Sea area. During the Oligocene, the first prograding deltaic complex developed, sourced from the Fennoscandian Shield. Late Oligocene–Early Miocene inversion and uplift of Norway and the Shetland Platform resulted in major progradation of coastal and delta plain systems. At the end of the Tertiary most of the North Sea basin was filled and the Fennoscandian Shield was flanked to the west by a broad, coalesced coastal plain.

Introduction

The Tertiary period of northern Europe was characterised by tectonic movements related to the opening of the North Atlantic and the Alpine Orogeny in southern and central Europe. Vigorous flood basalt volcanism occurred at the time of continental separation, as seen on the Faroe Islands. The collision between Greenland and Svalbard resulted in strong folding along the west-coast of Svalbard. In the North Sea Basin, the limestone deposition that characterised the earliest Tertiary gave way to deposition of deep marine clays with intercalated sandy gravity flows (Figure 1). On Svalbard, a transgressional foreland basin accumulated coastal plain, shallow marine and deepwater deposits. There was distinct uplift of the marginal areas of the Fennoscandian Shield in the Neogene and major deltas and adjacent coastal plains prograded into the basins. Present Iceland formed from Middle Miocene to recent time by increased hot spot activity at the Mid-Atlantic spreading ridge. At the end of the Tertiary, the Fennoscandian area was tilted towards the west (Figure 2). The climate was sub-tropical to tropical in the early part of the Tertiary, not least during a series of early Eocene hyperthermal intervals but a marked climatic deterioration occurred at the end of the Eocene and of the Pliocene. In the Scandinavian land area's Tertiary deposits occur only in Denmark, southernmost Sweden and in a single, isolated locality in northern Finland. On Svalbard and the Faroe Islands Palaeogene sediments are known whereas only post Oligocene deposits occur in Iceland.

Early Paleocene: Chalk deposition in the south and coastal plain deposition in the north

The Cretaceous/Tertiary boundary event (c. 65 Ma) is represented in Denmark by the distinctive Fish Clay, well exposed in the cliff at Stevns. In Denmark and the North Sea the Danian succession con-

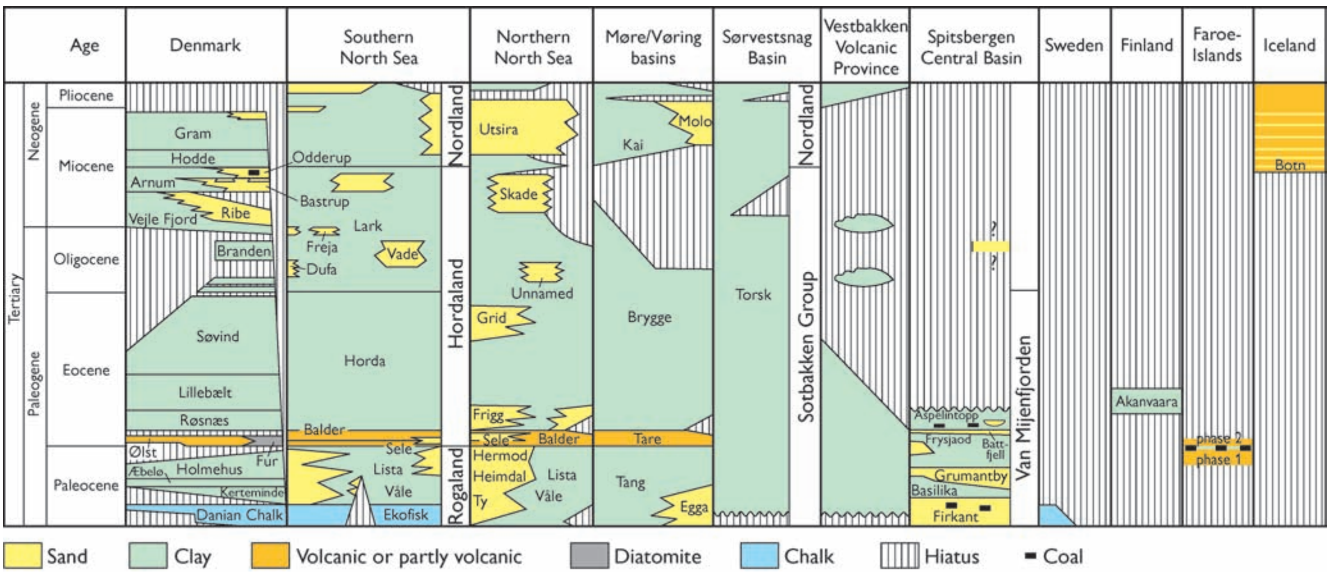

***Figure 1** Lithostratigraphy of basins off the Fennoscandian Shield (partly based on Rasmussen 2004; Martinsen & Nøttvedt 2006, Eidvin et al. 2007).*

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sists of up to 350 m thick limestone and chalk. Two main facies are recognized, 1) bryozoan limestones, often forming spectacular bioherms and including a few coral reefs and 2) fine-grained pelagic chalk composed mainly of coccoliths and planktonic foraminifera (Thomsen 1995; Surlyk et al., 2006). In the Atlantic realm muds with some incursions of sandy gravity flows were deposited; locally up to 700 m of sand were deposited (Martinsen & Nøttved 2006). On Svalbard the depositional environment was coal-forming delta plains, leading out to protected shallow marine basins (Steel et al. 1981; 1985). The water depth in the North Sea Basin decreased during the late Danian, and the easternmost parts may have been subaerially exposed. The relative sea level fall appears to have been primarily eustatic (Clemmensen & Thomsen, 2005), although thermal uplift caused by activity from the Proto-Islandic hotspot may also have been involved (Knox, 1996). The paleogrography is shown in Figure 3A.

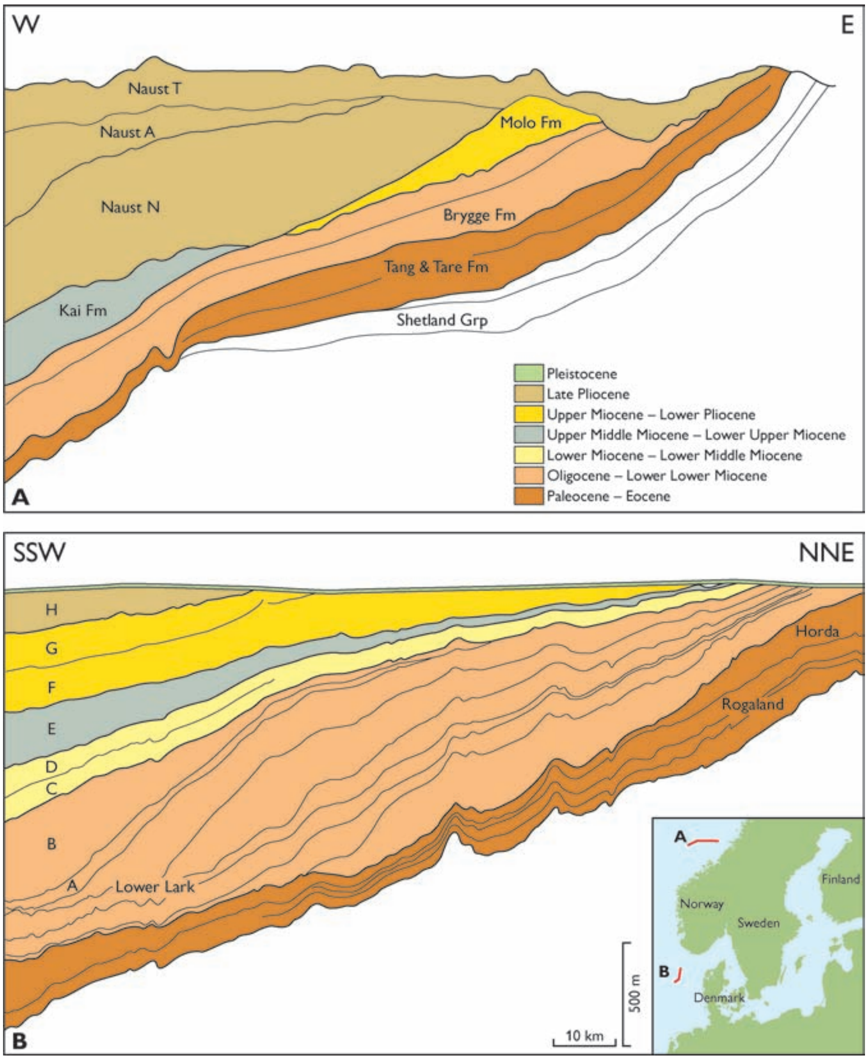

Figure 2 Tilted Tertiary successions from; A) North Atlantic and B) North Sea. Note that the same colour code has been used so it is possible to compare the two sections. For section A, Norwegian formations are indicated and for section B, sequences for the Neogene succession are indicated. Partly based on Eidvin et al. 2007.

Middle–Late Paleocene: volcanism, siliciclastic sedimentation and increasing water depth

In early Mid-Paleocene (c. 61 Ma), extrusion of flood basalts started almost simultaneously in a wide area extending from the British Isles, over the Faroe Islands, East and West Greenland to Baffin Island forming first phase of the North Atlantic Igneous Province (NAIP) (Figure 4) (Saunders et al., 1997). The lavas reach a total thickness of 3.3 km in the Faroe Islands and are underlain by > 1.2 km of hyaloclastites formed by magma-water interaction (Waagstein, 2006). The volcanism is usually taken to reflect a Proto-Icelantic hotspot, possibly the arrival of a mantle plume (e.g. White, 1989). However, some authors attribute the volcanism to extension during plate reorganisation (e.g. Lundin & Dore 2005). At the same time, a profound change to the marine clay-regime took place in the North Sea Basin after nearly 40 million years of chalk-deposition. The cause for this shift is probably a combination of increased clay input from erosion of the uplifted Shetland Platform and the new basalt covered areas and severed connections between the North Sea Basin and the warm oceans to the south (Ziegler, 1990; Clemmensen & Thomsen, 2005). Later in the Middle Paleocene, a major inversion pulse took place in the narrow Sorgenfrei-Tornquist Zone, situated between the North Sea Basin and the Fennoscandian Shield, probably as a result of stress relaxation (Nielsen et al., 2005). During the Middle and Late Paleocene, progressively deeper water and more offshore marine environments are represented by successive formations, including in Denmark the Kerteminde Marl, Æbelø Formation and culminating in the Upper Paleocene Holmehus Formation which processes a *Zoophycos* ichnofacies (Heilmann-Clausen et al., 1985). The regional deepening may be due to subsidence during reduced activity from the Proto-Icelandic hotspot (Knox, 1996). In the North Sea very similar marine clays occur, but with incursion of sand-rich gravity flow deposits. These are known as the Våle, Lista and Sele formations representing the fine-grained deposits and as the sand-rich deposits of the Ty, Heimdal and Hermod formations (Schiøler et al., 2007). On Svalbard, more open, shallow-marine sediments were deposited, known as the Basilika and Grumantbyen formations (Steel et al. 1985, Johannessen & Steel 2005).

Earliest Eocene: global warming event and rift-related volcanism

The Paleocene – Eocene (P/E) boundary (c. 55.8 Ma) coincides with the beginning of a thermal maximum, the PETM, an extreme global warming event lasting c. 200.000 years inferred to be caused by a huge carbon release to the biosphere and associated with profound biotic disturbances (e.g. Wing et al., 2003). The second phase of the NAIP peaked at about the same time along the final line of opening of the NE Atlantic extruding >5 km of flood basalts in E Greenland and >2 km in the Faroe Islands. The appearance of mid-ocean ridge type basalts appearing up-section suggests continental separation (Larsen et al. 1999, Storey et al., 2007). The carbon release referred to above may indirectly have been caused by the volcanism (Storey et al., 2007) or by rapid desiccation of a major epicontinental seaway and surrounding peat lands (Higgins and Schrag, 2006). Thus during the PETM the North Sea was reduced to a stagnant, lake-like water body (Figure 3B) (Knox & Harland, 1979). The major sea-level fall was probably caused by a new updoming of the entire NE Atlantic

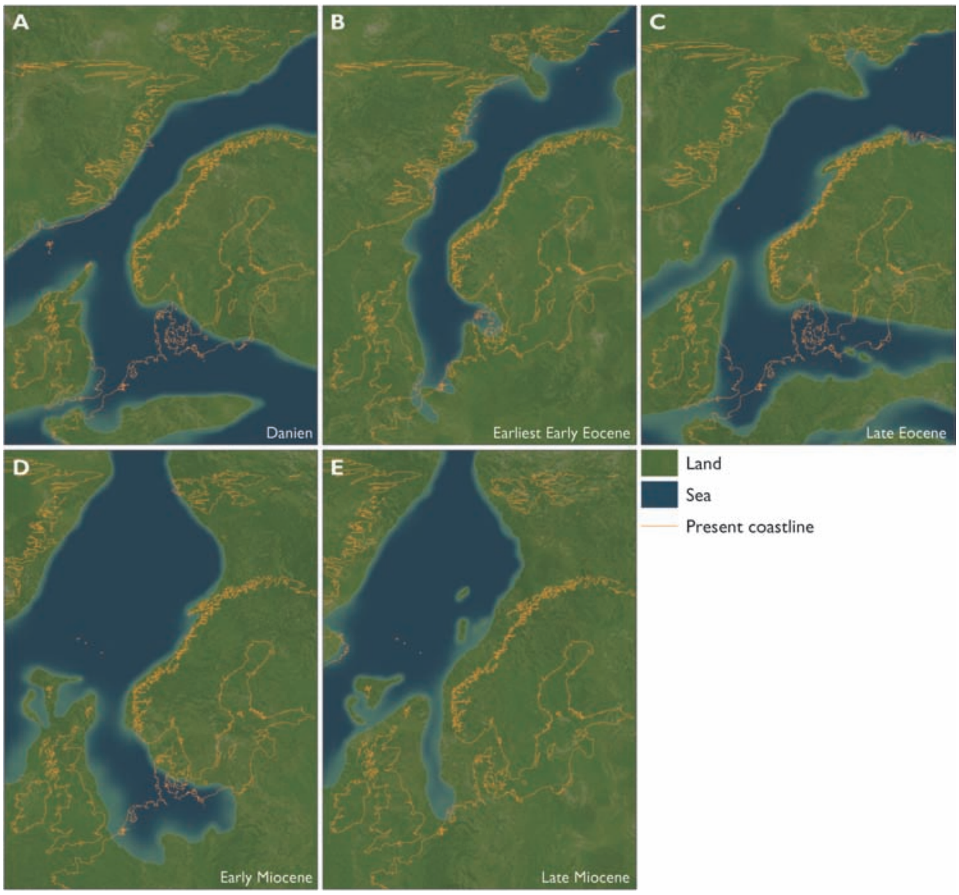

Figure 3 Paleogeographic reconstruction of the area during the; A) Danian, B) Earliest Early Eocene, C) Late Eocene, D) Early Miocene, E) Late Miocene. Based on Rasmussen (2004), Stoker et al. (2005), Løseth & Henriksen (2005), Heilmann-Clausen (2006), Martinsen & Nøttvedt (2006).

region in connection with the second phase 2 of increased hotspot activity (Knox, 1996; Jones & White, 2003). The PETM period is represented in Denmark by the c. 14 m thick, anoxic Stolleklint Clay (Heilmann-Clausen & Schmitz, 2000).

Numerous basaltic ash beds occur in the overlying succession all over the North Atlantic–NW European region as far away as the northern Tethys, 1900 km from the assumed source within the North Atlantic rift zone (Egger & Bruckl, 2006). This ash series, the 'positive series' of Bøggild (1918) is best known from NW Denmark where it is well exposed in a 60 m thick diatomite, the Fur Formation (Heilmann-Clausen, 2006). The extremely violent volcanism suggests that the volcanic edifices were located in shallow water (Waagstein & Heilmann-Clausen, 1995; Larsen et al., 2003). The thickest of the ash layers are among the largest basaltic ash-falls known in geological history, and they may have contributed to the global cooling after the PETM (Egger & Brückl, 2006). The diatomite of the Fur Formation (Figure 5) probably formed in an upwelling belt south and south-west of Norway (Bonde, 1979). The mainly anoxic diatomite is rich in exquisitely preserved fossils including the world's best known early post-PETM faunas of insects, fishes and birds (Heilmann-Clausen, 2006 and references herein). During this period the locally sand-rich Balder Formation was deposited in the North Sea region and the Tare Formation off mid and northern Norway. On Svalbard, deepwater marine muds of the Frysjaodden Formation were deposited followed by the progradation of the Battfjell Formation shelf to deepwater slope system (Figure 6) (Steel et al., 1985).

Figure 4 Coastal exposure of the Kulagjógv lava flow at Fróðba, Suðuroy, Faroe Islands. The flow belongs to NAIP Phase 1. The boundary between magnetochrons c25n and c24r is at the top of the flow while compound flows of Phase 2 are seen in the mountain slope behind (top left). The Kulagjógv flow has bulldozed through underlying wet volcanoclastics resulting in rapid chilling af the magma. This is evidenced by the development of a prominent columnar jointing growing at a right angle from the irregular contacts towards the centre of the flow.

Eocene bathyal, hemipelagic clays of the North Sea Basin

After the earliest Eocene (the Sparnacian Stage of Aubry et al., 2003), the major NW European Ypresian transgression occurred. In Denmark, a distinctly more offshore, mainly bathyal environment was established, with Ypresian water depths possibly reaching 600 m or more (Schmitz et al., 1996). A deep environment persisted for the entire Eocene, and up to 200 meters of extremely fine-grained clays (Røsnæs Clay, Lillebælt Clay and Søvind Marl formations) were deposited in western Denmark. These clays are very similar to the central North Sea succession, i.e., the Hordaland Group. As in the Middle–Late Paleocene, the large scale transgression may have been caused by reduced activity from the Proto-Icelandic hotspot (Knox, 1996). The transgression also affected the Faroes area where tuffeceous claystone and limestones were deposited on the Faroes platform before uplift in the Bartonian or Priabonian and later erosion (Waagstein & Heilmann-Clausen, 1995).

A climatically important Azolla-event at the Ypresian/Lutetian transition is recorded in the Polar Ocean and Northern Atlantic, and is suggested to represent a Polar Ocean freshwater overflow (Brinkhuis et al., 2006). The only onshore occurrence of this event is in Denmark.

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Figure 5 The post-PETM 'positive ash series' (Lower Eocene) is seen as black, sandy layers in the light grey diatomite of the Fur Formation in NW Jylland. The folds and faults are caused by Quaternary glacial tectonics.

Figure 6 Coastal plain, shelf and slope clinoforms of the Frysjaodden and Battfjellet formations, Central Tertiary Basin, Spitsbergen. See also Johannessen and Steel (2006) for details. (Photo Frode Hadler-Jacobsen, Statoil).

The present limit of the Eocene deep water sediments towards the Fennoscandian Shield is erosional, caused by late Tertiary uplift and Quaternary glaciations. The position of the Eocene coastline is speculative, but it was possibly situated in Southern Sweden (Figure 3C). On Svalbard, the marine setting was successively filled and coastal plain and fluvial deposits eventually became dominant (Steel et al., 1985; Plint-Bjørklund, 2005). An isolated marine Eocene clay unit, the Akanvaara Clay, occurs in northern Finland (Fenner, 1988).

From Eocene greenhouse to Oligocene icehouse

Towards the Eocene–Oligocene boundary (c. 34 Ma) the greenhouse climate, prevailing since the Mesozoic, changed to the modern icehouse climate (Zachos et al., 2001). This led to a profound change of the depositional regime. A generally lowered, but fluctuating eustatic sea level was caused by growing and waning of ice caps primarily on Antarctica, but probably also in Greenland (Eldrett et al., 2007). In Scandinavia, the climate probably became cooler (Buchardt, 1978). From the latest Eocene distinctly pulsed and localized coastal and deltaic progradation occurred south of present day Norway, which replaced the previous, dominantly hemipelagic sedimentation pattern in the basin (Michelsen et al., 1998). During Oligocene time, sediments in the eastern part of the North Sea Basin were sourced from the present Norwegian land mass, which was undergoing considerable erosion. The Oligocene consists mainly of thick, geographically restricted units that were quickly deposited in neritic environments, such as the Viborg Formation and the Branden/Skive Clays (Heilmann-Clausen, 2006). The units are separated by considerable stratigraphic gaps, with most of the Rupelian absent. West of Norway muds of the Brygge and Torsk formations were deposited in more open marine environments. However, most of the Chattian has been removed in the Tampen area in the northern North Sea (Eidvin & Rundberg, 2001; Rundberg & Eidvin, 2005), and in most areas of the eastern part of the Norwegian Sea continental shelf (Eidvin et al., 2007). Close to the Early/Late Oligocene boundary conglomerates, sandstones and sandy clay were deposited in the Forlandsundet "graben" in north-western Svalbard (Eidvin et al., 1998). In Late Oligocene a warm climate dominated (Heilmann-Clausen, 2006; Pers. Comm. Linda Larson).

Miocene: Uplift and deltaic progradation from the Fennoscandian Shield

At the transition from the Paleogene to the Neogene (c. 23 Ma) prominent polar ice caps again built up primarily in Antarctica. This resulted in a global sea-level fall and the formation of a distinct erosional boundary. Superimposed on this, the Alpine tectonic event, the “Savian Phase”, resulted in flexural uplift of the Central Graben and along the Sorgenfrei-Tornquist Zone. Extensive erosion below Lower Miocene deposits in the Tampen area in the northern North Sea (Eidvin & Rundberg, 2001; Rundberg & Eidvin, 2005) and off Mid Norway indicate similarly marked changes, i.e. uplift, in these areas (Eidvin et al., 2007). Also the margins of the Fennoscandian Shield, the so-called Northern - and Southern Scanes, and the south Swedish Dome, were uplifted. During the Early Miocene, coarse-grained sediments were flushed into the surrounding basins and resulted in deposition of deltaic sediments of the Ribe, Bastrup and Odderup formations in the part of the North Sea basin which in the present day constitutes Denmark (Rasmussen 2004, Figure 3D and 7). Further north, in the Viking Graben area of the North Sea basin, the sand-rich Skade Formation was build up by sediments which were sourced from the elevated Shetland Platform (Rundberg & Eid-

Figure 7 Coarse-grained deltaic sediments showing braided fluvial deposits of the Billund fluvio-deltaic complex, Ribe Formation. Photo Ole Rønø Clausen.

vin 2005, Figure 3D). Heavy mineral studies show that the source area for the sand-rich deltas in the present day Denmark were the present day Finland, Sweden and particularly Norway (Knudsen et al., 2005). The climate during most of the Early Miocene was changing from cool to warm temperate and frost was rare in the lowland areas.

A culmination in the uplift of the Fennoscandian Shield took place at the transition of the Early and Middle Miocene (Eidvin & Rundberg, 2001; Eidvin et al., 2007; Rundberg & Eidvin, 2005). In the Norwegian Sea, major compressional features, e.g. the Helland-Hansen Arch, formed (Ludin & Doré, 1996; Løseth & Henriksen, 2005). The uplift of the Fennoscandian Shield was accompanied by subsidence of the basins and flooding of former deltas and coastal plain environments. This flooding was partly tectonic and partly climatic in origin coinciding with the Mid Miocene climatic optimum (Zachos et al., 2001). South of the Fennoscandian Shield, the deposition of the clayey Hodde and Gram formations took place. In the western part of the Norwegian Sea continental shelf and in the Norwegian Sea the clayey and pelagic Kai Formation was deposited. In the Atlantic realm, the North Atlantic sediment drift that was initiated at the Eocene/Oligocene transition was intensified from the late Early to Middle Miocene (Wold, 1994). Major compression occurred around the Faroe Islands at same time (Boldreel & Andersen, 1993). The Iceland-Faroe and Iceland-Greenland ridges formed by increased Icelandic hot spot activity during the opening of the NE Atlantic and were probably above sea level initially. They were underlain by thick oceanic crust, like present day Iceland. Iceland itself was experiencing active sea-floor spreading and the oldest flood basalt exposures occur on the E and NW coasts dating back to Middle Miocene, when the island was vegetated by a temperate flora (Grimsson et al., 2006). The interbasaltic sediments include aeolian soils and various alluvial and lacustrine deposits, e.g. the Selardur-Botn Formation (Figure 1).

In the Late Miocene, the marked relief of the Fennoscandian Shield, accompanied by the general climatic deterioration (Utescher et al,. 2000, Zachos et al., 2001), resulted in pronounced out-building of coastal plains and deltas from the Fennoscandian Shield. On the Norwegian Sea, continental shelf sediments were deposited. These deposits were newly formal named the Molo Formation (Eidvin et al., 2007, Figures. 1, 3E). In the transition area of the Viking Graben and the Central Graben, the Utsira Formation was deposited as submarine tidal bars in a narrow strait connecting the North Sea and the Atlantic Ocean (Galloway 2002, Rundberg & Eidvin 2005, Gregersen & Johannessen 2007). The source was the Shetland Platform in the southern and middle part, and the Sognefjorden area in the northern part (Rundberg & Eidvin, 2005). South of the Fennoscandian Shield the deltas reached the Central Graben area, so the North Sea constituted a narrow gulf by the end of the Miocene (Sørensen et al., 1997; Rasmussen et al., 2005; Figure 3E).

Pliocene: Tilting of basins and climatic deterioration

In the early Pliocene, periodically warmer climate prevailed (Zachos et al., 2001; Utecher et al., 2000). Consequently, huge areas of coastal plain deposited during the Late Miocene were flooded. Resumed regression occurred in the Late Pliocene possibly associated with a falling sea level due to an overall climatic deterioration. In the Danish area this regression succeeded a tectonic event (Rasmussen et al., 2005). In the Atlantic area, a mid Pliocene tectonic event has also been documented (Stoker et al., 2005). The onset of more pronounced glaciation on the Fennoscandian Shield was initiated in the late Pliocene (c. 2.8 Ma; Fronval & Jansen, 1996). The Late Pliocene deposits that are the result of the regression and glaciations are named the Naust Formation in the Atlantic area (Eidvin et al., 2007). Similar huge packages of prograding units are seen in the North Sea (Eidvin & Rundberg, 2001; Rasmussen et al., 2005). However, it is in the southwestern part of the Barents Sea that the Upper Pliocene forms the most extreme sediment columns with depocenters close to 2500 m (Eidvin et al., 1998 and 2000). In most of these areas there are a pronounced hiatus below the Upper Pliocene glacial deposits (Eidvin & Rundberg, 2001; Eidvin et al., 2000 and 2007). Regional tilting of the area occurred in the late Pliocene (Figure 2) (Riis, 1996; Faleide et al., 2002; Japsen et al., in press). The distinct change in the structural pattern that occurred in the late Pliocene has been hotly debated during the last decade. The large amplitude of this phase may be related to movements within the upper mantle e.g. Japsen et al. (in press) and Stoker et al. 2005 or to changes in stress field e.g. Cloetingh & Van Wees (2005). According to Riis (1996) the isostatic effect of onshore erosion and offshore deposition has contributed to amplify the vertical movements. A dominantly climate-driven origin of Cenozoic uplift has been suggested by Nielsen et al. (2002).

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