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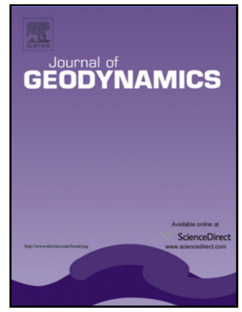

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The evolution of western Scandinavian topography : a review of Neogene uplift versus the *ICE* (isostasy-climate-erosion) hypothesis

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Abstract

Tectonics and erosion are the driving forces in the evolution of mountain belts, but the identification of their relative contributions remains a fundamental scientific problem in relation to the understanding of both geodynamic processes and surface processes. The issue is further complicated through the roles of climate and climatic change. For more than a century it has been thought that the present high topography of western Scandinavia was created by some form of active tectonic uplift during the Cenozoic. This has been based mainly on the occurrence of surface remnants and accordant summits at high elevation believed to have been graded to sea level, the inference of increasing erosion rates toward the present-day based on the age of offshore erosion products and the erosion histories inferred from apatite fission track data, and on over-burial and seaward tilting of coast-proximal sediments.

In contrast to this received wisdom, we demonstrate here that the evidence can be substantially explained by a model of protracted exhumation of topography since the Caledonide Orogeny. Exhumation occurred by gravitational collapse, continental rifting and erosion. Initially, tectonic exhumation dominated, although erosion rates were high. The subsequent demise of onshore tectonic activity allowed slow erosion to become the dominating exhumation agent. The elevation limiting and landscape shaping activities of wet-based alpine glaciers, cirques and periglacial processes gained importance with the greenhouse-icehouse climatic deterioration at the Eocene-Oligocene boundary and erosion rates increased. The flattish surfaces that these processes can produce suggest an alternative to the traditional tectonic interpretation of these landscape elements in western Scandinavia. The longevity of western Scandinavian topography is due to the failure of rifting processes in destroying the topography entirely, and to the buoyant upward feeding of replacement crustal material commensurate with exhumation unloading.

We emphasize the importance of differentiating the morphological, sedimentological and structural signatures of recent active tectonics from the effects of long-term exhumation and isostatic rebound in understanding the evolution of similar elevated regions.

Key words. Erosion, climate, isostasy, Caledonides, Neogene, uplift

1. Introduction

The Silurian Caledonide Orogeny (450-420 Ma) (Fig. 1) was the consequence of the continent-continent collision of Laurentia and Baltica (Soper et al., 1992; Cocks and Torsvik, 2002), and represents the most recent mountain-building process to affect the region of Scandinavia. Prior to this the Sveconorwegian Orogeny (1.15-0.9 Ga) affected southern Norway and south-western Sweden, mainly as a crustal thickening and topography producing event (Balling, 2000; Bingen et al., 2005) and without much accretion of new crust. Even older records of crustal amalgamation and mountain-building in southwestern Scandinavia date back to the Gothian complex of orogenic events from 1.75-1.55 Ga (Bogdanova et al., 2008).

Collapse and rifting processes began to dismember the Caledonides immediately after their formation. These processes ultimately produced the deep late Palaeozoic and Mesozoic sedimentary basins on the continental shelves of north-western Europe and east Greenland and also affected the onshore western Scandinavia (Dunlap and Fossen, 1998; Fossen and Dunlap, 1999; Andersen et al., 1999; Mosar, 2003). The prolonged continental rifting process between the North American-Greenland craton and Eurasia (Doré et al., 1999) led at ~62 Ma ago (mid Danian) to a sudden left-lateral translation through the proto North Atlantic area and the Arctic oceans (Nielsen et al., 2007a) with an associated phase of magmatism. This event finally graded into ocean formation in the North Atlantic and the Arctic oceans at ~56 Ma (late Paleocene, Tegner et al., 1998). The ensuing continental drift placed the remains of the Caledonide Orogeny in widely separate locations in E Greenland, western Scandinavia, Scotland, Ellesmere Island (Canadian Arctic) and on Svalbard (Andersen et al., 1991; Skogseid et al., 2000).

Given the age of the mountain building processes of the Baltic Shield it is not surprising that the topography at the present day generally is low, but for western Scandinavia (and Scotland) – the onshore European realm of the Caledonide Orogeny - it is different. Here a conspicuous mountain range stretches from south to north along the Atlantic coast and at present reaches peak elevations of above 2000 m in northern and southern Norway. Generally, the highest topography is west of or coincident with the Caledonide thrust front, but also in southern Norway east of the thrust front topography is high (Fig. 2).

The origin of this high topography in western Scandinavia is the cause of some controversy, and the present contribution addresses this. For example, it has long been thought that ancestral topography had been destroyed by rifting and eroded close to sea level towards the end of the Mesozoic era whereafter the widely advocated Cenozoic (mainly Neogene) tectonic uplift hypothesis should have produced the present high topography by a series of tectonically-driven Cenozoic uplift events with amplitudes on the ~1-2 km scale and wavelengths in the 400-500 km range (Fig. 2). While the proposed mechanisms differ considerably, the observational basis of this hypothesis are mainly (e.g. Reusch, 1901; Peulvast, 1985; Japsen, 1988; Doré, 1992; Riis and Fjeldskaar, 1992; Jensen and Schmidt, 1993; Doré and Jensen, 1996; Riis, 1996; Stuevold and Eldholm, 1996; Rohrman et al., 1995; Doré et al., 1999; Japsen and Chalmers, 2000; Lidmar-Bergström et al., 2000; Cloetingh et al., 2005; Bonow et al., 2007): (1) accumulation of increasingly coarser sediments at an increasing rate (particularly during the Neogene) in the North Sea and on the Norwegian Shelf, suggesting a tectonic rejuvenation in the sediment source area; (2) the onshore distribution of apatite fission track ages and lengths that have been interpreted in terms of an increased Neogene erosion rate caused by Neogene uplift; (3) the over-burial of sedimentary strata along the coast, a sea-ward tilt evolution, and the angular unconformity at the base of the Quaternary all together point to the occurrence of onshore and coast-proximal uplift and offshore subsidence; and (4) the presence of accordant summits (summit envelopes) and low-relief landscape elements at high-elevation interpreted as remnants of extensive erosion surfaces originally graded to sea level.

In the following we review this evidence in the light of new observations and the possible effects of geological processes, which are known to have occurred. We find that the above fundamental observations can consistently be explained without the resort to active Neogene tectonic uplift and that the evolution of western Scandinavian highlands is relatively simple: The present day high topography is better explained as the remnants of topography, which survived the extensional collapse, onshore and (mainly) offshore rifting processes following the Caledonian Orogeny, as well as erosion. A similar point of view has recently been expressed for the Scottish Caledonides (Macdonald et al., 2007). On this rifting background, the main contributions to the driving mechanism of our hypothesis are isostasy, climate, and erosion. Consequently, we use the term *ICE*-hypothesis (Nielsen et al., 2007b) If we accept the *ICE*-hypothesis then the concept of Cenozoic (mainly Neogene) tectonic uplift is not required, and the basis for understanding the geodynamic evolution of the region, including onshore-offshore relationships, becomes simpler. The sacrifice we have to make is the idea that flattish landscape elements in the western Scandinavian highlands convey information about tectonic uplift.

In fact, the geomorphological *interpretation* that these flattish landscape elements are erosional surfaces, which were graded to sea level e.g. during the Mesozoic and then uplifted during the Cenozoic to their present elevations is the only aspect of the overall debate that is not readily in agreement with the *ICE*-hypothesis. The *ICE*-hypothesis replaces this traditional tectonic interpretation of landscapes with climate control on landscape evolution via ice and periglacial processes such as frost weathering and frost-induced mass diffusion, which we return to later.

In a historical perspective, the origins of the Cenozoic tectonic uplift hypothesis can be traced back to pre-plate tectonic epirogeny concepts of the geosynclinal age. Not surprisingly, it was the immediately observable and presumably old flattish landscape elements at high elevation intersected by deep, young fjords that formed the basis for a Davisian-style interpretation of recent tectonic uplift, or landscape rejuvenation. This idea still is pivotal in more recent attempts to understand the geodynamic evolution, which then develops severe complications (see below) because fundamental structural and geophysical observations do not permit plate tectonic mechanisms like crustal shortening and thickening and magmatic underplating to produce surface uplift in western Scandinavia. As the geomorphological arguments continue to influence the tectonic-based community in (mainly) Scandinavia and central Europe, and has a major influence on developing geodynamic models, it is appropriate here to review and critique the underlying arguments.

2. About surfaces in western Scandinavia

It appears that the cyclic landscape evolution model of W. M. Davis (1850-1934) lies at the heart of denudation chronology applications to western Scandinavia. The simplest ideal case that Davis presented envisages the rapid tectonic uplift of a low relief surface close to sea level to form an elevated plateau (Davis, 1889, 1899). The resulting increase in river gradient leads to channel incision and the progressive valley deepening causes an increase in relief. This 'youthful' stage of the cycle is followed by the 'mature' stage characterized by a decrease in the rate of channel incision as base level is approached and a corresponding gradual reduction in slope gradients. The 'old age' stage is marked by a further lowering of interfluves and reduction in relief which eventually results in a peneplain – a low relief surface close to sea level. In this model a landscape comprising accordant summits or a more extensive high-elevation low relief surface dissected by valleys would be regarded as diagnostic of an uplifted peneplain. It is important to note that Davis (though often not other workers who adopted his scheme) regarded this as an ideal (end member) model primarily aimed at outlining the principles of landscape change through time. He fully acknowledged that gradual rather than rapid uplift could occur requiring the "consideration of erosion during uplift", but argued that in the initial presentation of the model it was desirable to consider the "elementary and temporary view" of rapid uplift before modifying this to "a nearer approach to the probable truth" (Davis, 1905).The understanding of the landscape elements of western Scandinavia was placed in a geomorphological framework in the late 1800s-early 1900s with the work of the Norwegian geologist Hans Reusch (1852-1922). Probably during a visit to Harvard University in 1895-1896, he became more familiar with Davis's landscape evolution model. Reusch (1901) suggested that the elevated low-relief surfaces and accordant summits, characteristic of the Norwegian highlands, were remnants of an uplifted peneplain in the Davisian sense and therefore indicative of uplift of the land surface from an original position close to sea level. Reusch termed this the ‘paleic’ surface, and in some places was apparently able to identify two surfaces with the upper level representing the older event, noting at the same time that the absolute ages of the uplift events could not be dated. Having the advantage of knowing the age of the thick offshore deposits of erosion products, later workers placed the main uplift phases during the Paleocene and particularly during the Neogene (e.g. Riis, 1996; Japsen and Chalmers, 2000). In his discussion of the general genesis of surfaces, Reusch interestingly noticed that although surfaces may form as a result of uplift they may also form as a result of a sinking of the peripheral areas and that Norway might be thought about also “as the remnant of a high land, which had a great extension westward in the Atlantic”, a quite prophetic remark, which shows that Reusch was aware of the ambiguity of the surface chronology approach to the unravelling of tectonic events.

The investigations into the meaning of the Norwegian landforms continued to be developed in the work of Gjessing (1967), who also provided a detailed discussion of previous work in the field. Gjessing reconstructed the ‘enveloping’ surface for the whole of Fennoscandia and discussed in more detail than previously the processes that might have been active in the formation of the paleic surface, including weathering. He was particularly concerned with the influence of past climate on the development of specific aspects of the paleic landforms. He concluded that the paleic landforms probably developed within a wide range of heights above base level and that they could not be associated with particular tectonic events because the probably climatically determined processes involved seemed to have been “of the most vital importance”.

Although it is now understood that erosion surfaces may be formed in complex ways that do not fit with Davis's original concept, it seems that it is the elementary end-member form of the Davisian cyclic landscape evolution model. Furthermore, the implied potential for recording episodes of tectonic uplift from the identification of uplifted peneplain remnants has remained central to some more recent attempts to understand western Scandinavian topography. For instance, Peulvast (1985) identified a pre-glacial and an older uplifted peneplain and suggested that they were the result of two separate uplift events. The first occurred at the time of opening of the Norwegian-Greenland Sea, and the second during the Neogene. Doré (1992) defined the palaeic surface by the summit envelope of southern Norway and suggested an early Cenozoic age through correlation with the offshore base Cenozoic surface in the northern North Sea. He further discussed how several mechanisms, including large scale flexure induced by in-plane stress as well as offshore/onshore loading by sedimentation and erosion, might have been active in creating the Cenozoic uplift in southern Norway and contemporaneous subsidence in the northern North Sea. This concept of onshore-offshore correlation was further elaborated by Riis (1996). He interpreted the Scandinavian summit level, including autochthonous block fields (to him a sign of only limited glacial erosion of an almost preserved peneplain), as the remains of a Mesozoic peneplain raised to its present elevation through Palaeogene and Neogene phases of uplift inferred from correlation with offshore surfaces. He furthermore extended the sub-Cambrian peneplain of southern Sweden to southern Norway noting that this extension is not stratigraphically constrained. Lidmar-Bergström et al. (2000) identified four distinct surfaces on the basis of summit envelopes and surface remnants in southern Norway: surface I (Late Jurassic or Early Cretaceous), surface II (Early Cretaceous or Coniacian), surface III (Coniacian or Paleocene), and surface IV (Paleocene or Oligocene). These were interpreted as resulting from changes in eustatic sea level combined with a domal, tectonic uplift and it was suggested that the maximum uplift of the Late Mesozoic envelope surface was about 1000 m in the Cretaceous-Palaeogene. The later uplift of the palaeic surface in southern Norway seemed to be a continuation of the Palaeogene doming and did not exceed 1200 m and was mainly a Neogene event. This might have been initiated in the late Eocene/early Oligocene. Bonow et al. (2007) used elevated erosion surfaces as an independent data set together with fission track data and geological information in a study of the landscape development in central West Greenland and related this to geomorphological key observations for the landscapes of southern Norway, particularly the elevated plateaux and the Mesozoic etch surfaces.

The above examples illustrate clearly how a direct line can be drawn from recent denudation chronology work back to the ideas of W. M. Davis. However, the use of the remnants of Davisian peneplains to underpin arguments of tectonic uplift now is considered flawed by many geomorphologists for over 40 years (e.g. Chorley 1965; Summerfield, 2000;

Phillips 2002). Davis himself acknowledged the apparent scarcity of present examples of erosion surfaces graded to sea level, just waiting for an uplift event to occur.

It is common to the above cited studies that the recognition of ancient, uplifted peneplains relies on the accordance of summit envelopes and drainage divides and on the implicit assumption that those at present similar elevations were once graded to base level controlled by sea level. However, this *equifinality* is a critical issue because a number of other plausible explanations exist for the accordance of summits and divides, some of which were pointed out immediately following Davis's presentation of his interpretation (Shaler, 1899; Penck, 1919). Phillips (2002) lists seven plausible mechanisms other than the uplifted peneplain that can result in the accordancy of summits. Here we mention only number seven, climate, which reaches back to Gjessing (1967) and which we suggest is relevant to the understanding of the geomorphology of the western Scandinavian highlands. Below we discuss the suggestions by Brozovic et al. (1997) and Mitchell and Montgomery (2006) that the long-term glacier equilibrium line altitude controls the development of topography.

In a further analysis Phillips (2002) demonstrated quantitatively that long-term landscape evolution (i.e. erosion and deposition) subjected to isostasy and climatic perturbations in principle represents an unstable physical system. More explicitly, distinct landscape elements are not stable over geological time. For example, surfaces at a high elevation are intrinsically unstable and do not survive unless, of course, a mechanism e.g. related to climate is constantly working against the destructive processes to maintain summit and divide accordancy. Although such a landscape would exhibit apparent surface remnants, they would not be surfaces in the Davisian sense.

In addition to this conceptual and theoretical reasoning questioning the origin and interpretation of high-elevation surfaces, there is unambiguous empirical evidence demonstrating that such surfaces would not survive unmodified over geological time. This comes from a growing body of data documenting long-term denudation rates from terrestrial cosmogenic nuclide inventories that show that even in low relief topography rates of denudation are at least of the order of 5-10 m Ma^{-1} in sub-humid to humid climates (Cockburn and Summerfield, 2004) and perhaps lower in currently arid climates (Belton et al 2004).

The range of plausible explanations of high-elevation surfaces other than the uplift of low-relief surfaces graded to sea level, together with the fundamental problem of how such uplifted surfaces, could be preserved over geological time spans, clearly raises important questions as to their use in documenting tectonic uplift events. Moreover, even if remnants of uplifted low-relief surfaces originally graded to sea level do exist and have been preserved, the problem of dating remains. Given the lack of directly associated dateable sediments for surfaces in western Scandinavia, there is no local stratigraphic age control and surface dating has been based largely on supposed correlation of surfaces with stratigraphic sequences elsewhere. The inherent uncertainty in this approach is illustrated by the range of surfaces identified by different workers and the diversity of chronological schemes that have been presented.

3. The ICE (isostasy-climate-erosion) hypothesis

Given the intrinsic difficulties of the surface chronology approach in western Scandinavia, we suggest it is better not to accept its unconstrained geomorphological premises and the complications (see discussion of Mosar (2003) below) that the associated tectonic interpretation implies for geodynamic models of the region. We instead consider the topography to be exhumed from topography produced during the Caledonian Orogeny, as for Scotland (Macdonald et al., 2007).

Apart from the failure of rifting processes in destroying the topography, it is the buoyant isostatic feeding of replacement crustal material and the slow Mesozoic-early Cenozoic erosion rates that conditions its longevity. This warrants paragraphs below on crustal thickness, gravity and topography and fission track thermochronology. The abandoning of the tectonic interpretation of surfaces in western Scandinavia is met with a paragraph on Cenozoic climatic control on landscape evolution.

3.1 Crustal thickness, gravity and topography

In general the elevated topography in collisional orogens is supported by the buoyancy of a thickened crustal root relative to the mantle. The implied correlation between topographic height, Bouguer gravity anomaly (reflecting the subsurface mass deficit) and crustal thickness applies to any collisional orogen. In western Scandinavia, the observed correlation between topography and gravity has demonstrated near local isostatic equilibrium (i.e. a close to zero or slightly positive free-air gravity anomaly) with a relatively shallow (upper mantle to lower and intra-crustal) support of the topography (Balling, 1980). Our new receiver function measurements of crustal thickness along two profiles (Svennigsen et al., 2007; Appendix A) (Fig. 3a) and re-analysis of crustal thickness variations reinforce the notion that the topography of southern Norway (Fig. 3abc) is supported mainly by a crustal root. Further north, along the axis of the mountains, crustal thickness data are more scarce, but our analysis indicates that a crustal root is present, although in this region intra-crustal sources of buoyancy (granites) may also be important (Ebbing and Olesen, 2005).

The buoyant support of topography means that a reduction of regional elevation by 1 km requires ~5- 6 km of erosion depending on the density of the mantle at the depth of compensation and the density of the eroding crust (Molnar and England, 1990; Fisher, 2002). This provides a compelling case against the view that the Scandinavian Caledonides were eroded close to sea level by the Late Mesozoic because the isostatic rebound in response to the unloading requires that the crustal root beneath the mountain belt be also removed. As long as a buoyant root is present, isostatically-supported elevated topography will be sustained, and erosional processes will most likely remain active. In the absence of a viable mechanism (see discussion below) to replace/recreate a root, the geophysical data therefore strongly suggest long-term erosion of topography that remained after the Devonian-Carboniferous gravitational collapse and the Late Paleozoic-Mesozoic rifting. Similar models have been proposed for south-eastern Australia (Stephenson and Lambeck, 1985) and for the Great Smoky Mountains of the Appalachians (Matmon et al., 2003).

The crust-mantle boundary (the Moho) is generally a first-order seismic and compositional boundary and is determined by seismic and seismological experiments and data analysis (mainly seismic refraction and reflection studies and analysis of teleseismic receiver functions). The Moho depth map of Kinck et al. (1993) for Fennoscandia has been updated for the study region (Fig. 3a) by recently published information (Iwasaki et al., 1994; Schmidt, 2000; Ottemöller and Midzi, 2003) and by our own new crustal thickness determinations from receiver function analysis beneath the highlands of southern Norway (Svenningsen et al., 2007; Appendix A).

The crustal thickness beneath Scandinavia varies between about 30 km along the coastal areas of Norway and 40-45 km inland beneath the higher topography to the south and north (Fig.3a). Beneath southern Norway we observe a close correlation between thick crust (up to 43 km), low Bouguer gravity (down to -90 to -100 mgal, Fig. 3b) and high topography (regional elevation more than 1000 m with local maximum elevations between 2000 and 2500 m). The elevated topography seems largely isostatically supported by the buoyancy of a relatively light crustal root as compared to the surrounding mantle material of higher density. Gravity modelling indicates a density contrast close to 300 kg/m^3 across the Moho.

Along the elevated topography to the north (northern Norway and the north-western part of Sweden with regional surface elevation of about 1000 m) we also observe low Bouguer gravity (down to -100 to-130 mgal, Fig 3b), but crustal thickness variations are more complex. The main feature is a strong crustal thickness gradient across the Atlantic passive margin with a general increase in crustal thickness eastwards towards the interior of the Baltic Shield (Fig. 3a and Kinck et al., 1993). We suggest that this strong gradient in depth to Moho from less than 20 km offshore to 45-50 km (and locally more) in the Shield interior is generally masking the existence of a low density crustal root beneath the areas of high topography. The existence of a low-density root is clearly indicated by the presence of regional low Bouguer gravity similar to observations in southern Norway, despite structural differences (Ebbing and Olesen, 2005).

In order to shed light on this complex deep structural situation, we have filtered the crustal thickness map (Fig 3a) by removing longer wavelengths. If crustal roots beneath the elevated topography are being partially masked by longer wavelength crustal thickness variations from the coastal areas of Norway to the Shield interior residual roots should appear after filtering. This is indeed the case, and the application of different filters results in slightly different amplitudes and positions of the crustal roots, but they are always present in the filtered models. The residual roots shown in Fig. 3c have been revealed by removing wavelengths longer than 800 km from the Moho depth map in Fig. 3a. Although our residual crustal thickness map emphasizes local structure but may underestimate amplitudes we note that, interestingly, our results are corroborated by a recent seismological profile across western Scandinavia close to Trondheim. Even here where the inland topography is relatively low, England et al. (2008) find indications that greater Moho depth correlates with high topography and low Bouguer gravity.

Common to the various filtered crustal thicknesses is the appearance of a crustal root in areas of high topography in the north and a reduction in the amplitude of the root already seen in the unfiltered crustal thickness in the south. Thus, the filtering is successful in revealing the local structure whereas the root amplitude is underestimated. For full isostatic compensation of topography deeper roots are needed (Ebbing and Olesen, 2005; Balling, 1980), although some compensation in the crust (Ebbing and Olesen, 2005) and beneath Moho in the uppermost mantle (Bannister et al., 1991; Bondo et al., 2008; Weidel and Maupin, 2008) may exist.

The crustal root under southern Norway is considered by some to be a false or imaginary root, implying that it only exists as a distinct topographic feature on the Moho surface because the crust has been thinned in the Permo-Carboniferous Oslo rift and offshore. Had there been no surrounding rifting processes, the deep Moho characteristic of the area east of the Oslo rift would continue to the west until meeting the zone of Palaeozoic and Mesozoic extension offshore. Clearly, the thinned crust in the Oslo region contributes to making the deeper Moho underneath southern Norway more conspicuous, as do the rifting processes that formed the Palaeozoic and Mesozoic sedimentary shelves.

Although the central part of the Silurian Caledonides (and the associated crustal root) now forms the basement of the offshore sedimentary basins, we still use the term ‘crustal root’ for the crust underlying the elevated topography of western Scandinavia *because by its buoyancy it acts as such*. This becomes apparent when analysing the relationship between topography and Bouguer gravity anomalies (Balling, 1980). East of the Oslo rift (Fig. 3ab) crustal thickness exceeds that in southern Norway, yet the topography is considerably lower and the Bouguer gravity anomaly is markedly less negative, indicating the presence of a lower crust of relatively high density, cf. also recent isostatic modelling by Ebbing (2007). In contrast, there is a clear correlation between crustal thickness, topographic height and negative Bouguer gravity to the west and north of the Oslo rift (Svennigsen et al., 2007), pointing to a lower crust of a relatively lower density. It is difficult to envisage how the occurrence of the Oslo rift could have produced this conspicuous difference in the fundamental characteristic parameters of crustal thickness, topography and Bouguer gravity anomaly. Rather, it seems to be the case that the Scandinavian crust exhibits a Pratt-type topographic compensation mechanism in the long wavelength E-W direction (e.g. Ebbing (2007) and that the Oslo rift formed in the transition region between continental crust of fundamentally different characteristics (e.g. composition/density). This difference could have been acquired in pre-Caledonian time (e.g. during the Sveconorwegian Orogeny), or, alternatively, the crust in southern Norway could have been modified (shortened and thickened) during the Caledonide Orogeny. For example, Hurich et al. (1989) have argued that what had previously been thought of as an autochtonous basement window of undisturbed Baltic crust underlying the Caledonian allochthon is in fact crystalline Baltic basement that has been activated, shortened and thickened during the Caledonide collision. This interpretation has been supported by Juhojuntti at al. (2001). Seismic reflection profiles (similar to those described and interpreted in Balling (2000)) across southern Norway (the Hardangervidda) perpendicular to the relevant orogenic fronts might be able to indicate to which extent the topography of southern Norway is of Caledonian or Sveconorwegian origin.

3.2 Long term exhumation (inferred from fission track analysis)

We wish to demonstrate here that the characteristics of the fission track data of western Scandinavia are consistent with the long-term exhumation concept of the *ICE*-hypothesis, which implies a steadily decreasing average surface elevation. However, for the present discussion, we limit the analysis to southern Norway using only the data of Rohrman et al. (1995) and Leighton (2007). Extension of the analysis to the entire western Scandinavia is in progress.

Generally, apatite fission-track ages from across southern Norway are in the range 100-250 Ma, with reduced mean track lengths (MTL) of 10.5-14 µm. The reduced MTL relative to estimated initial unannealed etchable track length of 16 µm requires that samples have been kept at annealing temperatures (>60ºC) until recently and this has generally been used to infer Neogene tectonic uplift, in order to induce recent rapid denudation and therefore cooling (Rohrman et al., 1995, 2002).

The general characteristics of the apatite fission track data set for samples close to sea level in western Scandinavia are (Fig. 3d): old ages (200-230 Ma) occur along the coast with a tendency to a further seaward increase on islands, and younger ages (90-120 Ma) along the fjords within regions of high elevation (Hendriks et al., 2007). This is particularly visible in the inland arms of the Sognefjord. High inland topography is associated with older ages. This age pattern apparently correlates with the Bouguer gravity anomaly, the topography and the crustal root (Fig. 3abc), suggesting the causal relationship that ancient crustal buoyancy has sustained inland topography, which then exhibits a fission track age-elevation relationship that is consistent with protracted exhumation. Here we test this causal relationship in a model of long-term exhumation of the present-day surface.

The *ICE* model exhumation history to produce the present-day surface (Fig. 4) assumes flexural isostasy with and elastic plate thickness of 10 km. This means that high peaks to some extent can be supported by regional isostasy. A density of 3250 kg/m^3 at the depth of compensation means that lowering of the average topography by 1 km requires removal of 5-6 km of crust of average density 2700 kg/m^3. With an initial topographic elevation of 3.5 km, the inferred initial depth of the present-day surface hence is between 10 and 20 km (Fig. 4a). The larger depths occur toward the coastline where the present-day topography approaches sea level. This is in general agreement with the exhumation depth of Fossen et al. (1997) for rocks along the coast of southern Norway west of Bergen.

The exhumation model does not explicitly state how the overburden is removed, except that flexural isostasy prevails. Thus, particularly along the coast, where late Palaeozoic and Mesozoic rifting occurred (Dunlap and Fossen, 1998; Redfield et al., 2004, 2005; Mosar, 2003), the exhumation is likely to result from both extension and erosion. Also the interior regions have experienced extensional reactivation (Dunlap and Fossen, 1998; Anderson et al., 1999; Mosar, 2003) although in our opinion not enough to destroy the topography, but probably enough to cause discontinuities in the observed fission track ages (Leighton, 2007). We suggest that inland southern Norway erosion is the most important exhumation agent, at least since the early Mesozoic (Dunlap and Fossen, 1998; Mosar, 2003). Therefore, the exhumation of the contiguous present-day surface (Fig. 4) in reality, and particularly in the early phases of the evolution, should be the exhumation of a discontinuous surface that gradually assembles vertically and laterally during exhumation. At present, this assembly history is not possible to reconstruct because of lack of information about movements on the most important faults inland (Mosar, 2003). As, furthermore, it would not be possible at the same time to consider the three-dimensional thermal effects of topography we rather understand the contiguous surface exhumation of Fig. 4 to represent a *default* model. Major discrepancies between the default model predictions and observed fission track ages and lengths could then be the result of faults, and perhaps even indicate the position of important fault movements.

During the last phase of exhumation through the partial annealing zone of apatite (~120-60 °C, corresponding to the depth interval from ~5 - ~3 km), it is important that the thermal effect of topography be considered (Braun, 2003). In order to achieve the large areal coverage required for an interpretation of southern Norway (~400 km × 400 km) and still retain a detailed resolution of topography we use a Fourier transform solution to the subsurface temperature field in the presence of topography (Thorsen and Nielsen, submitted). The atmospheric temperature gradient is 0.0065 K/m and the deep, undisturbed temperature gradient is 0.020 K/m, which with an average thermal conductivity of 3 W/m/K yields an average heat flux of 60 mW/m^2, in agreement with heat flow and conductivity measurements across Norway (IHF Commission, 2004; Balling, 1995). The topography of the model shown here evolves gradually from a flat surface at elevation 3.5 km at the onset of the evolution (at 400 Ma) to the present-day topography. The model results are not sensitive to the starting conditions (e.g. past heat flow) as long as the present-day surface at that time was at temperatures above the partial annealing zone for apatite. The starting depth for the present-day surface (Fig. 4a) could therefore be shallower, particularly along the coast.

The overburden (Fig. 4a) is divided into 20 slices, which are removed one after the other, gradually exhuming the present-day surface. With a starting time of 400 Ma the model enters the post-orogenic evolution after decollement backsliding at the onset of extensional collapse (Dunlap and Fossen, 1998). Removal of an overburden slice causes a change of surface topography and elevation and hence the surface temperature. After each removal the temperature of the buried present-day surface at its new depths are calculated for the new surface temperature boundary condition.

The a priori exhumation history assumes an exhumation rate that is constant in time at every location; however, this constant varies laterally with the variations of initial overburden thickness. The predicted distribution of apatite fission track ages from this a priori exhumation history shows large discrepancies with the observed fission track ages, particularly along the coast, where the modelled ages around 80 Myr are much too low (Fig. 5a) compared to commonly observed ages of more than 200 Myr. We used a Markov Chain Monte Carlo (Gallagher, 1995) inversion scheme and the fission track code of Ketcham et al. (1999, 2000) in order to investigate which changes to the a priori exhumation history the observed fission track ages and mean track lengths demand. Although it would be possible to utilize the full histogram of lengths for each fission track sample in the procedure, this would not add much additional information in the present case as the distributions are all unimodal (Leighton, 2007; Rohrman et al., 1995). The exhumation history was taken to be variable in the 9 corner points of the coarse grid covering the area (Fig. 5a). These exhumation histories were interpolated into the interior of the square elements using bilinear interpolation and tested against fission track ages and mean track lengths. We emphasize that it is not the corner temperature histories but rather the *timing* of exhumation of the present-day surface (slice removal) that is interpolated between the corner points. The exhumation model hence is locally rather than globally three-dimensional. The Chlorine-weight fraction of the samples was allowed a measure of uncertainty commensurate with the prior knowledge of this parameter; in case it had been determined by measurement (Leighton, 2007) only a narrow range of variability around this value was allowed. Furthermore, the temperature gradient at sample locations was allowed a +/- 1 mK/m standard deviation in order to allow for inevitable lateral variations of the thermal structure caused by, for example, heterogeneity in the thermophysical parameters of the removed overburden.

This inversion procedure yielded a significant improvement of the agreement between observed and modelled fission track ages and mean track lengths (Fig. 5b; Fig. 6; Fig. 7), as well as significant changes to the entirely linear a priori corner exhumation histories (Fig. 8). For example, at corner point 4 at the west coast and at point 2 at the south coast (Fig. 5a; Fig. 8), the relatively high observed fission track ages demand that deep exhumation happens relatively shortly after model onset of exhumation at 400 Ma to bring the coastal samples into the PAZ and start the retention of fission tracks. Inland, to the east, and in the north the onset of retention of fission tracks is significantly later (corner points 3, 5, 6, 7, 8, 9), although the data density is particularly low to the north. Corner point 1 to the southwest displays little change from the prior exhumation history because it is almost unconstrained by data.

The general picture of early exhumation along the coast and later exhumation inland is in agreement with the interpretation of Dunlap and Fossen (1998) that (mainly) late Palaeozoic rifting along the coast of southern Norway decreased the erosional base level and resulted in an increasing rate of erosional denudation. It furthermore seems that the three-dimensional joint interpretation of the fission track data set of southern Norway has managed to extract information about how the effects of the lowering of base level travelled inland. A slide series (available on request) based on the analysis of the entry of the present-day surface of southern Norway into the PAZ clearly shows how this occurred first along the coast to the west and the south in late Carboniferous-Permian (~300 Ma), and then propagated inland. The deep fjords are the last topographic elements to pass through the PAZ.

The posterior fission track age map (Fig. 5b) reproduces the general features of the data: High ages along the coast, relatively low ages at sea level along the fjords inland, and high ages on high topography inland. Particularly conspicuous are the low ages in the fjords. The very low ages of down to ~60 Myr occur in the inaccessible inner arms of the fjords at up to ~1000 m depth below sea level. Along the fjord shore lines predicted ages generally are in the range 120-140 Myr, in accordance with observed ages. Three effects add up to make the fjords develop warmer temperature histories that result in lower ages and shorter mean track lengths: 1) they are negative topographic features, which have been relatively deeper buried and therefore warmer throughout the exhumation history of the present-day surface, 2) toward the end of the exhumation, the three-dimensional thermal effect of the topography causes higher heat flow and therefore a higher temperature gradient below and in the vicinity of the fjords (and vice versa for ridges), and 3) the elevation dependent surface temperature boundary condition ensures that low topography and associated subsurface remains relatively warmer (and vice versa for ridges).

Along the coast about 20 km of material is removed in 400 Myr, which yields an average exhumation rate of 50 m/Myr, but the rate was clearly much higher initially (but unconstrained by apatite fission track data) and must be very close to zero at the present day.

Inland, the average exhumation rate amounts to about 30 m/Myr. These long-term model exhumation rates are similar to those obtained from other high elevation, passive margin regions such as the Appalachians (Matmon et al., 2003) and southern Africa (Brown et al. 2000, 2002). It is notable that the cooling rate and hence the exhumation rate generally becomes very low after the late Palaeozoic-early Mesozoic phase of rapid cooling and exhumation. Thus, the low exhumation rate and hence the low sediment production rate during the Late Cretaceous may be one explanation why the quite pure chalk lithology could develop in the North Sea area in spite of the relatively close proximity of clastic sources. Incidentally, the close proximity of a rocky coast does not necessarily prevent pure chalk sedimentation; early Campanian chalk in a coastal facies with granite inclusions, which prove the nearby presence of topography, is preserved at Ivö, southeastern Sweden (Surlyk and Kegel, 1974).

The fission-track annealing models are generally insensitive to the low-temperature end of thermal histories meaning that the amplitude and timing of the Neogene cooling visible in Fig. 8 is not well constrained (Donelick et al., 1990). In western Scandinavia we can, however, be confident that there is a real cooling event in the most recent portion of the thermal history as most samples are old (>100 Ma) yet have significantly reduced mean track lengths (10.5-13 μm), which requires a long residence in the partial annealing zone from which samples must have cooled to now be located at the surface. However, the precise timing and magnitude of any recent erosion event is difficult to constrain, also when many samples are interpreted jointly as here. We note here that inverse modelling of apatite fission track distributions yields a temperature history, which under certain assumptions (e.g. that the inferred temperature history is correct) can be converted to an erosion history. The further inference of a tectonic history (e.g. Neogene uplift) requires further assumptions or observations independent from the fission track data set. Fission track data are not capable of discriminating between different causal mechanisms that could produce the same cooling history. We emphasize that the exhumation history prior to entry into the PAZ is not constrained by the fission track data set; however, the present model could easily be combined with thermochronology systems with a higher closure temperature.

As mentioned, our regional scale default exhumation model does not consider local scale details such as differential vertical movements of crustal blocks during differential erosional unloading or as a result of localised tectonic movements along the Møre–Trøndelag Fault Complex (e.g. Redfield et al., 2005; Sommaruga and Bøe, 2002). Such movements have occurred also inland (Andersen et al., 1999; Mosar, 2003) and are likely to influence the inferred thermal history (Leighton, 2007). This, and thermal heterogeneity of the removed overburden, may contribute to the unexplained data variance of Figs. 6 and 7. However, interpretation of discontinuities in fission track data (to the extent that they are not a consequence simply of unrecognised and uncontrollable factors of the fission track system (Hendriks and Redfield, 2005)) should consider that already the default exhumation model shows relatively large variations over short distances of the age (and mean track length) (Fig. 5b). Furthermore, even relatively closely spaced samples from similar elevations inland generally do not exhibit the same age and mean track length. We suspect that these effects, together with relatively sparse sampling to obtain greater areal coverage, may easily lead to identification of discontinuities in age patterns which are not real, or to overlooking some which are there. Finally, it is customary to tie spatially separated fission track data taken at different elevations together using a one-dimensional thermal model as if the data set had been obtained in a vertical, one-dimensional borehole. This approach means that the significant fission track signal resulting from three-dimensional thermal topography effects mix into the parameter estimates (e.g heat flow and timing of exhumation) of the one-dimensional exhumation model, which therefore may become misleading.

We conclude that the *ICE*-hypothesis flexural isostatic exhumation model explains much of the signal in the fission track data set of southern Norway, which then to first order can be understood in terms of protracted exhumation from ancient topography. This exhumation now is significantly attenuated along the coast, but is still active inland because of isostatically-controlled feeding of crustal material by a buoyant crustal root, like in the Great Smoky Mountains of the Appalachians (Matmon et al., 2003). This explains the causal relationship between high topography, low Bouguer gravity and the fission track age-elevation relationship inland, as well as the higher ages along the coast.

3.3 Climate and erosion

As part of the *ICE*-hypothesis we suggest an alternative approach to understanding sediment production and landscape evolution of western Scandinavia during the Cenozoic. In the absence of early peneplanation and active tectonic surface uplift another agent must control the shaping of the characteristic landscape elements and the marked changes of sediment flux from the western Scandinavian highland during the Cenozoic. Our investigations strongly indicate that this agent is climate. In this section we demonstrate a switch on-switch off correlation between lithology variations in the eastern North Sea and climate change on the key Eocene-Oligocene greenhouse-icehouse transition, and indicate a possible relationship between climate change, sediment production and landscape forming processes.

3.3.1 Climate change and lithology

During the Cenozoic the Danish basin was a tectonically quiet trap for sediments from Scandinavia, except for moderate flexural inversion movements (Nielsen and Hansen, 2000; Hansen et al., 2000; Nielsen et al., 2005, 2007a), which were instrumental in preserving Cenozoic depocentres in gentle flexures and protected them from Quaternary erosion. It is therefore ideal for establishing a high-resolution proxy record of NW European climate. The critical Eocene-Oligocene transition (Zachos et al., 2001; Miller et al., 2005) was the target in two shallow core-holes (Kysing-4 and Horn-1) drilled to depths of ~ 150 m through lower Oligocene and Eocene strata. The sections were subjected to detailed analysis including biostratigraphy (coccoliths and dinoflagellates), sedimentology, stable isotope geochemistry, and magnetism (palaeomagnetic inclination and magnetic susceptibility). Some of the results have been published elsewhere (Heilmann-Clausen and Van Simaeys, 2005; Heilmann-Clausen et al., 2006).

The dramatic change in the nature of sedimentation in the North Sea (Nielsen et al., 1986; Michelsen et al., 1998) across the Eocene-Oligocene boundary has been an important argument for Cenozoic uplift and erosion of the Scandinavian Caledonides (Fig. 9). The Late Paleocene and Eocene of the eastern North Sea area were dominated by deposition of a condensed sequence of fine-grained, hemi-pelagic smectitic clays and marls (mainly sourced from the north-western North Sea, the northern British Isles and the Shetland Platform). At the Eocene-Oligocene boundary this sequence was succeeded by thick units of silty, quartz- and mica-rich, illitic mud prograding from the northeast, and clearly originating from the Scandinavian Shield (Fig. 9). Not surprisingly, this marked change has been taken to indicate the onset of a phase of tectonic uplift in western Scandinavian and in particular southern Norway. However, the timing of these changes coincided with the globally recognized late Eocene to early Oligocene temperature and sea-level fall (Zachos et al., 2001; Miller et al., 2005). This suggests that the shift instead may have been linked to climatic changes (Huuse et al., 2001; Huuse, 2002; Nielsen, 2002; Nielsen et al., 2002).

This has now been substantiated. The detailed litho-stratigraphy of the Kysing and Horn wells (Fig. 10a) reveals a brief change in the nature of the detrital content, dated to approximately 35.6 to 34.5 Ma, from hemipelagic, smectitic marl and clay sedimentation with a typical north-western source to silty muscovite/illite rich mud of Scandinavian type. The simultaneous disappearance of planktonic foraminifera and an increase in land derived organic matter (Heilmann-Clausen and van Simaeys, 2005) indicate that the shift was accompanied by a sea level fall. The shift has the character of a precursor event to the main sedimentary shift at the Eocene-Oligocene boundary. It coincides with a short-lasting global temperature fall, as indicated by correlating oxygen isotope changes in our shallow eastern North Sea core-holes and in Southern Ocean deep-sea cores (Bohaty and Zachos, 2003) (Fig. 10bc). From the base of the Oligocene, coinciding with the global climatic cooling, the deposition in the eastern North Sea Basin became dominated by sediments of Scandinavian origin forming several hundred meter thick fans in the north-eastern North Sea (Fig. 9), and the sediment accumulation rate increased nearly ten times (Michelsen et al., 1998).

We believe that the close switch on-switch off correlation between global and local temperature oscillations and the sedimentary input into the North Sea during the late Eocene and early Oligocene is a strong indication that climate and climate change rather than tectonism provided the control on sediment production in the source areas. A preliminary analysis indicates that the correlation between oxygen isotopes and lithology can be extended further into the Oligocene and the Neogene, and that variations in sediment accumulation rates in the North Sea may have mainly climatic rather than tectonic explanations, although inversion and small vertical flexural movements occurred (Nielsen et al., 2005, 2007a).

3.3.2 A possible link between climate change and erosion

There is some controversy related to the link between climate and erosion, for there exists apparently no globally recognisable correlation between intensity of rainfall (an expression of climate) and erosion rate in tectonically relatively stable granite-gneiss bedrock terrains like western Scandinavia (von Blanckenburg, 2006).

This is in line with Summerfield and Hulton (1994) who concluded that relief is the most important control on erosion, with runoff (essentially a measure of how humid the climate is) being rather less important. This study was based on the world's (exceeding 500,000 km^2) largest drainage basins so it does not necessarily apply to factors evident at smaller spatial scales. Therefore, in broadly sub-humid through humid to very humid climates there is not much effect of climate on erosion rates compared with the role of relief. In such environments little bedrock is exposed, there are well-developed soils and a more or less 100% vegetation cover; and all this tends to keep erosion rates fairly uniform in areas of similar relief even if the precipitation differs by quite a large amount. The Great Smoky Mountains of the Appalachians (in a vertically slightly enhanced version) may represent a contemporary example of what the western Scandinavian highland (in particular southern Norway) might have looked like (save for the obvious structural differences) during the warmer periods of the Cenozoic. Here, Matmon et al. (2003) used cosmogenic isotopes and other measures of erosion rate, including apatite fission tracks, to estimate an average erosion rate of ~ 30 m/Myr for the last 180 Myr. They concluded that the long-term stable rates of erosion are an expression of a quasi-steady equilibrium between fluvial erosion and the feeding of crustal material by isostatic uplift from a buoyant crustal root, in the same way as we envisage for the western Scandinavian highlands.

Therefore, as fluvial erosion in tectonically stable granite-gneiss bedrock terrains is a steady process not much affected by rather extreme variations in runoff we must – in the absence of significant onshore tectonism, which would strongly boost erosion - look elsewhere to find a possible reason for the documented changes in sediment output from Scandinavia during the Cenozoic. The most dramatic change in sediment flux occurs on the Eocene-Oligocene boundary, contemporaneous with a well documented and dramatic global cooling (the greenhouse-icehouse transition), which involved the growth of an ice shield in Antarctica. Since it is well known that glaciers are efficient erosional agents (e.g. Hallet et al., 1996), and because it is highly likely that a transition from a fluvial to a glacial erosional regime will result in significantly increased erosion rates as the fluvial landforms are modified to shapes that are optimal for the transmission of ice, we propose to invoke a climatically controlled increase in the occurrence of wet-based mountain glaciers (cirques) and periglacial processes in the inner highlands of western Scandinavia to explain the close to exact correlation between global climate change and sediment flux to the North Sea around the Eocene-Oligocene transition (Fig. 10). This suggestion utilises the fact that in the *ICE*-hypothesis the western Scandinavian highlands are the remnants of old topography, i.e. the average topographic elevation was higher in the past than it is at present. The first significant increase in glacial activity would then be associated with the latest Eocene Vonhof cooling episode of duration ~ 1 Myr (Vonhof et al., 2000), giving rise to the eastern North Sea Moesgaard Formation (Fig. 10, The Kysing well, Heilmann-Clausen and van Simaeys, 2005). The return to a warmer climate briefly reduced glacial a dn periglacial activity until they again became significant with the final Eocene-Oligocene greenhouse-icehouse transition. The recently suggested bipolar symmetry of global cooling (Moran et al., 2006) and the observation of Eocene-Oligocene ice-rafted debris in ODP-drillings in the Norwegian-Greenland Sea and the inference of glacial activity in east Greenland (Eldrett et al., 2007) lend further support to the proposed increase in ice activity for the western Scandinavian highlands: There apparently were large glaciers reaching the sea on the other side of the N Atlantic strait.

How would a climatic cooling modify the landscape of the stable granite-gneiss bedrock and thrust sheet terrains of western Scandinavia, which was inherited from the warm Mesozoic and Palaeogene time periods? First of all, the vegetation limit would decrease making soils and elevated parts of the weathering mantle available for erosion and transport, and transport rates could increase because of increased seasonality in runoff. This may produce a first transient sedimentation event offshore. Second, the area influenced by glacial and periglacial processes in the highlands would increase. We believe this is important because there is growing evidence that cirques and alpine glaciers may efficiently limit topographic height and control the overall morphology of mountain ranges. Thus, the traditional view that glacial erosion mainly acts to increase relief and cause peak uplift (e.g. Molnar and England, 1991) has long been challenged (Summerfield and Kirkbride 1992; Brozovic et al., 1997; Whipple et al., 1999; Mitchell and Montgomery, 2006). From an analysis of hypsometry and snow limit heights Brozovic et al. (1997) suggested that the height obtained by the Himalayas is a function of the long-term glacial equilibrium line altitude (ELA) rather than of rock uplift rates. They found that the ELA represents an upper envelope of topography development through which only a small amount of material transport occurs (i.e. the alpine peaks and ridges). This suggestion has been supported by Mitchell and Montgomery (2006) who from an analysis of climate and topography found that glacial erosion like a "glacial buzzsaw" limits the height and controls the morphology of the Cascade Range, western United States. Finally, Pedersen et al. (2008), in a study similar to Brozovic et al (1997), found that the topography envelope along the west coast of South and North America exhibits a strong correlation with latitude. This agrees with the findings of Montgomery et al. (2001) that latitudinal climate changes yield a first order control on the morphology of the Andes.

While the glacial buzzsaw is the rough tool that efficiently takes the top of mountain ranges, it may not be able to finish the job and produce flattish surfaces. For this we may turn to the finer "sanding" tools of periglacial processes. In the late 1800s A. Penck and M. Dawson had already suggested that higher frost intensity at high latitudes and altitudes would limit mountain heights (see references in Brozovic et al. (1997)). More recently Anderson (2002) in a study from the Wind River Range, Wyoming, quantified how the mechanisms of frost weathering and frost creep efficiently can flatten the interfluves between the range's deep glacial troughs, which have a remarkable similarity to the glacially modified valleys of western Scandinavia.

Anderson (1998) concluded from an analysis of the annual temperature cycle and the exponentially attenuated diffusion of surface temperatures into the subsurface that in some cases the frost cracking intensity (fraction of a year of a point in the subsurface spend in the frost cracking window) decreases monotonically with depth, while in other circumstances there is a distinct maximum of cracking intensity at some (shallow) depth. Particularly at the low mean annual temperatures at high latitude and altitude should the frost cracking maximum amplify with increasing depth making the process more efficient. While frost weathering contributes to regolith production, frost creep (the downhill motion resulting from repeated frost heaving and melting collapse of the regolith (Anderson, 2002)) makes the regolith move. Combining this transport process with mass balance and a regolith production function, Anderson (2002) found that regolith production and transport, and hence bedrock surface evolution, is governed by a diffusion equation (here stated in two dimensions):

$$\nabla \cdot (k \nabla H) - \frac{\partial R}{\partial t} = -\frac{\rho_b}{\rho_r} w$$

$$H(x, y, t = 0) = H_o(x, y) \qquad (1)$$

where ∇ is the horizontal gradient operator, k is the landscape diffusivity (depends on regolith thickness, frost susceptibility and climatic forcing parameters), H is the surface elevation, t is time, R is local regolith thickness, ρ_b and ρ_r are bedrock and regolith densities, respectively, w is the regolith production rate function (depending on regolith thickness, frost susceptibility and climate forcing parameters), x and y are horizontal coordinates, and $H_0(x, y)$ is the surface elevation at the onset of the time evolution.

The general characteristics of the solution to eq (1) are known very well. The initially ridge-shaped interfluve, $H_0(x, y)$, evolves on a characteristic time scale (e.g. 0.1-10 Myr, depending on the landscape diffusivity and the characteristic length scale of the interfluve) toward smooth and gently curving flattish surfaces pinned between the edges of the deep glacial troughs that provide the boundary where the regolith transport ends in a plunge into the trough. Following Anderson (2002) such surfaces are developing as 'truly isolated features, islands in the alpine landscape'.

Isostatic uplift commensurate with erosional unloading is a much gentler and gradual uplift process than would result from active convergence tectonics, leaving ample opportunity for the long-term ELA and periglacial processes like frost weathering and frost diffusion to control topography height and form flat landscape elements at high elevation in western Scandinavia. Such landscape elements are not surfaces in the Davisian sense. They are maintained by climatically controlled processes, which explain their elevation accordancy, and using them to reconstruct imaginary erosional surface once graded to sea level obviously is without meaning. We note that other mechanisms also may have been active in forming some high elevation surfaces in western Scandinavia (Phillips, 2002).

4. Further observations and predictions

In this section we aim to demonstrate how the *ICE*-hypothesis is consistent with a range of data that have been used in support of models advocating Cenozoic surface uplift in western Scandinavia.

4.1 The coast as a stable hinge zone

It is a feature of the *ICE* model that in the absence of active tectonics the coastal area becomes a relatively stable hinge zone, both vertically and laterally. Driven by erosional unloading (onshore), and sediment loading with a Mesozoic extension-derived component of thermal subsidence (offshore), this hinge zone separates the onshore area of isostatic uplift from the offshore regions of isostatic subsidence. Its location is stable even when flexural isostasy is taken into account since the landward migration of the coast that would occur because of offshore sediment loading is compensated by the seaward movement of the coast that would arise from erosional unloading onshore.

Interestingly, the concept of a long-term stable hinge zone at the coast has been invoked by Fossen et al. (1997) to explain the occurrence of thermally immature, shallow water sediments of Jurassic, possibly Oxfordian, age (the Bjorøy Formation) at a location on the coast of south-western Norway west of Bergen. The vitrinite reflectance values of 0.28 –

to 0.29% R_o of the formation, and the preservation of wood-fibre structures in coal fragments, are indicative of a very low degree of thermal maturity, which is clearly in disagreement with any deeper burial (e.g. Doré and Jensen, 1996). This implies a stable sea-level position of the Bjorøy Formation, with only shallow burial since the time of deposition during the late Jurassic, which is consistent with the hinge line prediction of the *ICE*-hypothesis. The discovery of the Bjorøy formation and the important results that emerged are strong motivation for a search (as also suggested by Fossen et al. (1997)) for other preserved pockets of Mesozoic sediments in protected positions along the coast of western Scandinavia in order to test further the stable hinge zone concept of the ICE model.

The concept of the coast as a stable hinge line by and large applies to the majority of the Norwegian coast line of southern Norway and the stretch between slightly north of Trondheim to south of Lofoten. However, modifications must be applied in the area of the Möre-Trøndelag fault zone and in the Lofoten-Vesterålen area, where tectonic activity has continued more recently and fault movements prevail. For example, the higher maturity of preserved Jurassic strata along the Møre-Trøndelag Fault Complex (Sommaruga and Bøe, 2002) and discontinuities in fission track data (Redfield et al., 2004, 2005) are evidence of local tectonic movements (Olsen et al., 2007). Likewise, fault movements have occurred and are still occurring in the Lofoten-Vesterålen area (Bergh et al., 2007; Osmundsen et al., 2008). However, we do not consider these fault movements to be signs of active tectonic uplift of the inner highlands of western Scandinavia. The contemporary movements could well be related to lateral gradients in the velocity of post-glacial rebound. See also the discussion of rift flanks below.

4.2 Over-burial and the base Quaternary unconformity

The pre-Quaternary sedimentary sequences along the coast of Norway and into the eastern North Sea area show a conspicuous angular unconformity at the base of the Quaternary. Together with over-burial (previous burial at a depth greater than at present – see discussion in Riis and Jensen (1992)) estimates from sonic transit times and truncated vitrinite reflectance profiles (Jensen and Schmidt, 1992) this unconformity has been taken as evidence of coast-proximal uplift and erosion consistent with Cenozoic surface uplift of the hinterland (Japsen, 1988; Jensen and Schmidt, 1993; Hansen, 1996a). Fig. 11 shows the over-burial estimates produced by Hansen (1996a) from anomalous sonic velocities of carefully selected shale intervals relative to an equally carefully established reference velocity-depth profile derived from wells with normally compacted shale (Hansen, 1996b).

The long-term stable coastal hinge line of the ICE model is incompatible with the observed over-burial amplitudes if these are produced by active tectonic uplift. Within the hinge-line concept the coast proximal offshore area would gradually become occupied by clino-form sediment deposits (controlled by global sea level variations and sediment flux), and it is difficult to imagine that over-burial of up to 600-800 m could develop, although a minor fraction of the over-burial may reflect erosion in response to the long-term Cenozoic sea level fall and exposure of coast proximal sediments (Nielsen, 2000; Nielsen et al., 2002; Miller et al., 2005).

However, in view of the widespread base Quaternary unconformity and the deep ice-stream scarring on the Norwegian Shelf and in the North Sea (Fig. 11), we suggest that the vast majority of the missing section could have been removed by glacial erosion. Much evidence testifies to the erosional power of the Quaternary glaciers (e.g. Hallet at al., 1996, although the very high glacial erosion rates they report seem to be, at least in part, an artefact of the time-interval of the sedimentary sequences used, onshore and offshore. Geophysical and borehole data show thick depocenters of glacially-derived material, known as trough mouth fans, along the shelf breaks off the Norwegian coast (Vorren, 2003). They are typically located at the mouths of major Quaternary ice streams and continue for hundreds of kilometers seaward from the past grounding lines. The two largest, the Bear Island Fan (Vorren et al., 1989) (215.000 km^2) and the North Sea Fan (Sejrup et al., 2003) (110.000 km^2), consist of multiple stacks of diamictic debris flow aprons hundreds of meters thick (Sejrup et al., 1995) re-deposited from shelf edges where the material was first laid down at the glacier margin. The total volume of the North Sea Fan of more than 20,000 km^3 found at the extension of the Norwegian Channel corresponds to an average of about 150 m of erosion in southern Norway from around 1.1 Ma ago, when the Norwegian Channel Ice Stream was activated (Sejrup et al., 1996), up to the last (Weichselian) glaciation which left a distinct geomorphic imprint at the channel bottom (Ottesen et al., 2001; Ottesen et al., 2005). Further evidence of the important role of ice streams as erosional agents during the Quaternary is provided by the additional substantial quantities of sediment that drifted off the grounding lines as meltwater plumes and was deposited as far north as the Vøring Plateau (Sejrup, 2003).

Furthermore, the voluminous Pliocene-Quaternary sediment package (Stuevold and Eldholm, 1996; Rise et al., 2005) on the Norwegian Shelf consists of bedrock fragments and reworked Cenozoic and older sedimentary material derived in parts from on-shore glacial erosion and a seaward directed glacial reworking of previously deposited coastal sediments.

Thus, the erosional power of glaciers both onshore and on the Norwegian shelf and on North Sea margins is significant. In order to demonstrate that the observed geometry and over-burial of the coast-proximal sedimentary sequence can be obtained in the purely passive isostatic response in the *ICE*-model, we performed a flexural back-stripping and reconstruction of some costal transects in response to erosion at the base of Quaternary glaciers.

To achieve this we first interpreted seismic sections in terms of sedimentary ages and converted to depth using borehole information and published sections (Jensen and Schmidt, 1993; Odinsen et al., 2000). The sedimentary layers were then decompacted from the present-day burial to zero burial depth using exponential compaction relationships appropriate for the Norwegian margin (Hansen, 1996b). However, because of the unknown coast-proximal erosion, the present-day burial depth along the coast is less than the true maximum burial depth which should be used in the initial decompaction. This maximum burial depth must therefore be obtained in an iterative procedure in which the thickness of missing sediment is reconstructed. This involves laying down the sedimentary layers on the margin starting with the oldest identified layer (Triassic or Jurassic). As new layers are added the underlying sedimentary layers are compacted according to the achieved maximum depth of burial. During deposition of each sedimentary layer the assumed missing coast-proximal sediment is reconstructed from the current sea level at the coast to the present-day erosional limit of the layer, the position of which has been identified by the truncation at the base of the Quaternary. This reconstruction affects the inferred burial depth so the procedure is repeated until the maximum burial obtained during the sedimentary margin reconstruction no longer changes. Finally, the erosional effect of Quaternary glaciers is simulated by removing the additional pre-Quaternary sedimentary material that was required to build out the margin during the reconstruction, and then adding the Quaternary deposits.

Fig. 12 a-g shows the result of applying the procedure to a profile perpendicular to the coast of southern Norway (Jensen and Schmidt, 1993) (Profile A of Fig. 3d). There has been no attempt to remove the effects of salt movements, which cause the protruding structure in Fig. 12a. Also the Early Cretaceous rifting of the Farsund Basin causes an apparent depression of the Late Jurassic surface (Fig. 12b), which was not there at that time. This is the expression of a narrow graben which developed during Early Cretaceous but remained filled with sediment (Fig 11c). The presence of this structure does not influence the reconstruction of the Jurassic coastal sediments because the erosional limit is well landward of the depression.

The limit of reconstruction of the coast-proximal sediment is indicated by the arrows. The glacial erosion occurs from Fig. 12f to Fig. 12g, the latter profile being exactly identical to the depth-converted present-day profile of Jensen and Schmidt (1993). Also shown in Fig. 12g is the over-burial of the base Quaternary sediments produce by glacial erosion. It amounts to a maximum of ~600m, a value that is consistent with over-burial estimates (Hansen, 1996a).

Fig. 13ab shows an EW profile across the northern North Sea around the outlet of the Sognefjord (Profile B of Fig. 3d). The final glacial erosion gives rise to a maximum of 800 m of over-burial of the sediments at the base of the Quaternary. The glacial erosion in this model causes a maximum of ~500 m of isostatic basement uplift of the coast proximal area.

It is also apparent from the profile examples that an angular unconformity develops at the base of the Quaternary. This angular unconformity is strongly accentuated in Figs. 11

and 12 because of a significant vertical exaggeration. Similarly large vertical exaggeration (in cases by a factor of 60) of the angular unconformity in geological sections (which may not even be depth converted but have a TWT axis representing 'depth') in a number of articles may have contributed in overplaying its potential significance (in terms of tectonics) along the Norwegian coast and in the eastern North Sea. However, our simple model examples clearly demonstrate that the *ICE* hypothesis incorporating glacial erosion can produce significant over-burial and an angular unconformity at the base of the Quaternary. Contrary to previously suggested tectonic interpretations we therefore believe that the Cenozoic (particularly Neogene) tilt evolution of the offshore is explained by: 1) the isostatic response to erosional unloading onshore and sediment loading offshore; 2) compaction of previously deposited sediments; and 3) a small offshore thermal subsidence component from Mesozoic rifting. The final glacial redistribution of sediments, in which coastal sediments are eroded and deposited at a more distal position on the margin (e.g. Rise et al., 2005) contributed to this tilting.

From the above examples it seems that glacial erosion can produce several hundred metres of over-burial of coast-proximal sediments, and in deeply eroded channel sections even more. Two-dimensional restoration of sediment cover in the Norwegian channel (Riis, 1996; own calculations) shows that more than 1100 m of sediment is required to fill the channel where it is the deepest. Over-burial from glacial erosion hence represents a significant 'noise' component in relation to detection of erosion caused by Neogene tectonic uplift, which, it has been suggested, is of a similar magnitude. Hansen (1996a) interpreted over-burial estimates in terms of Neogene tectonic uplift because the Neogene tectonic uplift hypothesis was the inescapable point of departure, with no consideration of the over-burial effects of glacial erosion. Given an uncertainty of over-burial estimates of plus or minus some hundred metres (Hansen, 1996a) and the distribution of wells in Fig. 11, it is clear that the particular realisation of over-burial iso-curves of Fig. 11 relies on the prior assumption of uplift of the hinterland and the coast-proximal shelf. Likewise, the surface morphology study of Bonow et al. (2007) has the tectonic uplift hypothesis as a hard prior assumption. Such deterministic outsets make these studies interesting examples of the puzzle-solving activity of normal science (Kuhn, 1970), which is characterised by finding proper places to the well defined jigsaw pieces (e.g. PhD-projects) of the paradigm, which itself is never questioned.

Similarly, we suspect that the conclusions of other over-burial, surface morphology and fission track studies may have been biased by the hypothesis they wished to confirm.

5. Discussion and conclusions

According to the *ICE*-hypothesis the present high topography of western Scandinavia has been exhumed through early Palaeozoic orogenic collapse and late Palaeozoic-early Mesozoic continental rifting processes (Dunlap and Fossen, 1998) with erosion as an exhumation agent becoming relatively more important as rifting abated. The present day high topography is supported by crustal buoyancy, which formed as part of a much thicker crust to the west during the Caledonian Orogeny, simultaneously with the topography. In southern Norway east of the present-day Caledonide thrust front the topography may alternatively have been exhumed from topography produced during the Sveconorwegian Orogeny. Irrespective, we believe that the topography (and its associated root) has been modified slowly over time by erosion.

This exhumation model implies a large upward displacement of the crustal column (crustal uplift) since, when isostatic equilibrium is maintained, erosional lowering of mean topography by 1 km requires erosion of ~5-6 km of crust given typical densities for the crustal rocks eroded and the mantle at the depth of compensation. Therefore, in the *ICE*-hypothesis mean regional elevation will have progressively decreased, although flexural isostatic effects could have resulted in local, short-term increases in land surface elevation (e.g. Gilchrist and Summerfield, 1990). This scenario of generally decreasing surface elevation contrasts with an increase in topographic elevation (surface uplift) of up to 1-2 km that is suggested for the various proposed Cenozoic active tectonic uplift models.

Taking the traditional geomorphological interpretation of surfaces in western Scandinavia for hard data that invariably must be satisfied leads to hard challenges for geodynamic model building. Thus, it is significant that none of the proposed tectonic mechanisms have been satisfactory enough to gain broad acceptance. The fundamental problem is that the amplitude of the required surface displacement is on the order of magnitude 1-2 km with a wavelength on the order for 400-500 km. Furthermore, from the volume-age relationship of Cenozoic erosion products it seems that the surface uplift post dates the latest major geodynamic event of the region, the initial tectonism and volcanism at ~62 Myr ago and the Paleocene-Eocene volcanic opening of the North Atlantic Ocean. The fundamental tectonic mechanisms of thickening of the continental crust by compressional shortening (orogenesis) or magmatic underplating, which both could produce km-scale surface displacements, are not readily accommodated due to the absence of (1) inland Cenozoic magmatism and (2) conspicuous deformation systems that would have resulted from the required crustal shortening. Furthermore, these are the only mechanisms which readily satisfy the geophysical constraint of a low Bouguer gravity associated with high topography and close to local isostatic equilibrium (Balling, 1980; Ebbing and Olesen, 2005).

Understandably, the opening of the Norwegian-Greenland Sea with the possible plume influence has an instigating role in many of the proposed mechanisms, either as a source of stress that could cause lithospheric flexure or as a perturbation of the lithosphere-asthenosphere system that could produce magmatism, mantle diapirs or base lithosphere erosion (Stuevold and Eldholm, 1996).

Although magmatic underplating (e.g. Brodie and White, 1994) provides a causal and contemporaneous mechanism for Paleocene-Eocene crustal thickening and surface uplift in some of the magmatic provinces of the North Atlantic, for example E and W Greenland, available data suggest that, for Scandinavia, basaltic magmatism and related underplating and sill intrusions are limited to the offshore ocean-continent transition (Skogseid et al., 2000) and the adjacent Møre and Vøring sedimentary basins (Svensen et al., 2004). Conspicuously absent in the Scandinavian Caledonides is coast-proximal and onshore evidence of extrusives derived from the 5-10 km thick magmatic underplating that would be required to produce the magnitude of onshore uplift (Brodie and White, 1994). High-velocity bodies (Christiansson et al., 2000) in the lower crust or upper mantle in the northern North Sea may be of magmatic origin, but they thin toward the east, are not in the appropriate position to support inland topography and are most likely of Permian or Triassic age like dykes along the coast of south-western Norway (Fossen and Dunlap, 1999). We conclude that underplating not a viable mechanism to explain Cenozoic surface uplift in western Scandinavia.

The close to local isostatic conditions in western Scandinavia implies buoyant support of the topography, which invalidates flexurally based uplift mechanisms (Løseth and Henriksen, 2005; Hendriks and Andriessen, 2002), such as lithospheric buckling by in-plane stress and rift shoulders, as significant contributors to long-wavelength surface deflection because they involve shallowing of the crust-mantle boundary in the area of uplift in contrast to the observed Bouguer gravity low. Other proposed tectonic uplift mechanisms, such as deep mantle diapirism with intrusion into the lithosphere (Rohrman and van der Beek, 1996) require *ad hoc* assumptions as to timing, crustal thickness variations and erosion. Moreover, such a mechanism may be physically unviable given the uplift required, the gravity minima and the surface heat flow. Lithospheric delamination (Nielsen et al., 2002) or erosion of the base of the lithosphere by small-scale convection induced by the gradient in the lithosphere-asthenosphere boundary could produce uplift by two processes: 1) the replacement of lithosphere with less dense asthenosphere, and 2) by heating and thermal expansion of the remaining lithosphere in response to the change of the boundary condition at the base of the lithosphere. However, given the km-scale amplitude of the required uplift, the change in lithospheric potential energy would cause a significant reduction of the in-plane tectonic stress, which would produce much more significant extensional reactivation of fault zones than have actually been observed (like in the Sierra Nevada Mountains, Le Pourhiet et al., 2006).

Mosar (2003) presented an in depth review and re-examination of fault activity on the continental shelf and onshore western Scandinavia from Caledonian extensional collapse till the present day. He introduced the inner boundary fault (IBF) running north-south in western Scandinavia as the approximate eastern limit of onshore extensional activity, and defined the passive margin width to be between the continent-ocean boundary (COB) and the IBF (Fig. 2). The width of this redefined passive margin ranges from 550 km in the south to over 700 km in mid-Norway to 165 km north of Lofoten. The IBF is located mainly slightly to the west of the topographic high and always west of the present-day Caledonide thrust front. Rifting and faulting on the IBF started in Permo-Carboniferous. The successive rift phases (culminating in continental break-up and the formation of the North Atlantic) between

Permian and Cretaceous worked toward the future breakaway fault, as also evidenced by the ages of offshore rift basins (se also Doré et al., 1999; Wangen and Faleide, 2008). Although it has been demonstrated that portions of the IBF such as the Lærdal-Gjende fault (Fig. 2) and other normal rift-related faults were active in Permian and Jurassic/Cretaceous, the ages and loci of the most important normal faults during the different rifting events are generally unknown (Mosar, 2003).

This history of extensional tectonic activity is background on which the *ICE*-mechanisms evolve. The observed succession of mainly off- and onshore rift phases represents the extensional destruction (offshore) and decrease (onshore) of topography produced in the Caledonide Orogeny. Thus, the IBF of Mosar (2003) is merely the Baltic Shield's last stand against encroaching extensional stress systems active during the late Palaeozoic and Mesozoic, and the eastern limit of the passive continental margin in our opinion is coincident with the present-day steep Moho gradient along the coast where significant sediment deposition and basin formation begin. The present-day asymmetry of the western Scandinavian highlands with a relatively steeper gradient toward the west primarily is a consequence of the onshore-offshore distribution of mainly Palaeozoic and early Mesozoic rifting, which shows increasing intensity (Dore et al., 1999; Mosar, 2004; Wangen and Faleide, 2008) and therefore an increasing, commensurate surface lowering from an originally increasing surface elevation toward the west. The first order association of the present high topography with the negative gravity anomaly remains a feature acquired during the Caledonide Orogeny, as is the case for any other orogen.

However, insisting on satisfying geomorphological tectonic interpretations of the flattish landscape elements of western Scandinavia as erosional surfaces graded to sea level and later uplifted, the explanation of Mosar (2003) for the present-day high topography and the associated negative gravity anomaly develops complications. First, it is problematic to produce the 1-2 km of surface uplift in a tectonic environment that was extensional from the late Palaeozoic through the Mesozoic. Such an environment is characterised by crustal thinning and surface subsidence (McKenzie, 1978), although large normal faults will produce localised footwall uplift, as can be seen offshore (e.g. Mosar, 2003). Second, the main phases of surface uplift is supposed to be Cenozoic, at which time ridge push from the North Atlantic would have reduced (if not terminated) previous (and already limited) extensional onshore tectonic activity. The offshore inversion structures are indications of this compression (Doré et al., 1999), but significant reverse activation onshore is apparently not very conspicuous. For example, the latest suggested movement on the Lærdalen-Gjende Fault is extensional and of early Cretaceous age. Third, the suggested tectonic mechanism, rift flank uplift, relies on regional flexural isostatic compensation of changes to the lithospheric density distribution produced during rifting (Braun and Beaumont, 1989), in short - somewhere nearby the surface of the lithosphere must subside and Moho must become elevated for rift flank uplift to occur. The amplitude of topography which is supported depends on (1) the wavelength of lithospheric necking (i.e. the distance from unaffected to fully stretched lithosphere, which in the terminology of Mosar (2003) would be the distance from the IBF to the COB), and (2) the flexural loading wavelength (a proxy for the strength of the lithosphere). The close to local isostatic balance visible in the first order relationship between high topography and low Bouguer gravity in western Scandinavia implies a relatively low strength of the lithosphere and therefore a short flexural wavelength, much shorter than the necking wavelength of the redefined continental margin of Mosar (2003). Inland rift flank uplift by extension therefore cannot have contributed to inland topography because isostatic compensation is local rather than regional. Parts of the observed fault movements in the interior could well have been caused by brittle accommodation of differential, flexural isostatic rock column uplift as a consequence of differential erosional unloading.

On the other hand, rift flanks are likely to have occurred in places along the coast adjacent to offshore sedimentary basins. Judging from the Moho depth gradient along the coast (Fig. 3a) the lithosphere necking wavelength here could be short enough to have supported the existence of rift flanks in spite of a the relatively weak continental lithosphere. The age of this topography rejuvenation is given by the age of the syn-rift sedimentary deposits in the coast-proximal sedimentary basins, which provided the buoyancy for the rift flanks (Braun and Beaumont, 1989). Along the Trøndelag and Horda Platforms and the coast of southern Norway ages are mainly late Palaeozoic and early Mesozoic. However, the topography of the Lofoten-Vesterålen archipelago could well have been uplifted by the rift flank mechanism during Mesozoic-Palaeogene rift phases (Bergh et al., 2007). However, the Moho depth beneath the archipelago would then be expected to be slightly greater than that of the surrounding basins, contrary to Fig. 21 in Bergh et al. (2007). It is an interesting question if Cretaceous rifting in the Møre Basin would be close enough to support significant coast-proximal rift flank uplift in the Møre-Trøndelag Fault Zone area.

Recent active fault movements in the Møre-Trøndelag and Lofoten-Vesterålen areas have been detected by radar interferometry (Osmundsen et al., 2008). Together with the proposed presence (Fjeldskaar et al., 2000) of a weak tectonic uplift component concentrated in the northern and southern high topography areas of western Scandinavia, this suggests that tectonic uplift other than post-glacial rebound is active at the present day (e.g. Mosar, 2003). However, present day fault movements could result from the lateral gradients in the post-glacial rebound and far-field changes in the lithospheric stress system. Furthermore, the approach of Fjeldskaar et al. (2000) relies on the difference between the actually observed present-day pattern of uplift rates and the uplift rates predicted by a numerical model, which, although sophisticated, surely does not include all lithospheric and asthenospheric properties relevant to uplift rate modelling, such as e.g. lateral variations in lithospheric flexural rigidity and the viscosity of viscous layers. In a laterally homogeneous model the only way of obtaining laterally varying uplift rates is by a laterally varying loading history. As part of the observed lateral variations in uplift rate is bound to be caused by lateral variations in lithospheric and asthenospheric rheological properties from the offshore across western Scandinavia and into the central Baltic Shield, uncertainty is introduced when uplift data are modelled by loading of a laterally homogeneous model. The applied glacial loading history, however carefully determined using a laterally homogeneous model and other independent sources, may therefore not be correct and the obtained difference in observed and modelled uplift rates may not be well resolved enough to infer a particular tectonic component reliably. Attempts to interpret present-day uplift rates as a sum of two components (glacial isostasy and tectonics) require models that include both effects simultaneously. The success of such an endeavour depends on the extent to which the response functions of the two processes are linearly independent at data locations. The solution space for this problem could be very large.

Several of the above cited proposed tectonic mechanisms clearly demonstrate the problems that develop in any attempt to satisfy the traditional geomorphological tectonic surface interpretation in western Scandinavia. We suggest that more realistic landscape forming processes are appropriate, including the long-term effects of climate controlled ice activity and periglacial processes, the topography limiting and shaping potential of which have been clearly demonstrated. Given the arguments presented here, an explanation involving Cenozoic tectonic uplift is not required to explain the fundamental observations relevant to the topography of western Scandinavia. Indeed, in an earlier study (e.g. Nielsen et al., 2002), we also missed the role of the ice: first by causing sediment production mimicking tectonic uplift since the latest Eocene, and secondly, during the Plio-Pleistocene glaciations by producing effects which also could be mistaken for active tectonic uplift, including sedimentary structures resulting from the extreme lowering of erosional base level by glaciers on the continental shelf and increases in local elevation as a result of the isostatic response to highly selective glacial erosion inland.

The proposed *ICE*-hypothesis lies wide open to a range of tests. For example, it predicts a strong correlation between climate (more or less ice and periglacial process activity) and sediment production and deposition, which could be tested by detailed comparison of the record of detrital sediment mass and lithology deposition in the North Sea and on the Norwegian shelf and the records of global and local temperature proxies. The clue to distinguishing tectonic and climatic effects in the sedimentary record is detailed temporal correlation between lithology changes and climate proxies, as obtained in the eastern North Sea shallow wells (Fig. 10). Although the warmer period during the mid Miocene climatic optimum (Zachos et al., 2008) with presumably less alpine glacier and periglacial activity in the Scandinavian highlands also was associated with a high sediment flux from Scandinavia, it is quite likely that the sediment production, transport and storage system is dynamic enough to explain this apparent anomaly. Also the quantitative, process oriented surface evolution model implied by eq (1) could be tested. It would, for example, be consistent with a Quaternary alpine landscape containing many flattish landscape patches at a similar elevation, or which show a regional elevation trend that correlates e.g. with the distance from the coast and with latitude. Furthermore, there are issues relating to the time scale of evolution.

In summary, we suggest it is worth considering the possibility that western Scandinavian topography has evolved from higher to lower elevation from the Caledonide Orogen until the present day, *without* intervening peneplanation and Cenozoic tectonic uplift. Initially, following Dunlap and Fossen (1998), gravitational collapse and backsliding was the dominant contributor to destroying topography (and in bringing eclogite into exhumation distance of the surface). Rifting in Permo-Carboniferous time produced further offshore subsidence and was the last major rift phase seriously affecting the onshore through rift flank formation in places along the coast, onshore rifting and lowering of erosional base level. Later onshore rifting activity apparently was much reduced as compared to the Permo-Carboniferous phase; at least it has not succeeded in destroying the topography entirely. During this, onshore erosion and commensurate flexural isostatic uplift of the crustal column contributed to topography reduction and landscape evolution. Erosion rates were high during the early periods of tectonic activity, but decreased with the declining onshore tectonic activity during late Palaeozoic-early Mesozoic, and probably were very low during the warm climates of the Late Cretaceous-early Palaeogene when a relatively large fraction of the topography could have been covered by vegetation. Although wet based alpine glaciers, cirques and periglacial processes may have been active in the inner highlands all along, the efficiency of these processes depend much on climate and they suddenly gained importance by occupying a larger area of the inner highlands with the greenhouse-icehouse climatic deterioration on the Eocene-Oligocene boundary. Most importantly, these processes are known to limit mountain height and possess the capability of producing flattish surfaces, suggesting an alternative to the traditional tectonic interpretation of these landscape elements in western Scandinavia. Given this, it is possible that similar issues of ambiguity during interpretation have led to the incorrect identification of Neogene tectonic activity elsewhere

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Appendix A. Receiver function analysis in southern Norway

Determination of depth to a seismic boundary within the Earth from receiver functions makes use of the difference in arrival time between a direct P- wave from distant earthquakes and the equivalent P to S converted wave arriving from the seismic boundary (Vinnik, 1977). We make use of P to S conversion at the crust-mantle boundary. The time difference between the direct P-wave and the P to S converted wave was recorded at mobile seismological stations across the southern highland of Norway. This time difference is a direct measure of the distance from receiver (seismological station) to Moho along the ray paths of the seismic waves. In practice, the arriving P-wave describes a complex waveform of long duration so that a specific processing is required.

As an example of receiver functions, Fig. A1 shows the seismological registrations at the permanent array NORSAR and at one of our temporary stations near the centre of the southern highland of Norway. Data are band-pass filtered (0.1-4 Hz) and rotated so that the component *Q* contains mainly the arriving S-wave, and the orthogonal component L contains mainly the P-wave.

Clearly, both the incoming P-wave (~ L-component) and the converted S-wave (~ Q-component) form long and complex wave trains. The receiver function is computed by deconvolution of the Q-component with the filter which “spikes” the L-component. Thus, the receiver function approximates the arriving S-wave for an impulsive incoming P-wave (Vinnik, 1977; Svenningsen and Jacobsen, 2004).

We note that the receiver functions at both stations display several oscillations partly due to noise, partly due to complexity in the crust. However, the Moho conversion stands out clearly as the most prominent positive peak. The time to depth conversion may be computed as (Kind and Vinnik, 1988)

$$H_{Moho} = \Delta t_{PS} \Big/ \left(\sqrt{V_S^{-2} - p^2} - \sqrt{V_P^{-2} - p^2} \right)$$

where Δt_{PS} is the time delay, V_P and V_S are velocities of P- and S-waves respectively, and p is the slowness of the arriving P-wave. The depth axes in Fig. A2 are computed for an assumed P-wave velocity of 6.4 km/s and a corresponding S-wave velocity of 3.7 km/s. Actual average crustal velocities are very unlikely to deviate more than 5 % from these values.

Fig. A2 shows the receiver functions from several earthquakes at the same two stations. The receiver functions differ because of noise and because of differences in crustal scattering for different directions of P-wave arrival. However, the Moho conversion stands out consistently for both stations. We read a crustal thickness of about 39 km at NORSAR on the northern margin of the Olso Rift, where the crust may be slightly thinned and topography is moderate, and a crustal thickness of about 43 km in the area of high topography. This analysis was performed at a total of 24 temporary and 8 permanent stations (locations shown in Fig 3a).

Appendix B. Apatite fission track methodology

Sixty-six new outcrop samples were taken from a variety of Precambrian and Phanerozoic rocks in Norway. Apatite crystals were separated from 2-3 kg of rock by crushing and sieving followed by standard heavy-liquid and magnetic separation techniques. The grains were mounted in epoxy resin and then polished. For etching, we used 5.0 M nitric acid (HNO_3) for 20 seconds at 20ºC (Hurford, 1990). The apatite samples were irradiated with muscovite mica detector to record induced track densities at the well-thermalised Hi Flux Australian Reactor Lucas Heights in Sydney, Australia. We used the CN5 dosimeter at either end of the sample can to monitor gradients in the neutron flux.

Fission tracks in each mount were counted in transmitted light using a dry objective at a magnification of x1250. A total number of ~ 20 individual crystals were analysed and a set of approximately 100 confined track lengths were measured for each sample. Track lengths were measured in the standard way, using a digitising tablet and drawing tube attached to the microscope and we only consider horizontal confined tracks. For calculating the fission track ages, we use the zeta calibration (Hurford and Green, 1983) with a zeta of 355.5±11.6. The ages are given as central ages with percent variation (Galbraith and Laslett, 1993). The track length data are summarized through the mean and standard deviation of the distribution. To account for compositionally controlled variation in annealing kinetics between samples (Barbarand et al., 2003) we measured the weight % chlorine using a JEOL probe on 12 samples, and this was always < 0.1 %. Further details may be found in Leighton (2007).

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Figure captions

Figure 1. Plate configuration at the time of North Atlantic break-up with generalized structural elements redrawn mainly after Skogseid et al. (2000) and Andersen et al. (1999). The sedimentary basins separating the onshore remains of the Caledonides are the result of Late Palaeozoic through Mesozoic episodes of post-orogenic continental extension. The position of teleseismic profiles in southern Norway and shallow core holes are shown. FSP: Faero-Shetland Platform; HP: Horda Platform; HSZ: Hardangerfjorden Shear Zone; LGF: Lærdal-Gjende Fault; MB: Møre Basin; MTFZ: Møre-Trøndelag Fault Zone; NS: North Sea; OF: Olestøl Fault ; OG: Oslo Graben; TP; Trøndelag Platform; VB: Vøring Basin; VG: Viking Graben; SC: Scotland; STZ: Sorgenfrei-Tornquist Zone.

Figure 2. Topography and bathymetry with some structural elements, mainly after Mosar (2003). HSZ: Hardangerfjorden Shear Zone; LGF: Lærdal-Gjende Fault; MTFZ: Møre-Trøndelag Fault Zone; OF: Olestøl Fault.

Figure 3. Colours represent topography and bathymetry of Norwegian Caledonides and adjacent areas, with red representing higher elevation. a) Depth to base crust (Moho), ci 2.5 km. White circles show receiver functions transects. b) Bouguer gravity minimum with emphasis on -50 mGal (white) and -75 mGal (blue). c) Residual crustal roots; wavelengths between 100 km and 800 km, only positive contours 2 km (white) and 4 km (blue). d) Apatite fission track ages close to sea level. Ages are particularly low in shaded areas. The compilation of fission track ages close to sea level is based on our own data (Leighton, 2007) and those of others (Cederbom et al., 2000; Grønlie et al., 1994; Hendriks, 2003; Huigen and Andriessen, 2004; Murrell, 2003; Redfield et al., 2004; Rohrman et al., 1994; Rohrman et al., 1995; Zeck et al., 1988). Profiles A and B correspond to figures 12 and 13.

Figure 4. Prior exhumation model. Depth to the present-day surface at the onset a) and later b) during flexural isostatic exhumation. c) present-day situation. White dots are locations of fission track data points. Colours on the upper surface represent topography (m) according to the colour bar. Colours of the buried surface represent temperature variations without scale. Fission track data demand initially faster exhumation along the coast.

Figure 5. a) prior fission track age map from constant rate exhumation of the present-day surface (Fig. 4). Red dots show location of corner nodes where the exhumation history is variable. The constant exhumation rate varies laterally with variations in initial overburden thickness. b) posterior fission track age map after inverse modelling of ages and mean track lengths for samples in southern Norway. Circles are data locations and numbers are fission track ages in Ma. The annealing model of Ketcham et al. (1999, 2000) was used.

Figure 6. The relationship between observed and modelled mean track length. Dots are for the prior model, and circles with error bars are for the posterior model. Inversion improved the fit considerably. Unexplained variance may be due to unrecognised processes of the apatite fission track system, thermal heterogeneity of the removed overburden, and faults.

Figure 7. The relationship between observed and modelled fission track ages. Dots are for the prior model, and circles with error bars are for the posterior model. Inversion improved the fit considerably. Unexplained variance may be due to unrecognised processes of the apatite fission track system, thermal heterogeneity of the removed overburden, and faults.

Figure 8. Prior and posterior corner node temperature histories. Node locations and numbers are shown in Fig. 5a. Reduction of data misfit requires considerable changes to the timing of the exhumation history at the corner points. These change are interpolated into the map by bilinear interpolation. The partial annealing zone of fission tracks in apatite is indicated by horizontal broken lines.

Figure 9. Main sediment input directions and position and progradation of major shelf break points during the Cenozoic. A major change occurred on the Eocene-Oligocene boundary. Redrawn after Huuse et al. (2001).

Figure 10. a) Composite lithology log for the upper Eocene (Kysing 4 boring) and lower Oligocene (Horn 1 boring) in the central Danish Basin, and major shifts in the content of planktonic foraminifera. The gamma log reflects mineralogical shifts; higher counts indicate increasing amount of muscovite and illite. Ages are from Luterbacher et al. (2004). b) oxygen isotope variations obtained in Kysing 4 and Horn 1. c) oxygen isotope variations in benthic foraminifera from ODP core 748B on the Kerguelen Plateau (modified from Bohaty and Zachos, 2003) correlate with oxygen isotope variations obtained in Kysing 4 and Horn 1. The temporary shift in sediment source in the North Sea Basin from primarily a western source to a Scandinavian source (the Moesgaard Formation) correlates with a North Sea cooling event and a significant cooling event in the Southern Oceans between approximately 35.5 and 34.5 Ma (named the Vonhof et al. (2000) cooling event by Bohaty and Zachos, 2003). The Moesgaard Formation cold spell is therefore related to a global cooling which must also have affected the high topography of western Scandinavia. Grey shading indicates colder climate.

Figure 11. Over-burial interpretation and the wells used by Hansen (1996a) superimposed on the topography of the region. It is apparent that Quaternary ice stream erosion causing overburial potentially has influenced the wells with over-compacted shale to various degrees. Sedimentary structures produced by erosion at the base of Quaternary glaciers comprise: VF=Vestfjorden; HB=Haltenbanken; SKD=Sklinnadjupet; TD=Trænadjupet; SB=Sklinnabanken; SD=Suladjupet; FB=Frøyabanken; MP=Måløyplatået; NT=Norwegian Trench; TB=Trænabanken; LG=Langgrunna; SK=Skagerrak; T=Trondheim Modified after Ottesen, D. et al. (2001).

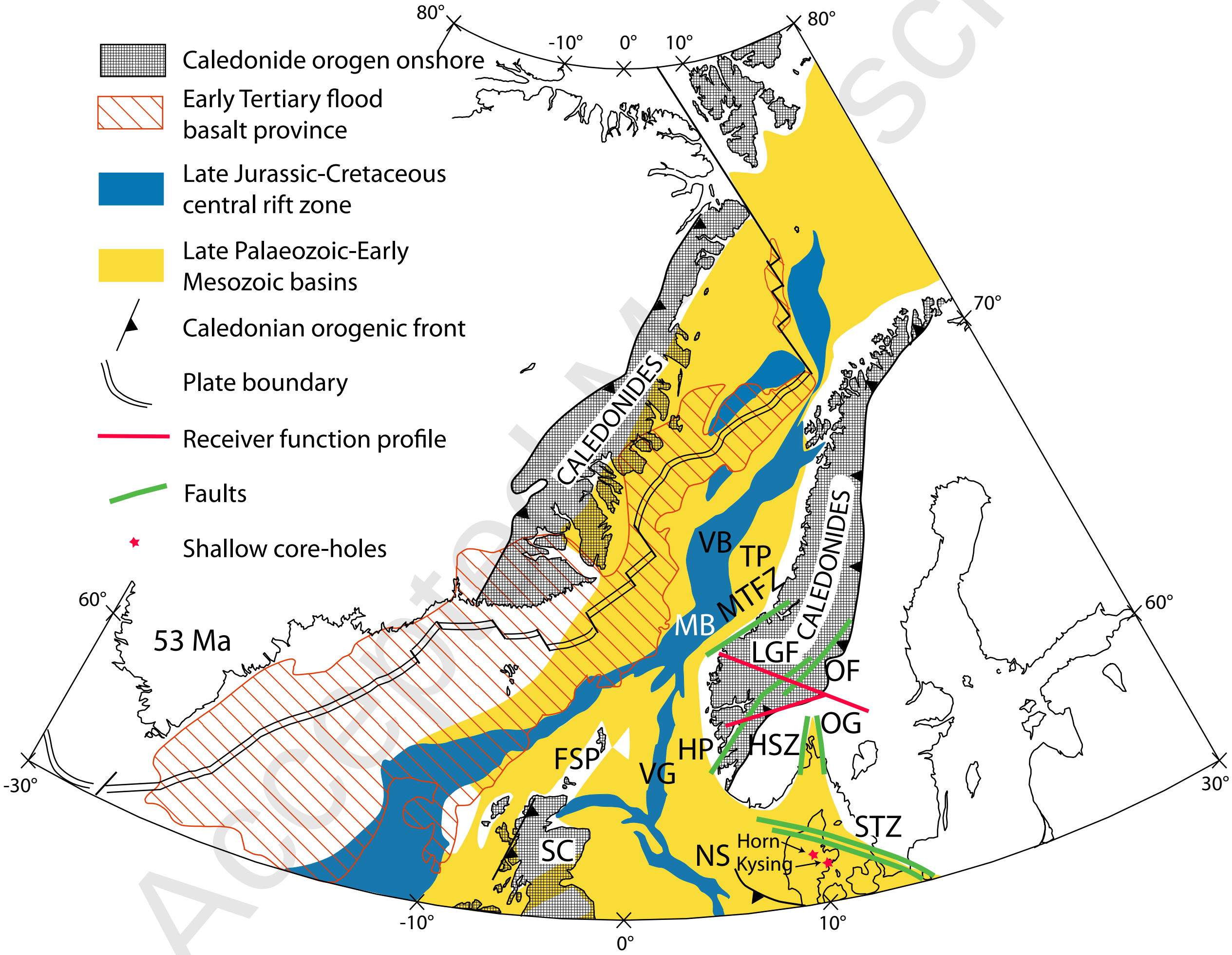
Figure 12. Back-stripping and reconstruction of sedimentary transect (Jensen and Schmidt, 1993) perpendicular to the cost of southern Norway (Fig 3d, profile A). The arrow indicates the present-day erosional limit of reconstructed sedimentary layers. a: End Permian. The protruding structure is salt; b: End Late Jurassic; c: End Early Cretaceous; d: End Late Cretaceous; e: End Oligocene; f: End Pliocene; g: Present-day profile. From f to g the reconstructed coast-proximal sediments are eroded, and Quaternary deposits are added. It is apparent that a marked angular unconformity (much enhanced by vertical scaling) is created by Quaternary erosion. Vertical scaling ×15.

Figure 13. Back-stripped Sognefjord profile (Fig 3d, profile B). Upper panel shows the present-day transect. Lower panel shows the reconstructed transect prior to Quaternary erosion obtained by the same procedure as in Fig. 12. The Quaternary erosion produces over-burial of the pre-Quaternary sediment and tilting because of the removal of coast-proximal sediments. Vertical scaling ×9. Compaction of previously deposited sediments and a weak tectonic subsidence component also contribute to the tilt evolution.

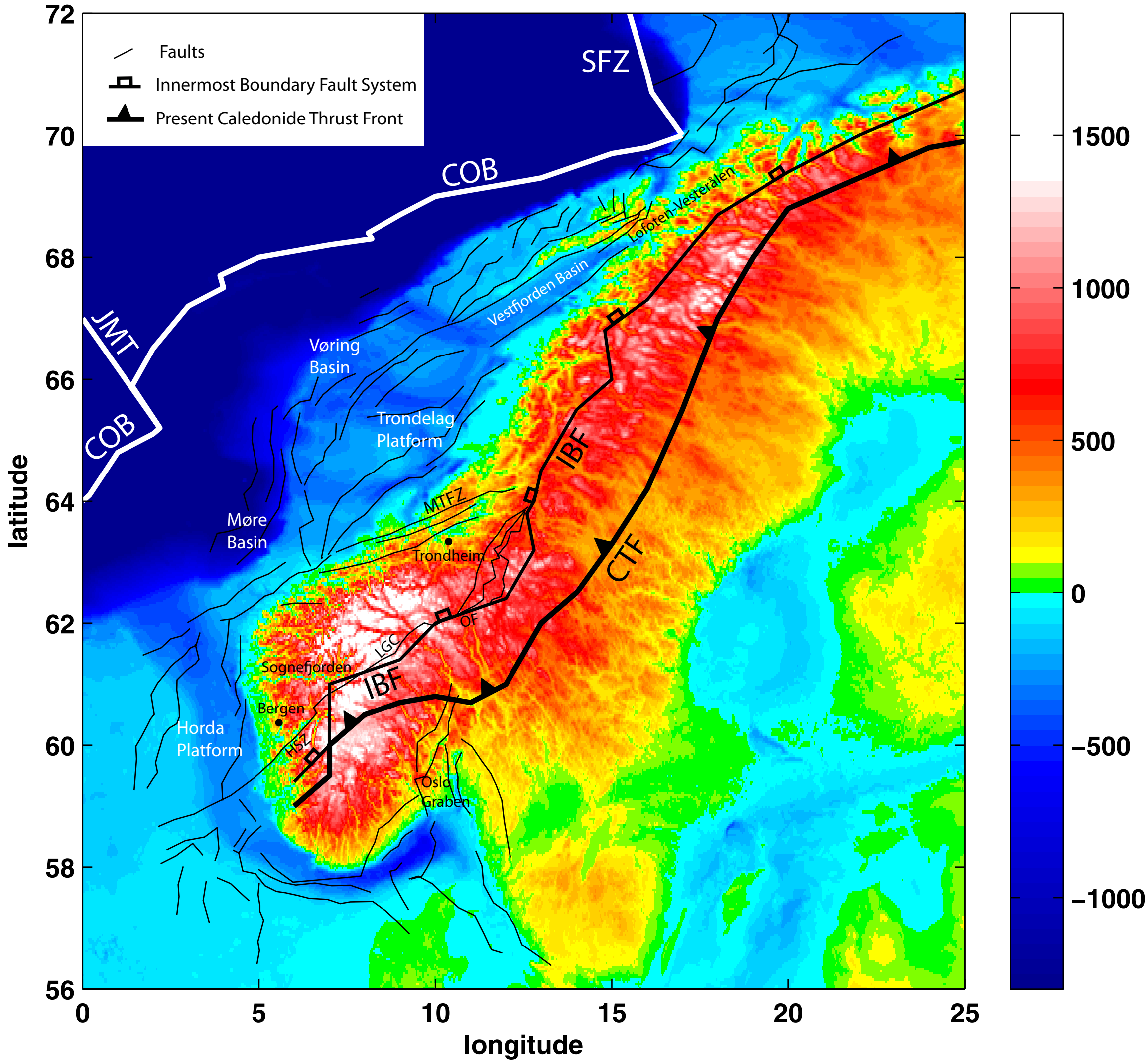
Figure A1. Upper row: The three recorded seismograph components (up-down, east-west and north-south) of two different teleseimic earthquakes recorded at two different stations. To the left a temporary CENMOVE station (JH03) and to the right and a permanently installed NORSAR station (NC204). Middle row: The three components were rotated into the direction of the incoming P-wave, where. the L (upper) approximates the P-displacement, and Q (lower) approximates the *SV*-displacement. Bottom row: The receiver function estimates (lower trace) for the earthquake recordings, i.e. the Q components deconvolved with the L components. The arrival of the P-to-S conversion from Moho stands out for both stations. The additional depth axis shows the corresponding P-to-S conversion depths, assuming a typical crustal average velocity of V_P of 6.4 km/s and a V_P/V_S of 1.73.

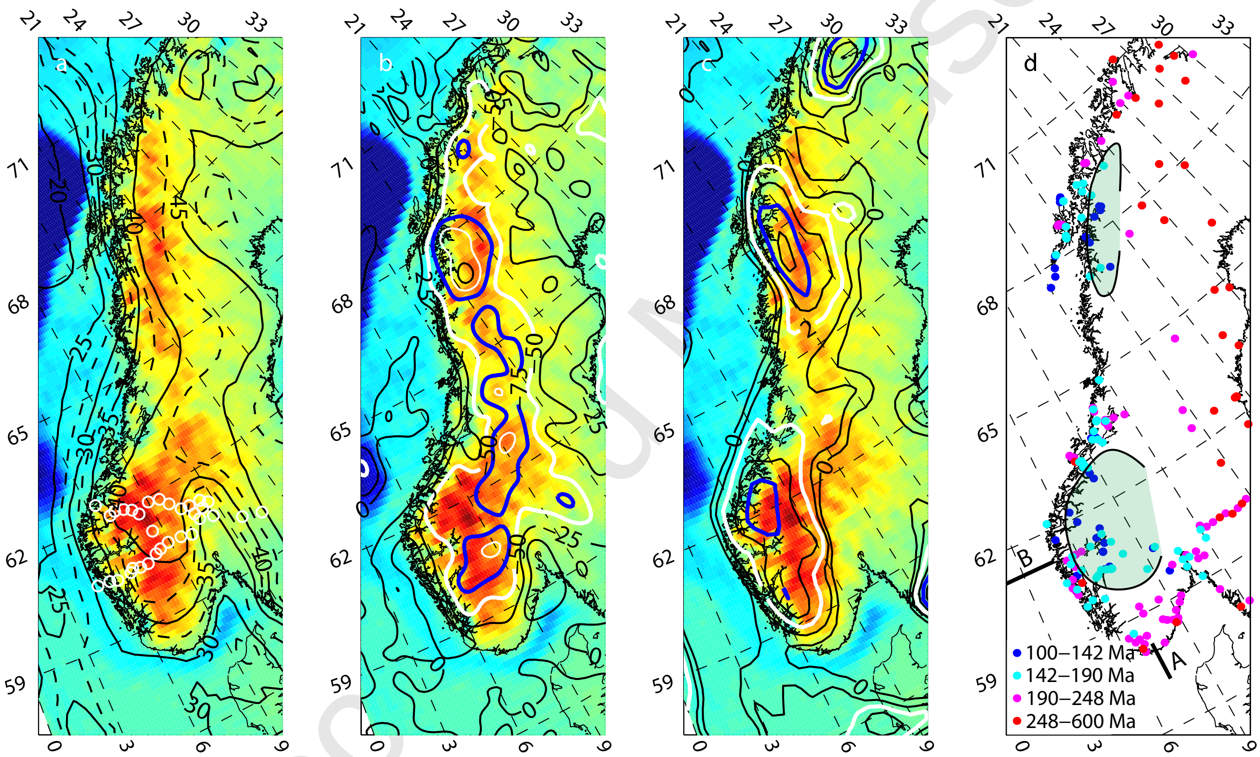
The sensitity of this assumption is, however, not very critical. Based on the Moho conversion arrival times we may read preliminary Moho depths of about 44 km for JH03 and about 39 km for NC204.

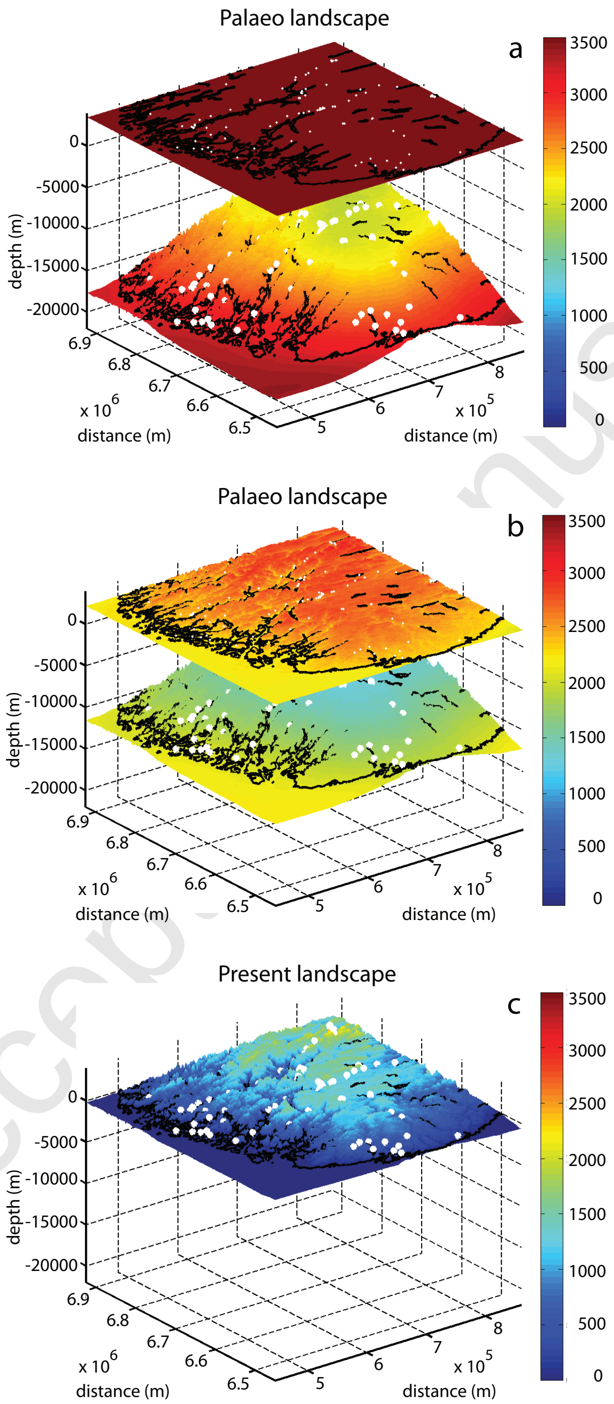
Figure A2. Receiver function estimates (Q_{RF}) from many earthquakes measured at temporary station JH03 (left) and at permanent (NORSAR) station NC204 (right). For both datasets the time axis as well as the equivalent depth axis for assumed V_P =6.4 km/s and V_P/V_S=1.73 are shown. Notice the clear and repeated P-to-S conversion from Moho at about 5.1 s for JH03 and 4.5 s for NC204, corresponding to crustal thicknesses of 43 km and 39 km respectively. For both stations the receiver functions are sorted after the direction to the earthquake (clockwise from north from bottom and up). For JH03 the P-S delay time varies periodically between about 4.8 s and 5.3 s, indicating a dipping Moho. Several other lineaments are observed, which are due to secondary crustal boundaries and multiples hereof.

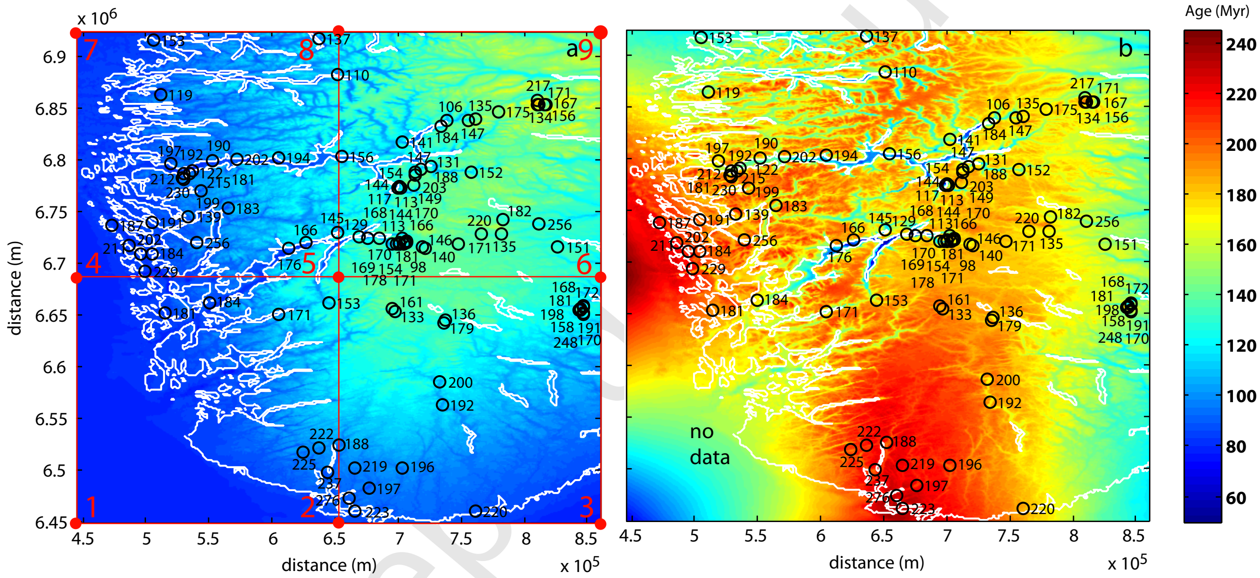


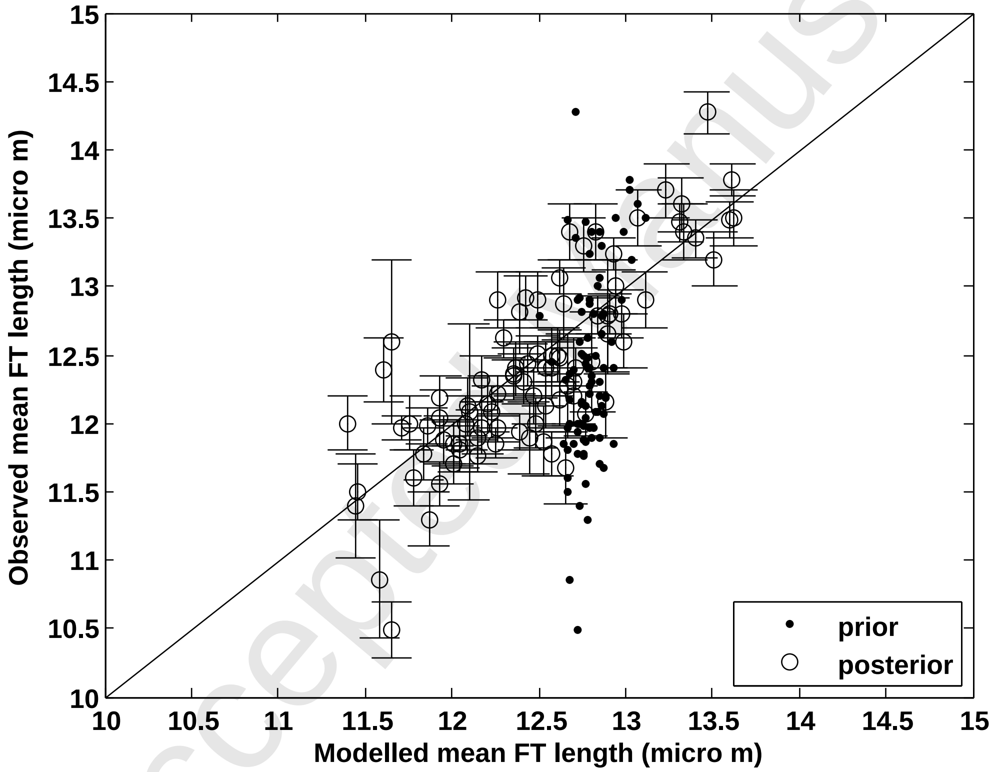
Caledonide orogen onshore
Early Tertiary flood basalt province
Late Jurassic-Cretaceous central rift zone
Late Palaeozoic-Early Mesozoic basins
Caledonian orogenic front
Plate boundary
Receiver function profile
Faults
Shallow core-holes
53 Ma
80°
-10°
0°
10°
80°
70°
60°
60°
-30°
30°
-10°
0°
10°
CALEDONIDES
CALEDONIDES
VB
TP
MTFZ
MB
LGF
OF
OG
HSZ
HP
VG
FSP
SC
NS
Horn
Kysing
STZ

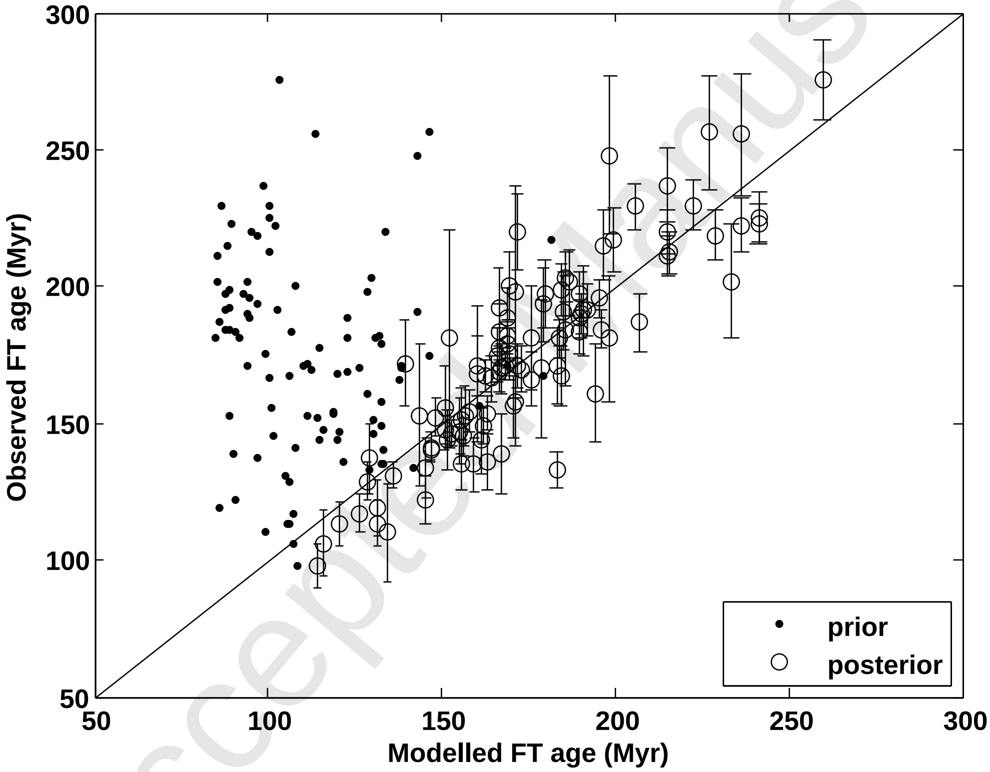

Faults
Innermost Boundary Fault System
Present Caledonide Thrust Front
SFZ
COB
JMT
COB
Lofoten-Vesterålen
Vestfjorden Basin
Vøring Basin
Trondelag Platform
Møre Basin
MTFZ
Trondheim
IBF
CTF
OF
LGC
Sognefjorden
IBF
Bergen
HSZ
Horda Platform
Oslo Graben
latitude
longitude
72
70
68
66
64
62
60
58
56
0
5
10
15
20
25
1500
1000
500
0
−500
−1000


a
b
c
d
100–142 Ma
142–190 Ma
190–248 Ma
248–600 Ma
A
B

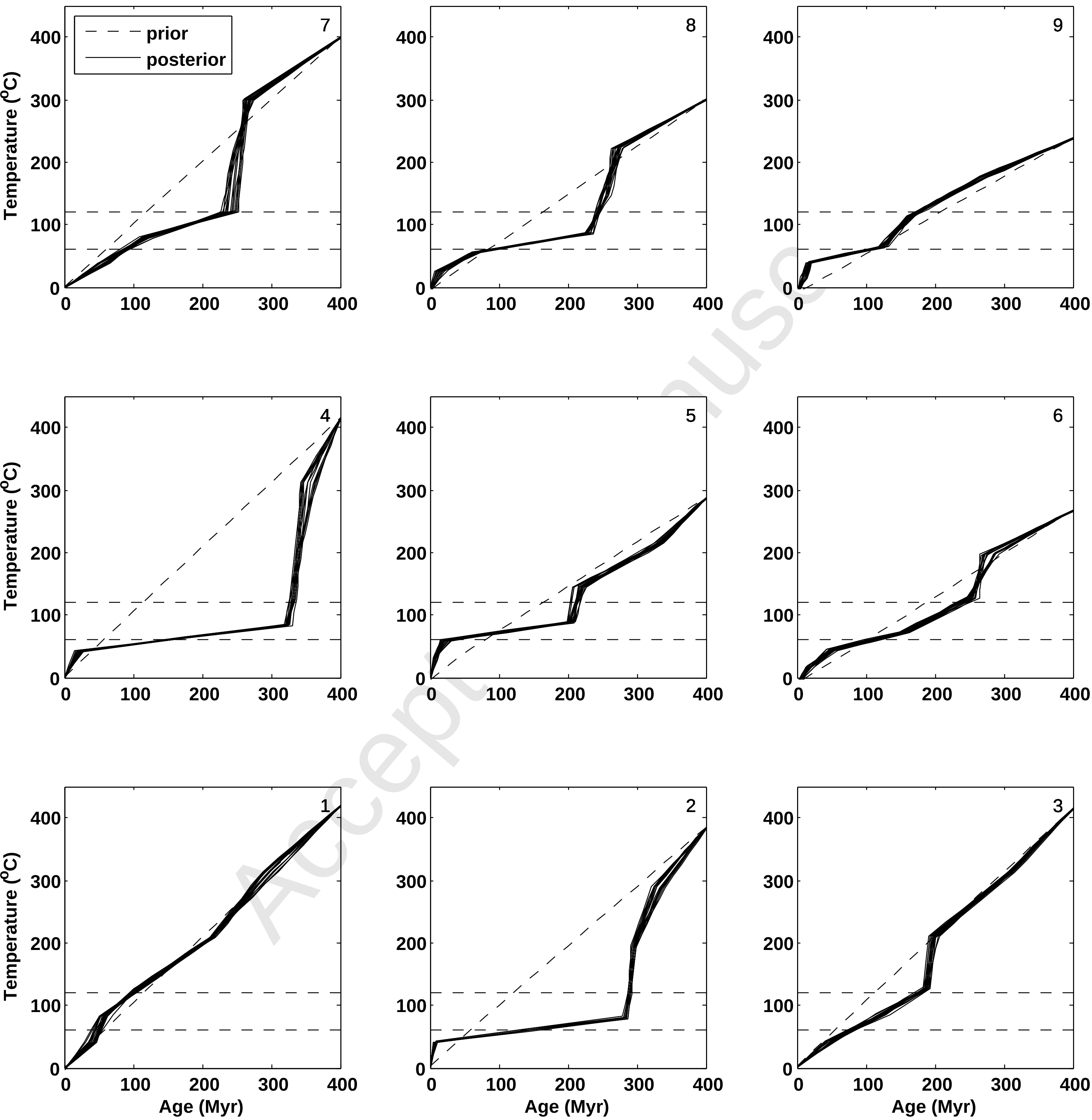

Palaeo landscape
a
depth (m)
0
-5000
-10000
-15000
-20000
6.9
6.8
6.7
6.6
6.5
x 10^6
distance (m)
5
6
7
8
x 10^5
distance (m)
3500
3000
2500
2000
1500
1000
500
0
Palaeo landscape
b
Present landscape
c

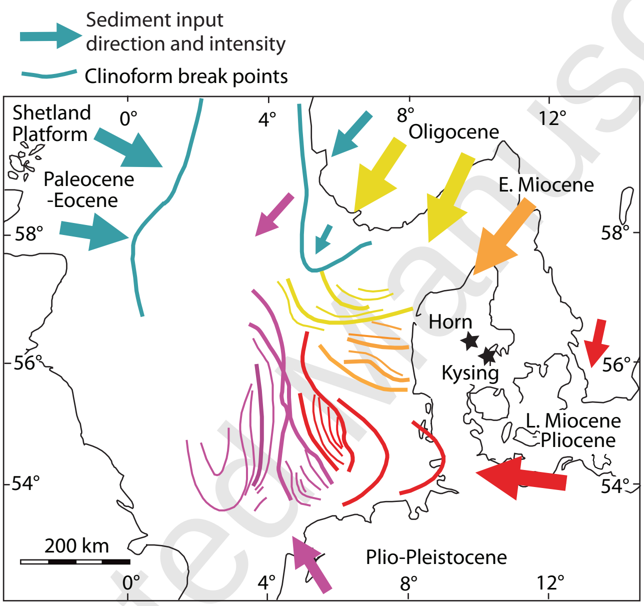

a
b
x 10^6
distance (m)
distance (m)
x 10^5
distance (m)
x 10^5
no data
Age (Myr)
240
220
200
180
160
140
120
100
80
60


Observed mean FT length (micro m)
Modelled mean FT length (micro m)
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
10 10.5 11 11.5 12 12.5 13 13.5 14 14.5 15
prior
posterior

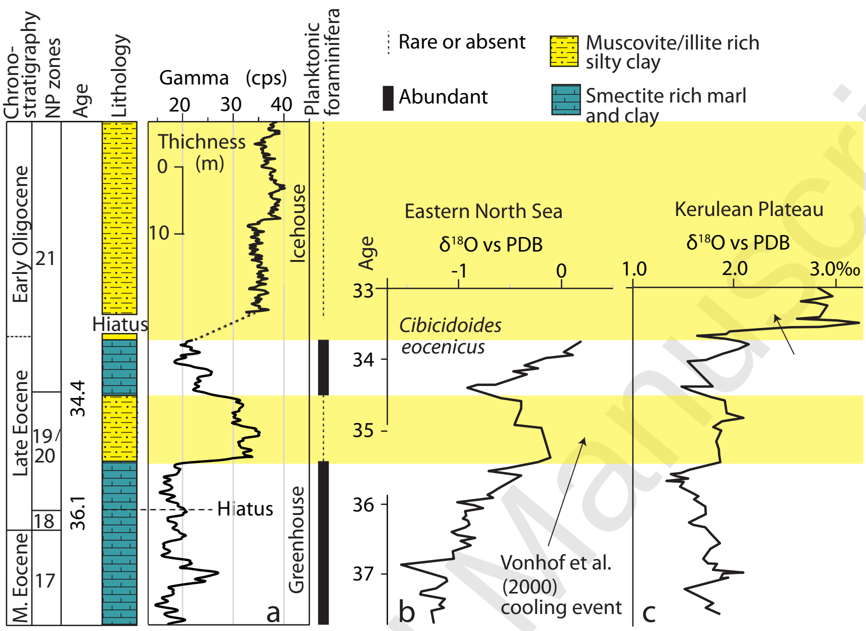


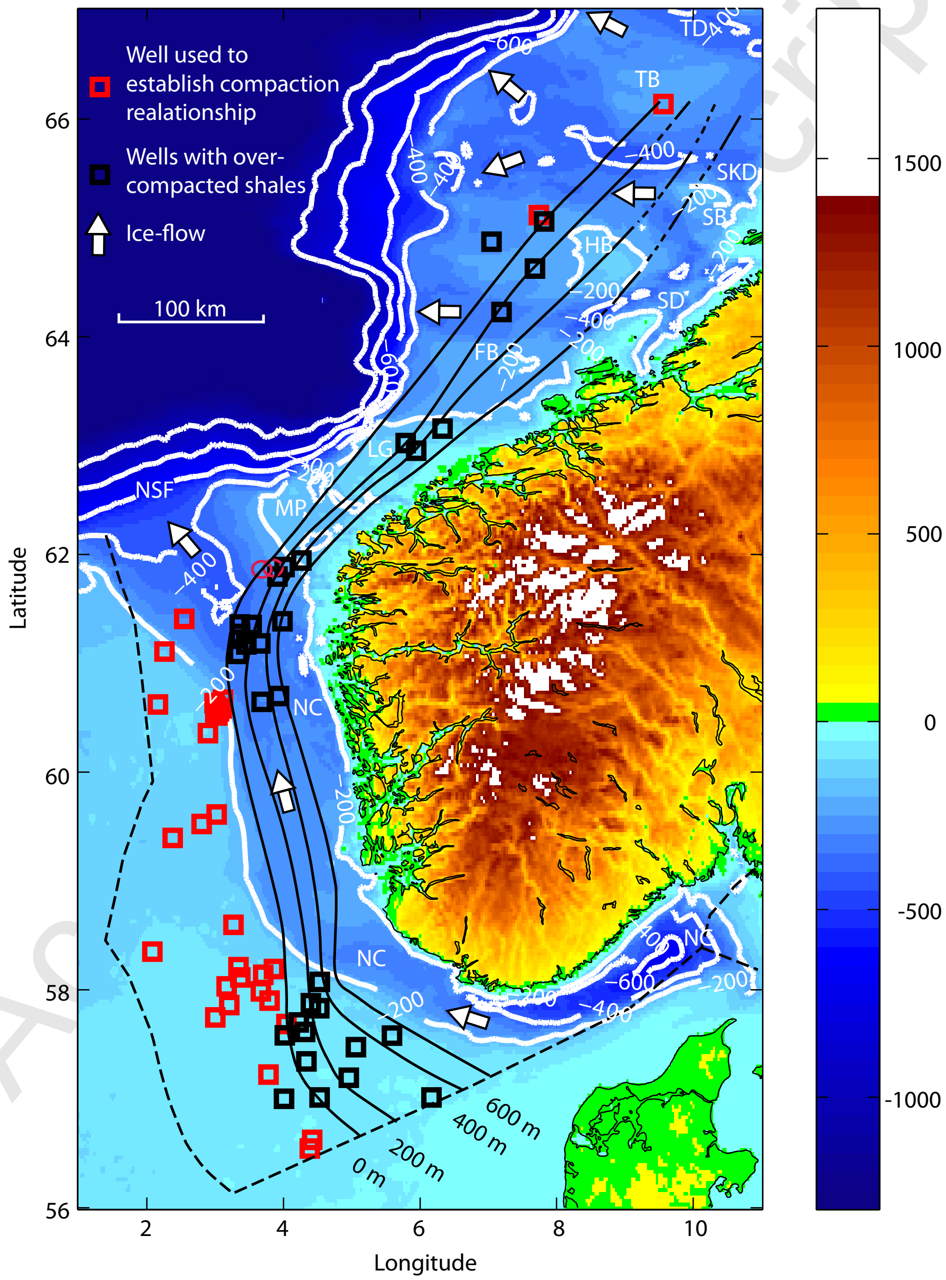
300
250
200
150
100
50
50
100
150
200
250
300
Observed FT age (Myr)
Modelled FT age (Myr)
prior
posterior

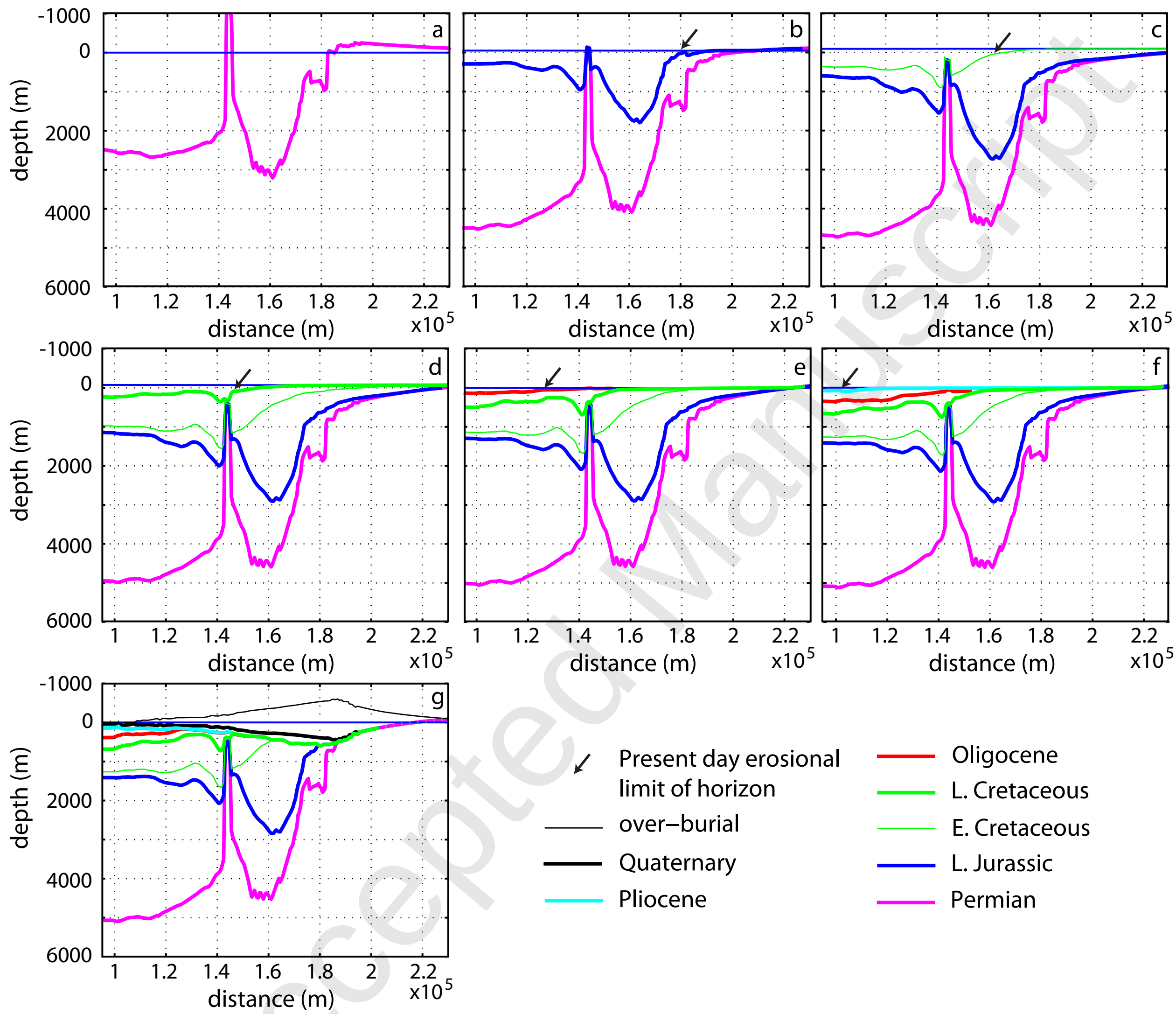

prior
posterior
7
8
9
4
5
6
1
2
3
Temperature (⁰C)
Age (Myr)
0
100
200
300
400



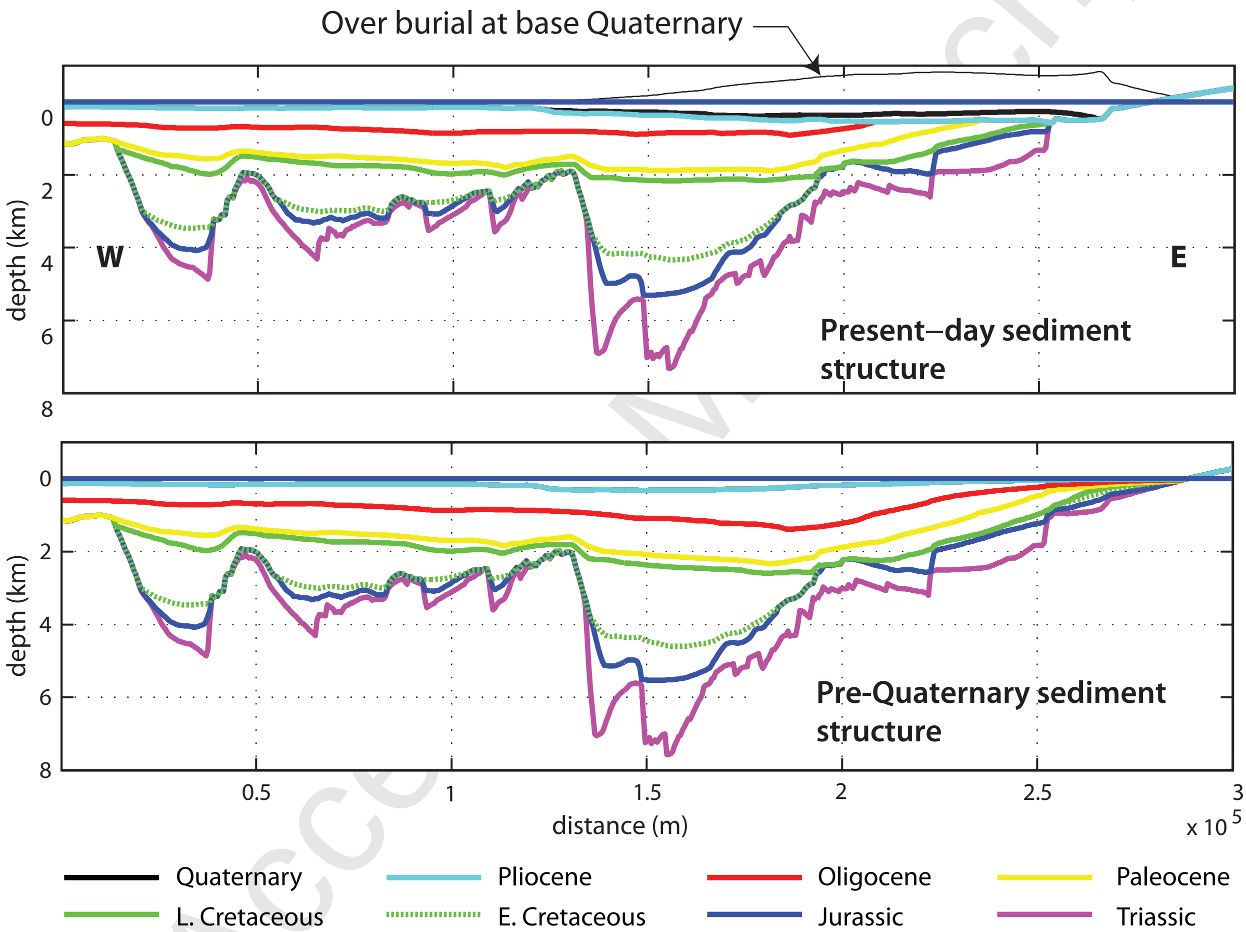
Sediment input direction and intensity
Clinoform break points
Shetland Platform
Paleocene -Eocene
Oligocene
E. Miocene
Horn
Kysing
L. Miocene
Pliocene
Plio-Pleistocene
200 km
0°
4°
8°
12°
58°
56°
54°

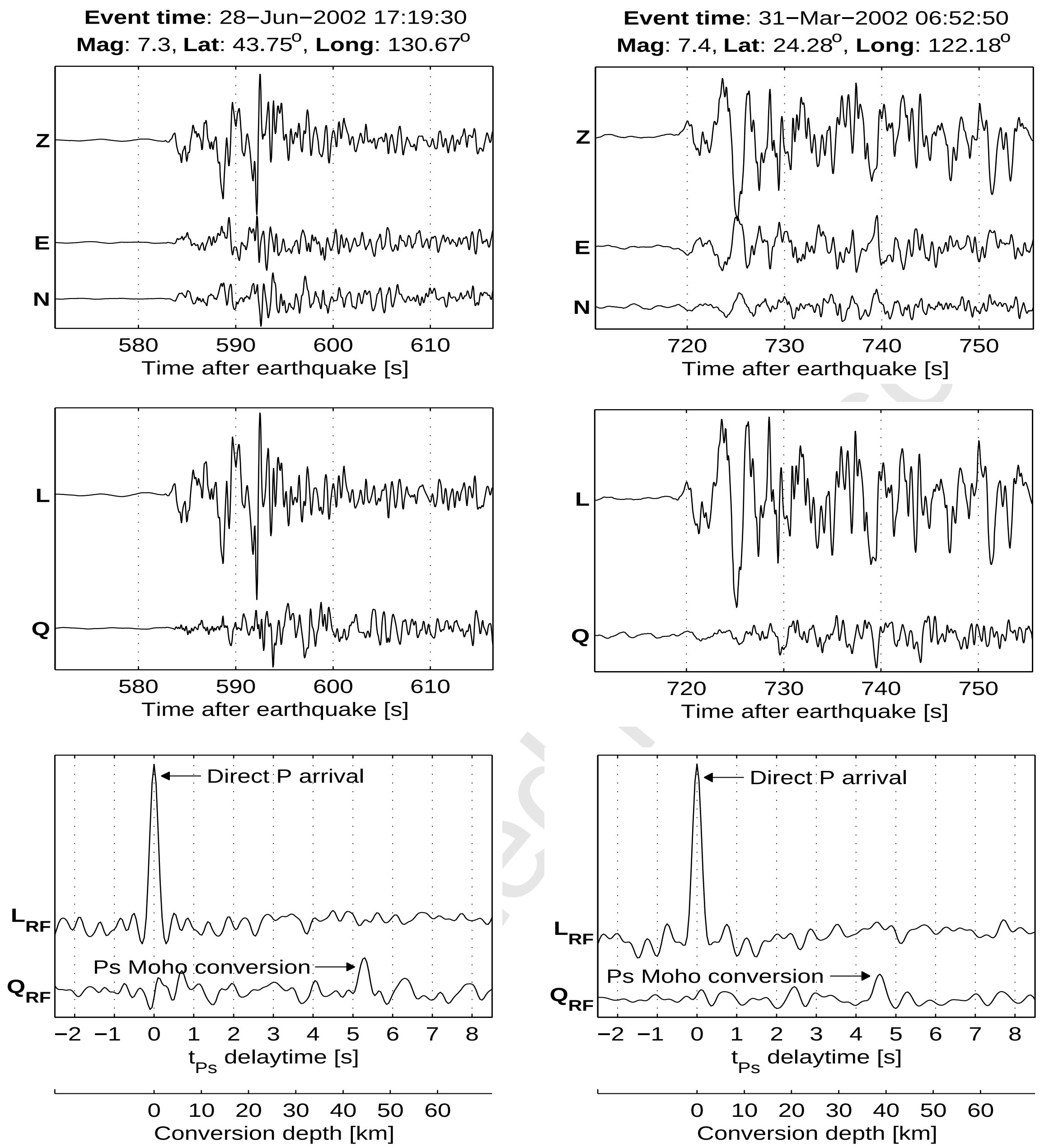

Chrono-stratigraphy
NP zones
Age
Lithology
Gamma (cps)
20 30 40
Planktonic foraminifera
Rare or absent
Abundant
Muscovite/illite rich silty clay
Smectite rich marl and clay
Thichness (m)
0
10
Early Oligocene
21
Hiatus
Icehouse
Late Eocene
19/20
34.4
18
36.1
Hiatus
M. Eocene
17
Greenhouse
a
Eastern North Sea
δ18O vs PDB
-1
0
Age
33
34
35
36
37
Cibicidoides eocenicus
Vonhof et al. (2000) cooling event
b
Kerulean Plateau
δ18O vs PDB
1.0
2.0
3.0‰
c


Well used to establish compaction realationship
Wells with over-compacted shales
Ice-flow
100 km
Latitude
Longitude
600 m
400 m
200 m
0 m
NSF
MP
LG
FB
HB
SD
SB
SKD
TB
TD
NC
1500
1000
500
0
-500
-1000



-1000
0
2000
4000
6000
depth (m)
distance (m)
x10^5
1
1.2
1.4
1.6
1.8
2
2.2
a
b
c
d
e
f
g
Present day erosional limit of horizon
over–burial
Quaternary
Pliocene
Oligocene
L. Cretaceous
E. Cretaceous
L. Jurassic
Permian


Over burial at base Quaternary
depth (km)
0
2
4
6
8
W
E
Present–day sediment structure
Pre-Quaternary sediment structure
0.5
1
1.5
2
2.5
3
x 10 5
distance (m)
Quaternary
Pliocene
Oligocene
Paleocene
L. Cretaceous
E. Cretaceous
Jurassic
Triassic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Mag: 7.3, Lat: 43.75°, Long: 130.67°
Event time: 31−Mar−2002 06:52:50
Mag: 7.4, Lat: 24.28°, Long: 122.18°
Z
E
N
L
Q
Time after earthquake [s]
580 590 600 610
720 730 740 750
Direct P arrival
Ps Moho conversion
L_RF
Q_RF
−2 −1 0 1 2 3 4 5 6 7 8
t_Ps delaytime [s]
0 10 20 30 40 50 60
Conversion depth [km]

Figure A1

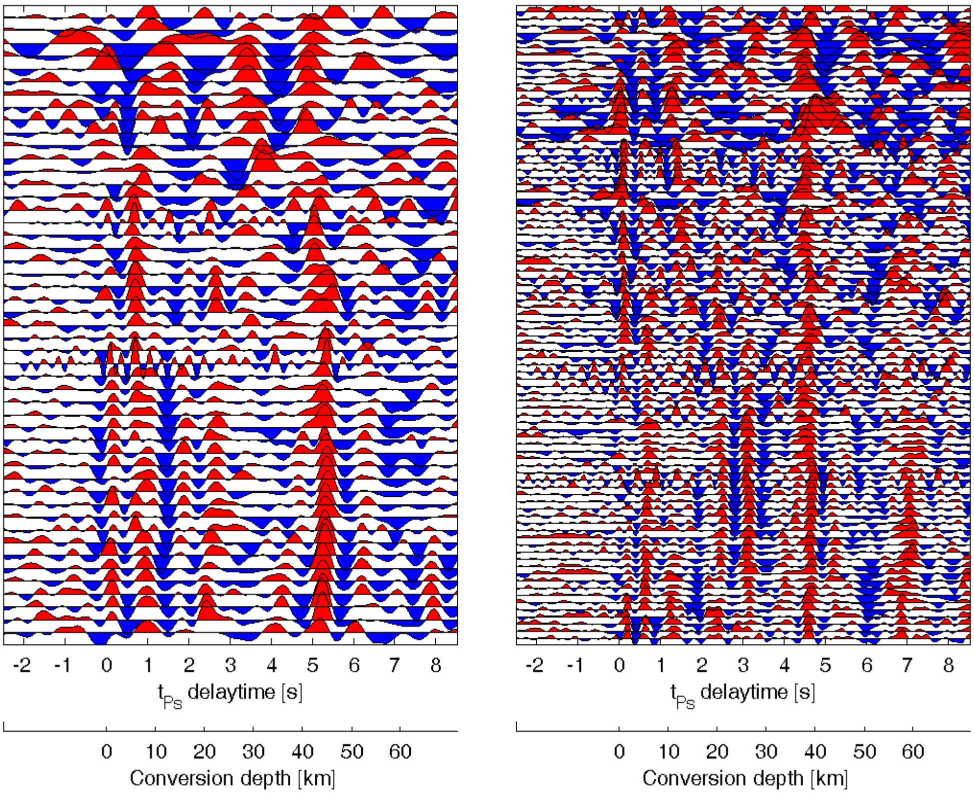
-2
-1
0
1
2
3
4
5
6
7
8
t_{Ps} delaytime [s]
0
10
20
30
40
50
60
Conversion depth [km]

Figure A2