ELSEVIER

Global and Planetary Change 24 (2000) 165–173

GLOBAL AND PLANETARY CHANGE

www.elsevier.com/locate/gloplacha

Neogene uplift and tectonics around the North Atlantic: overview

Peter Japsen [*], James A. Chalmers

Geological Survey of Denmark and Greenland (GEUS), Thoravej 8, DK-2400, Copenhagen NV, Denmark

Received 8 November 1999

Abstract

There appear to have been at least two significant episodes of uplift around the North Atlantic during the Cenozoic, and in many places it is not easy to separate the two. Effects related to emplacement of the Iceland plume probably caused one episode, mostly in the Palaeogene. The second episode took place in the late Cenozoic, and comprised uplift of basin margins as well as accelerated subsidence of basin centres adjacent to the uplifted landmasses. Cenozoic uplift of Scandinavia and of the British Isles has been suggested since at least the beginning of the 20th century. However, it is only recently being recognised in the literature that a major Neogene tectonic event has affected nearly every continental margin in the area (including western and eastern Greenland) and far into the European craton.

Pre-Cenozoic rocks are generally exposed onshore and the pre-Quaternary sediments offshore are generally of Neogene age. Between the two, inclined Palaeogene and older beds are truncated by erosional unconformities along many coastlines. This structural configuration is in accordance with a Neogene uplift of the continents.

A variety of methods have been used to investigate uplift, erosion and redeposition: studies of maximum burial, fission tracks, geomorphology, sediment supply and structural relations. These methods each investigates only one aspect of the phenomenon, and a thorough understanding of the processes of uplift and erosion can only be achieved if results from these methods are integrated.

The main mechanisms suggested in the literature for the large-scale, late Cenozoic events are: emplacement of magma in and at the base of the crust leading to isostatic uplift, flow of asthenospheric material into active diapirs, isostacy associated with glacial erosion, phase changes in the lithosphere due to pressure relief and regional compression of the lithosphere. It is premature to judge between these mechanisms because of the insufficient regional analyses carried out so far. A general model must be constrained by observations from all affected areas, it must separate the effects of Palaeogene uplift from those of Neogene uplift that reach beyond the passive margins, and also include the subsidence patterns observed adjacent to the landmasses.

Keywords: Neogene; uplifts; subsidence; North Atlantic

1. Introduction

During the last few years, it has become clear that the landmasses around the northern North Atlantic have been affected by a major tectonic event during the Neogene that has hitherto been poorly reported in the literature (Fig. 1, place names are indicated in Fig. 2). The event is generally recognised in Scandinavia from studies driven primarily by the oil industry. But there is much less appreciation that a similar event took place at nearly every continental margin around the northern North Atlantic and far into the European craton. In May 1998, the Geological Sur-

---

[*] Corresponding author. Fax: +45-38-142-050.
E-mail address: pj@geus.dk (P. Japsen).

PII: S0921-8181(00)00006-0

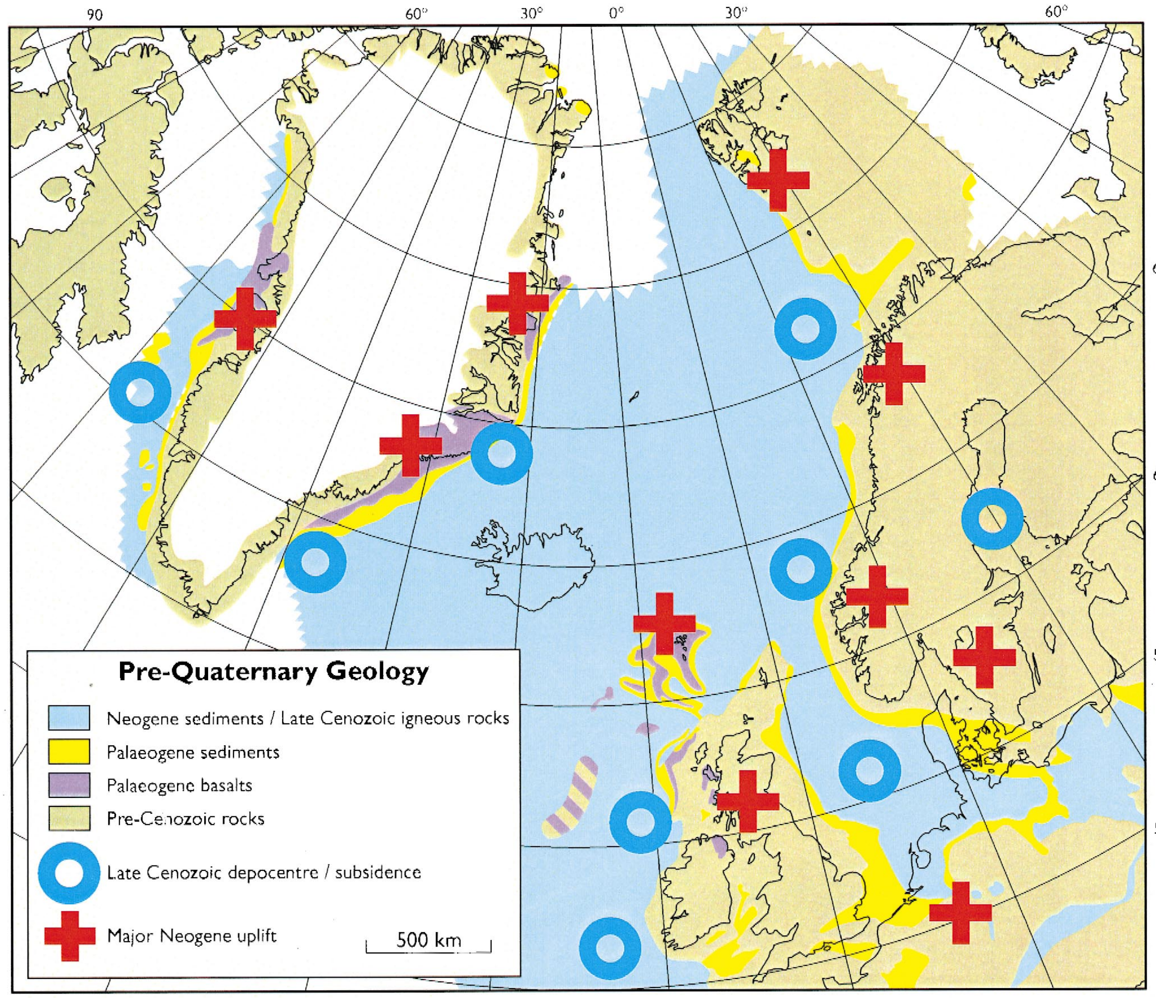

Fig. 1. Pre-Quaternary geology around the North Atlantic showing areas of Neogene/Late Cenozoic uplift/erosion and of accelerated subsidence/deposition. Greenland: Chalmers (2000-this issue), Johnson and Gallagher (2000-this issue), Larsen (1990), Hansen (1995), Mathiesen et al. (1995, 2000-this issue), Mathiesen (1998). British Isles/North Sea: George (1966), Bulat and Stoker (1987), Evans (1997), Japsen (1997). Faroe Islands: Andersen et al. (2000-this issue). Rhenish Massif: Meyer (1983). Svalbard/Scandinavia/North Sea: Jensen and Schmidt (1992), Nyland et al. (1992), Riis and Fjeldskaar (1992), Jordt et al. (1995), Rohrman et al. (1995), Doré and Jensen (1996), Hansen (1996), Lidmar-Bergström (1996, in press), Riis (1996), Stuevold and Eldholm (1996), Japsen (1998), Japsen and Bidstrup (1999). Geological basemap drawn after Choubert and Faure-Murat (1976), Larsen (1990), Håkansson and Pedersen (1992), Shannon et al. (1993), Sigmond (1993), Boldreel and Andersen (1994), Fredén (1994), Escher and Pulvertaft (1995), Pharaoh et al. (1996), Whittaker et al. (1997), Chalmers (2000-this issue).

vey of Denmark and Greenland (GEUS) hosted a 2-day workshop in Copenhagen to discuss Neogene uplift and tectonics around the North Atlantic. The collection of papers published here results from that workshop.

Cenozoic uplift of Scandinavia (see Stuevold and Eldholm, 1996 for a summary of the literature) and the British Isles (e.g. George, 1966) has been suggested since at least the beginning of the century (e.g. Geikie, 1901; Reusch, 1901). These suggestions were based primarily on morphological studies of successive phases of erosional planation surfaces (e.g. the ‘paleic surface’ in southern Norway) that may have been caused by marine erosion and subse-

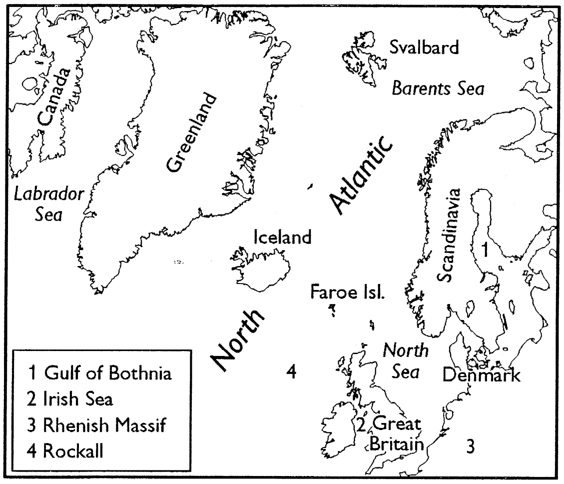

Fig. 2. Place name map. See details in Fig. 1.

quently uplifted. Studies of such surfaces continue (e.g. Riis, 1996; Lidmar-Bergström et al., 2000-this issue).

Recent studies of Cenozoic uplift around the North Atlantic have been prompted by two different, but perhaps overlapping, themes. On the one hand, Cenozoic uplift and erosion are significant factors in the exploration for petroleum, and are generally recognised to be the cause for the disappointing results in, e.g. the Barents Sea (Doré and Jensen, 1996). On the other hand, theoretical studies of plume dynamics predict that mechanical uplift should accompany the arrival of the plume at the base of the lithosphere, and that isostatic uplift should accompany the emplacement of magma in and at the base of the crust (e.g. Nadin et al., 1997).Various authors have studied the uplift and subsidence of the cratons around the North Atlantic as they moved relative to the Iceland plume (e.g. Clift et al., 1998). Examination of the literature suggests that authors from the two groups have a tendency to ignore each other, with the first group tending to focus on the late Cenozoic and the second group tending to ignore it.

2. Methodology of studies of uplift and erosion

It is important to note that uplift relative to the geoid must be distinguished from removal of overburden (England and Molnar, 1990). Reduction in the amount of overburden can be caused by accelerated erosion from climatic changes alone (e.g. increased rainfall), so independent information, such as the presence of truncational unconformities, is needed to infer that erosion is caused by uplift of the earth's surface. The inference of (and even the term) uplift must thus be used cautiously if measurements result only in estimates of removed overburden or changes in sediment supply. Bulat and Stoker (1987) used the term 'apparent uplift' and Riis and Jensen (1992) used 'net uplift' for estimates of reduced burial depth. A more neutral term is 'burial anomaly' relative to some reference, e.g. a normal velocity-depth trend (Japsen, 1998).

Several different techniques have been used to study uplift and erosion and, to some extent, the different emphases by authors are due to their conclusions being based on a single technique in a limited area. The five main techniques used are the following:

(1) Maximum-burial studies leading to estimates of removed overburden. These estimates are based on measurements of sonic velocity, density or vitrinite reflectance and on predictions of how these parameters change with burial depth (e.g. Bulat and Stoker, 1987; Jensen and Schmidt, 1992; Japsen, 1998, 2000-this issue).

(2) Fission-track studies leading to a model of the temperature history of a sample. To some extent, this can be interpreted in terms of the burial and unroofing of the sample, although changes in the temperature gradient also cause changes in the sample's temperature history. Statistical uncertainties also become important when modelling the most recent cooling history based on the relatively few younger tracks (e.g. Green, 1989; Rohrman et al., 1995; Hansen, 2000-this issue; Johnson and Gallagher, 2000-this issue; Mathiesen et al., 2000-this issue).

(3) Geomorphological studies of the present topography leading to the identification of denudation events and to estimates of where and when uplift and subsidence occurred (e.g. Doré, 1992; Riis, 1996; Lidmar-Bergström, 2000-this issue)

(4) Sediment-supply studies leading to estimates increased erosion rates and therefore possibly uplift in the basin's hinterland. Tectonic pulses cannot be differentiated from eustatic sea level changes using sequence stratigraphic mapping alone, and the se-

quence stratigraphic mapping cannot indicate from where the deposited material ultimately originated (e.g. Jordt et al., 1995; Stuevold and Eldholm, 1996; Andersen et al., 2000-this issue; Clausen et al., 2000-this issue; Evans et al., 2000-this issue).

(5) Structural studies leading to estimates of relative uplift and removed overburden. These studies are based on the present structure and relative attitudes of sediments of different age within a basin and correlation of these with morphological studies of nearby exhumed landmasses (e.g. Riis, 1996; Andersen et al., 2000-this issue; Chalmers, 2000-this issue).

The five methods all address the general problem of uplift and erosion, but there are fundamental differences in the results obtained from the application of each method. Critical aspects in all of these studies are to deduce whether uplift of the earth's surface took place, at what time it happened, when rocks were eroded, and what ages are ascribed to the eroded rocks. A thorough understanding of uplift, erosion and deposition can only be achieved if results from all of the above methods are integrated.

3. Extent of late Cenozoic uplift and accelerated subsidence

We have compiled a map to show the areas of Neogene uplift and areas of accelerated subsidence and/or substantial deposition around the North Atlantic (Fig. 1). Pre-Cenozoic rocks are generally exposed onshore and the pre-Quaternary sediments are generally of Neogene age. Especially revealing, we believe, are the marginal areas bordering the oceanic basins and the North Sea. In all these areas, Palaeogene sediments or volcanics lie either at outcrop or at subcrop to an unconformity at the base of the Pleistocene, and dip towards the basin centre. All of the Palaeogene outcrop/subcrop patterns that we have examined appear to be caused by structural relationships of the type described by Riis (1996) and Chalmers (2000-this issue). This structural configuration is in accordance with a Neogene uplift of the continents.

Cross-sections of the uplifted/subsided areas are also revealing, since several of the uplifts appear to be asymmetric. Scandinavia (e.g. Riis and Fjeldskaar, 1992), Scotland (e.g. Boulton et al., 1991) and the Faroe Islands verge towards the west, i.e. towards the Atlantic. Whether the uplifted Greenland and North American margins are also asymmetric is not clear from existing data, but the fact that the high mountains in all these areas are not far from the coast may be a clue. The uplifted landmasses are commonly associated with pronounced late-Cenozoic depocentres; Doré (1992) correlated the summit-level of southern Norway with the Base Tertiary surface offshore, which then represents a consistent surface with a half-wavelength of about 300 km and an amplitude of about 4 km.

That uplift of landmasses has occurred in the late Cenozoic is without doubt. It has been documented along the Scandinavian margin from Svalbard to the North Sea and south to Denmark and South Sweden (see summary in Doré and Jensen, 1996; Japsen and Bidstrup, 1999). It occurred along the western margin of the North Sea (Japsen, 1997, 1998; and references therein), in England and the Irish Sea (e.g. Green, 1989; Duncan et al.,1998; and references therein), and in Scotland (George, 1966). South of the North Sea, the Rhenish Massif was subject to accelerated uplift during the late Cenozoic (Meyer, 1983).

The Faroe-Rockall area, on the Atlantic margin, suffered compression in the Cenozoic (Boldreel and Andersen, 1993; Andersen et al., 2000-this issue) which also affected offshore central Norway (Doré and Lundin, 1996).[1]

On the other side of the Atlantic, uplift affected much of East Greenland (Larsen, 1990). Palaeogene uplift may have been related to the passage of the Iceland plume (e.g. Clift et al., 1998), but the rate of uplift seems to have accelerated in the Neogene (Johnson and Gallagher, 2000-this issue; Mathiesen et al., 2000-this issue). Mathiesen (1998) showed that West Greenland suffered uplift during the Cenozoic, and Chalmers (2000-this issue) gives evidence

---

[1] Significant late Cenozoic uplift of the Faroes has been deduced from the large volumes of post-mid-Miocene sediments deposited in a major progradational wedge on the eastern margin of the Faroe Platform (Andersen et al., 2000-this issue).

that the uplift was later, certainly substantially later than mid-Eocene and possibly as late as the Plio-Pleistocene. The late Cenozoic uplift extended at least as far as the margins of eastern Canada (Eyles, 1996; references therein).

Accelerated subsidence and sedimentation affected some basin centres during the late Cenozoic; the North Sea (e.g. Nielsen et al., 1986; Cloetingh et al., 1990; Kooi et al., 1991; Japsen, 1998), offshore Norway (e.g. Doré and Jensen, 1996), Canada and possibly southern West Greenland (Cloetingh et al., 1990) and the Gulf of Bothnia east of Scandinavia (Lidmar-Bergström, 1996)

4. Timing of Cenozoic uplift and erosion

While there is good evidence that many areas around the North Atlantic underwent uplift, the timing of the events is unclear and controversial. There is ample evidence, from many more sources than is possible to list here, that events associated with emplacement of the proto-Iceland plume and the onset of sea-floor spreading in the Palaeogene led to uplift and erosion of many areas in northwestern Europe (see, e.g. Nadin et al., 1997; and references therein). In both West and East Greenland, too, there is evidence for rapid uplift followed by subsidence in the early Palaeogene, shortly before the onset of Palaeogene volcanism (e.g. Dam et al., 1998).

However, in many areas there is also evidence for a Neogene episode of uplift, quite distinct from the Palaeogene one. Palaeogene uplift and erosion could not have caused the structural and erosional configurations documented, e.g. by Riis (1996) west of Norway, because sediments as young as Pliocene have been uplifted and eroded. Japsen (1997) showed that there were two distinct uplift episodes in the western North Sea and eastern Britain; one in the Palaeogene and one in the Neogene. Johnson and Gallagher's (2000-this issue) fission track studies in East Greenland show an episode of warming between about 60 and 40 Ma (presumably associated with passage of the Iceland plume) followed by an episode of rapid cooling that started at about 20 Ma. Mathiesen et al. (2000-this issue) describes Cenozoic cooling of Jameson Land, East Greenland, that accelerated during the Neogene. Dam et al. (1998) describe episodes of uplift followed by rapid subsidence in both East and West Greenland that took place prior to eruption of Paleocene volcanics, and which they interpret as events associated with emplacement of the plume, whereas Chalmers (2000-this issue) describes an event that took place in West Greenland much later than those described by Dam et al. (1998). Interestingly, however, there seems to be no clear distinction between the two events in the North of England/Irish Sea area, where fission track evidence (e.g. Green et al., 1997; Duncan et al., 1998) suggests a single episode of cooling that started at about 60 Ma and decelerated during the Neogene.

Other anomalous areas may be those around the Faroes and offshore mid-Norway, where Miocene compression is observed (Boldreel and Andersen, 1993; Andersen et al. 2000-this issue). This activity may have been caused by local space problems associated with NW–SE transfer zones that segment and offset the continental margin (Doré and Lundin, 1996). However, such an explanation cannot account for all observations of Neogene uplift around the North Atlantic.

5. Causes of the Neogene uplift and subsidence

Explanations for the Neogene tectonism must account for both the uplift and the accelerated subsidence. They must also account for uplift and subsidence taking place along the margins of both an actively spreading ocean, the North Atlantic, and the Labrador Sea where spreading had certainly ceased by the Middle Miocene and was very slow after the Early Eocene (Roest and Srivastava, 1989). Several explanations for Neogene uplift are current in the recent literature. Some of the explanations do not account for all the observed phenomena.

During the Palaeogene, the North Atlantic area was affected by the emplacement and subsequent evolution of the plume now present under Iceland (see, e.g. Saunders et al., 1997 for a summary). The plume appears to have caused uplift during the Palaeogene due both to mechanical support of the lithosphere by upward convecting plume material (Campbell and Griffiths, 1990) and to emplacement of magma in and at the base of the crust (underplating) (White et al., 1987). It is possible that this could be the only explanation for the uplift around the North Atlantic, as many authors (e.g. Clift et al., 1998) propose. If so, the apparent acceleration of ‘uplift’ during the Neogene could be an increase in denudation rates, caused, for example, by changes to a wetter climate during the Neogene and ultimately to glacial erosion during the Pleistocene.

However, there are problems with the ‘plume model’ as the only explanation of the observed uplift. It gives no clear explanation for the increased Neogene subsidence rates reported by, e.g. Kooi et al. (1991) from the central North Sea. Dam et al. (1998) describe evidence for plume-related uplift and subsequent subsidence in both east and west Greenland prior to the main phases of Palaeogene volcanism and this is a quite different phenomenon from the uplift reported by Chalmers (2000-this issue), which took place well after the main phase of Palaeogene igneous activity. Furthermore, the Neogene uplift postdates the North Atlantic breakup and predates the onset of glaciation (Rohrman and van der Beek, 1996).

A variation on the ‘plume model’ has been proposed by Rohrman and van der Beek (1996) where the uplift was generated not just by isostatic uplift from underplating, but by active diapirism of partially melted asthenospheric material under Scandinavia and the British Isles. This hypothesis could account for the accelerated subsidence between the uplifted ‘domes’ by flow of asthenospheric material from there into the diapirs.

Undoubtedly, considerable amounts of glacial erosion took place in many areas around the North Atlantic during the late Pliocene and Pleistocene. For example, during the last 3 million years, between 500 and 1500 m of sediment appear to have been removed from the Barents Shelf and redeposited mainly in fans along the continental margin (see, e.g. papers in Solheim et al., 1996a,b; Evans et al., 2000-this issue). Isostacy associated with the glaciation appears to be an important factor in the uplift, and Blythe and Kleinspehn (1998) think it is enough to account for all the uplift in Svalbard, whereas Riis and Fjeldskaar (1992) calculate that it does not account for all the uplift. No one seems to have tried to use this mechanism to account for the accelerated subsidence in the North Sea. Riis and Fjeldskaar (1992) speculate that the residual uplift not accounted for by isostacy could be caused by phase changes in the lithosphere due to pressure relief.

Cloetingh et al. (1990) suggested that both the uplift and accelerated subsidence could be explained by regional compression of the lithosphere. Their model predicts both accelerated subsidence in the basins and basin-flank uplift, and the patterns of uplift predicted appear to be in agreement with observation (compare Cloetingh et al.’s (1990) Fig. 7 with Chalmers’ (2000-this issue) Fig. 3). Cloetingh et al.’s (1990) calculations also predict that the uplifted basin margins should also verge towards the basin, an effect seen, for example, in southern Norway. One difficulty with Cloetingh et al.’s (1990) model is that the amounts of uplift and subsidence that it predicts appear to be too small by an order of magnitude (their Fig. 3). Another difficulty is in explaining how lithospheric compression could be transmitted across the actively-spreading mid-Atlantic Ridge, below which Iceland-plume material is interpreted to be spreading outwards in the asthenosphere (White et al., 1995).

6. Summary

There appear to have been at least two significant episodes of uplift around the North Atlantic during the Cenozoic and, in many places, it is not easy to separate the two. One episode, mostly in the Palaeogene, was due to emplacement of magma from the Iceland plume in and below the crust as well as marginal uplift at the start of sea-floor spreading. The second episode took place during the late Neogene and Quaternary. It comprised not only uplift of basin margin areas, but also accelerated subsidence of at least some of the basin centres. Isostatic rebound from glacial erosion during the Quaternary appears undoubtedly to be an important element in explaining uplift of at least the Scandinavian mountain ranges. Whether it is enough to explain all the uplift is still an open question, and no one has used this mechanism to explain the accelerated late-Cenozoic subsidence in, e.g. the North Sea and possibly other areas.

Explanations for these observations have commonly been local, involving mechanisms not applicable to the entire area. However, the phenomena appear to have affected many, if not all, continental margins around the North Atlantic. A model that explains these large-scale, Cenozoic phenomena must separate the effects of Palaeogene, plate boundary- and plume-related uplift from those of Neogene intraplate uplift, and include the subsidence patterns observed adjacent to the landmasses (Stuevold and Eldholm, 1996; Japsen, 1997). Such a model must be constrained by regional observations of these events based on independent methods rather than by data from a single area, and by the fact that their effects reach beyond the passive margins.

References

Andersen, M.S., Nielsen, T., Sørensen, Å.B., Boldreel, L.O., Kuijpers, A., 2000-this issue. Cenozoic sediment distribution and tectonic movements in the Faroe region. Global Planet. Change.

Blythe, A.E., Kleinspehn, K.L., 1998. Tectonically versus climatically driven Cenozoic exhumation of the Eurasian plate margin Svalbard: fission track analyses. Tectonics 17, 621–639.

Boldreel, L.O., Andersen, M.S., 1993. Late Paleocene to Miocene Compression in the Faeroe-Rockall Area. In: Parker, J.R. (Ed.), The Geological Society, London, pp. 1025–1034.

Boldreel, L.O., Andersen, M.S., 1994. Tertiary development of the Faeroe-Rockall Plateau based on reflection seismic data. Bull. Geol. Soc. Denmark 41, 162–180.

Boulton, G.S., Peacock, J.D., Sutherland, D.G., 1991. Quaternary. In: Craig, G.Y. (Ed.), Geology of Scotland. The Geological Society, London, pp. 503–543.

Bulat, J., Stoker, S.J., 1987. Uplift determination from interval velocity studies, UK, southern North Sea. In: Brooks, J., Glennie, K.W. (Eds.), Petroleum Geology of North West Europe. Graham and Trotman, London, pp. 293–305.

Campbell, I.H., Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts. Earth Planet. Sci. Lett. 99, 79–93.

Chalmers, J.A., 2000. Offshore evidence for Neogene uplift in central West Greenland. Global Planet. Change 24, 311–318.

Choubert, G., Faure-Murat, A., 1976. Geological World Atlas (1:10,000,000). UNESCO, Paris.

Clausen, O.R., Nielsen, O.B., Huuse, M., Michelsen, O., 2000. Geological indications for Palaeogene uplift in the eastern North Sea Basin. Global Planet. Change 724, 175–187.

Clift, P.D., Carter, A., Hurford, A.J., 1998. The erosional and uplift history of NE Atlantic passive margins; constraints on a passing plume. J. Geol. Soc. London 155, 787–800.

Cloetingh, S., Gradstein, F.M., Kooi, H., Grant, A.C., Kaminski, M., 1990. Plate reorganization; a cause of rapid late Neogene subsidence and sedimentation around the North Atlantic. J. Geol. Soc. London 147, 495–506.

Dam, G., Larsen, M., Sørensen, J.C., 1998. Sedimentary response to mantle plumes: implications from Paleocene onshore successions West and East Greenland. Geology 26, 207–210.

Doré, A.G., 1992. The base Tertiary surface of southern Norway and the northern North Sea. Nor. Geol. Tidsskr. 72, 259–265.

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 Planet. Change 12, 415–436.

Doré, A.G., Lundin, E.R., 1996. Cenozoic compressional structure on the NE Atlantic margin: nature, origin and potential significance for hydrocarbon exploration. Pet. Geosci. 2, 299–311.

Duncan, W.I., Green, P.F., Duddy, I.R., 1998. Source rock burial history and seal effectiveness; key facets to understanding hydrocarbon exploration potential in the East and central Irish Sea basins. Am. Assoc. Pet. Geol. Bull. 82, 1401–1415.

England, P., Molnar, P., 1990. Surface uplift, uplift of rocks, and exhumation of rocks. Geology 18, 1173–1177.

Escher, J.C., Pulvertaft, C., 1995. Geological Map of Greenland (1:2,500,000). Geological Survey of Greenland, Copenhagen.

Evans, D.J., 1997. Estimates of the eroded overburden and the Permian-Quaternary subsidence history of the area west of Orkney. Scott. J. Geol. 33, 169–182.

Evans, D., McGiveron, S., McNeill, A.E., Harrison, 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 Planet. 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.

Fredén, C., 1994. Geology, National Atlas of Sweden. SNA Publishing, Stockholm.

Geikie, A., 1901. The Scenery of Scotland. London.

George, T.N., 1966. Geomorphic evolution in Hebridean Scotland. Scott. J. Geol. 2, 1–34.

Green, P.F., 1989. Thermal and tectonic history of the East Midlands shelf (onshore UK) and surrounding regions assessed by apatite fission track analysis. J. Geol. Soc. London 146, 755–774.

Green, P.F., Duddy, I.R., Bray, R.J., 1997. Variation in thermal history styles around the Irish Sea and adjacent areas; implications for hydrocarbon occurrence and tectonic evolution. Geol. Soc. London, Spec. Publ. 124, 73–93.

Håkansson, E., Pedersen, S.S., 1992. Geologisk kort over den danske undergrund [Geological Map of the Danish Bedrock (1:540,000)]. Varv, Copenhagen.

Hansen, K., 1995. Thermotectonic evolution of a rifted continental margin: fission track evidence from the Kangerlussuaq area, SE Greenland. Terra Nova 8, 458–469.

Hansen, K., 2000. Tracking thermal history in East Greenland: an overview. Global Planet. Change 24, 303–309.

Hansen, S., 1996. Quantification of net uplift and erosion on the Norwegian Shelf south of 66°N from sonic transit times of shale. Nor. Geol. Tidsskr. 76, 245–252.

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

Japsen, P., 1998. Regional velocity-depth anomalies, North Sea Chalk: a record of overpressure and Neogene uplift and erosion. Am. Assoc. Pet. Geol. Bull. 82, 2031–2074.

Japsen, P., 1. Investigation of multi-phase erosion using reconstructed shale trends based on sonic data. Sole Pit axis, North Sea. Global Planet. Change 24, 189–210.

Japsen, P., Bidstrup, T., 1999. Quantification of Neogene erosion in Denmark based on sonic data and basin modelling. Bull. Geol. Soc. Denmark 46, 79–99.

Jensen, L.N., Schmidt, B.J., 1992. Late Tertiary uplift and erosion in the Skagerrak area; magnitude and consequences. Nor. Geol. Tidsskr. 72, 275–279.

Johnson, C., Gallagher, K., 2000. A preliminary Mesozoic and Cenozoic denudation history of the North East Greenland onshore margin. Global Planet. Change 24, 261–274.

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. Mar. Pet. Geol. 12, 845–879.

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

Larsen, H.C., 1990. The East Greenland shelf. In: Grantz, A., Johnson, L., Sweeney, J.F. (Eds.), The Arctic Ocean Region. Geological Society of America, Boulder, CO, pp. 185–210.

Lidmar-Bergström, K., 1996. Long term morphotectonic evolution in Sweden. Geomorphology 16, 33–59.

Lidmar-Bergström, 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. Geol. Soc. London, Spec. Publ. 162, 85–91.

Lidmar-Bergström, K., Ollier, C.D., Sulebak, J.C., 2000. Landforms and uplift history of southern Norway. Global Planet. Change 24, 211–231.

Mathiesen, A., 1998. Modelling of uplift history from maturity and fission track data, Nuussuaq, West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport 1998/87, 90 pp.

Mathiesen, A., Christiansen, F.G., Bidstrup, T., Marcussen, C., Dam, G., Piasecki, S., Stemmerik, L., 1995. Modeling of hydrocarbon generation in the Jameson Land Basin East Greenland. First Break 13, 329–341.

Mathiesen, A., Bidstrup, T., Christiansen, F.G., 2000. Denudation and uplift history of the Jameson Land Basin, East Greenland — constrained from previous maturity and new apatite fission track data. Global Planet. Change B 24, 275–301.

Meyer, W., 1983. Pre-Quaternary uplift in the central part of the Rhenish Massif. In: Fuchs, K., von Gehlen, K., Mälzer, H., Murawski, H., Semmel, A. (Eds.), Plateau Uplift. The Rhenish Shield — A Case Story. Springer, Berlin, pp. 39–46.

Nadin, P.A., Kusznir, N.J., Cheadle, M.J., 1997. Early Tertiary plume uplift of the North Sea and Faeroe-Shetland Basins. Earth Planet. Sci. Lett. 148, 109–127.

Nielsen, O.B., Sørensen, S., Thiede, J., Skarbo, O., 1986. Cenozoic differential subsidence of North Sea. Am. Assoc. Pet. Geol. Bull. 70, 276–298.

Nyland, B., Jensen, L.N., Skagen, J.I., Skarpnes, O., Vorren, T.O., 1992. Tertiary uplift and erosion in the Barents Sea; magnitude, timing and consequences. In: Larsen, R.M., Brekke, H., Larsen, B.T., Telleraas, E. (Eds.), Structural and Tectonic Modelling and its Application to Petroleum Geology. Elsevier, Amsterdam, pp. 153–162.

Pharao, T.C., Morris, J.H., Long, C.B., Ryan, P.D., 1996. Tectonic Map of Britain, Ireland and Adjacent Areas (1:1,500,000). British Geological Survey, Keyworth, Nottingham.

Reusch, H., 1901. En ejendommelighet ved Skandinaviens hovedvannskille. Nor. Geol. Unders. 32, 124–263.

Riis, F., 1996. Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. Global Planet. Change 12, 331–357.

Riis, F., Fjeldskaar, W., 1992. On the magnitude of the late Tertiary and Quaternary erosion and its significance for the uplift of Scandinavia and the Barents Sea. In: Larsen, R.M, Brekke, H., Larsen, B.T., Telleraas, E. (Eds.), Structural and Tectonic Modelling and its Application to Petroleum Geology. Elsevier, Amsterdam, pp. 163–185.

Riis, F., Jensen, L.N., 1992. Introduction; measuring uplift and erosion; proposal for a terminology. Nor. Geol. Tidsskr. 72, 223–228.

Roest, W.R., Srivastava, S.P., 1989. Sea-floor spreading in the Labrador Sea; a new reconstruction. Geology 17, 1000–1003.

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., van der Beek, P., Andriessen, P., Cloetingh, S., 1995. Meso-Cenozoic morphotectonic evolution of southern Norway: Neogene domal uplift inferred from apatite fission track thermochronology. Tectonics 14, 700–714.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J., Kent, R.W., 1997. The North Atlantic igneous province. Geophys. Monogr. 100, 45–93.

Shannon, P.M., Moore, J.G., Jacob, A.W.B., Makris, J., 1993. Cretaceous and Tertiary basin development west of Ireland. In: Parker, J.R. (Ed.), Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. The Geological Society, London, pp. 1057–1066.

Sigmond, E.M.O., 1993. Bedrock Map of Norway and Adjacent Ocean Areas (1:3 million). Geological Survey of Norway, Oslo.

Solheim, A., Andersen, E.S., Elverhoi, A., Fiedler, A., 1996a. Late Cenozoic depositional history of the western Svalbard continental shelf, controlled by subsidence and climate. Global Planet. Change 12, 135–148.

Impact of Glaciations on Basin Evolution: Data and Models from the Norwegian Margin and Adjacent Areas. Solheim, A., Riis, F., Elverhøi, A., Faleide, J.I., Jensen, L.N., Cloetingh, S. (Eds.), Global Planet. Change 12, 1–450.

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

White, R.S., Spencer, G.D., Fowler, S.R., McKenzie, D.P., Westbrook, G.K., 1987. Magmatism at rifted continental margins. Nature 330, 439–444.

White, R.S., Bown, J.W., Smallwood, J.R., 1995. The temperature of the Iceland plume and origin of outward-propagating V-shaped ridges. J. Geol. Soc. London 152, 1039–1045.

Whittaker, R.C., Hamann, N.E., Pulvertaft, C., 1997. A new frontier province offshore Northwest Greenland: structure, basin development and petroleum potential of the Melville Bay area. Am. Assoc. Pet. Geol. Bull. 81, 987–998.