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Cenozoic erosion and flexural isostasy of Scandinavia

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ABSTRACT

The presence of Cenozoic deposits along the Norwegian Atlantic margin required extensive erosion of the Scandinavian Mountains in a generally cooling climate from the Oligocene to the present. The volume of the deposits implies that the transfer of mass from the inland area to the offshore shelf induced isostatic displacements on a kilometer scale. However, except for glacial excavation of the deep fjords, little is known about the distribution of Cenozoic inland erosion. A long-lasting paradigm incorporates remnants of peneplains at high elevation and assumes very little Cenozoic erosion on these surfaces through time. This scenario has recently been challenged by quantitative geomorphological studies indicating that the matrix of Cenozoic sediments deposited offshore must have been sourced from these surfaces. An alternative explanation for the present-day high-elevation low-relief surfaces is therefore that they evolved throughout the Cenozoic because of glacial and periglacial erosion processes that are known to vary strongly with altitude. Here we explore the implications of the latter scenario by reconstructing a pre-Cenozoic fluvial landscape without elevated low-relief surfaces. We use the present-day offshore sediment volumes for constraining the total Cenozoic erosion, and we find that a likely pre-Cenozoic fluvial landscape is only in few places more than 1 km higher than today. The rock mass of the offshore sediments is generally used for filling the fjords created during the Quaternary glaciations and for restoring concave river profiles from sea level to the peaks. Our reconstruction is based on a fluvial landscape algorithm and considers the isostatic response to the transfer of rock mass – from the basins onto the onshore area. A comparison between the reconstructed and the present-day topography demonstrates that offshore tilting of pre-Cenozoic strata can be partly explained by flexural isostatic compensation in response to the Cenozoic erosion and deposition. Locations of future thermochronometry studies for testing Scandinavian landscape evolution models are suggested based on temperature estimates of the present-day surface buried beneath the erosion products restored from the offshore basins.

1. Introduction

The high topography of western Scandinavia partly coincides with the outline of the Caledonian orogen, which experienced its main phase of deformation during the collision of the Baltica and Laurentia plates at ca. 420–400 Ma (Roberts, 2003). The present Scandinavian landscape shows significant traces of Quaternary glacial erosion since ca. 2.7 Ma (Jansen et al., 2000). The Norwegian fjords and the voluminous glacigenic deposits on the Norwegian shelf are the most obvious links between intense erosion and rapid deposition in the surrounding basins. The interpretation of offshore datasets (Gołędowski et al., 2012; Ziegler, 1990) (Fig. 1), enables a quantitative analysis of the sediment mass transfer and related isostatic effects in the form of subsidence in the basins and a rebound inland. Such isostatic adjustment has been argued to be the main mechanism for rock column uplift in tectonically inactive orogens (Champagnac et al., 2007; Medvedev et al., 2008; Small and Anderson, 1998) and the primary driver for long-term exhumation of Scandinavia (Doré, 1992; Huuse, 2002; Nielsen et al., 2009).

The Scandinavian Mountains experienced a partial gravitational collapse in Devonian times (ca. 405–390 Ma: Roberts, 2003). The subsequent episodic continental rifting processes led to creation of large sedimentary basins and eventually to orogen separation, continental break-up and creation of the North Atlantic Ocean in the Paleogene (Skogseid et al., 2000). However, owing to orogenic crustal thickening, the Caledonides had a significant amount of buoyant crustal root comparable to that found in the present-day Himalayas (based on similar amounts and duration of crustal shortening; Streule et al., 2010), which must have been a long-time rock feeder to the decaying topography.

The present high topography in western Scandinavia displays a series of low-relief surfaces in the form of summit flats between the fjords or as long flattish hillslopes leading from the fjord areas to existing cirque glaciers higher in the landscape (e.g., Nesje and Whillans, 1994). It has been argued that the low-relief surfaces

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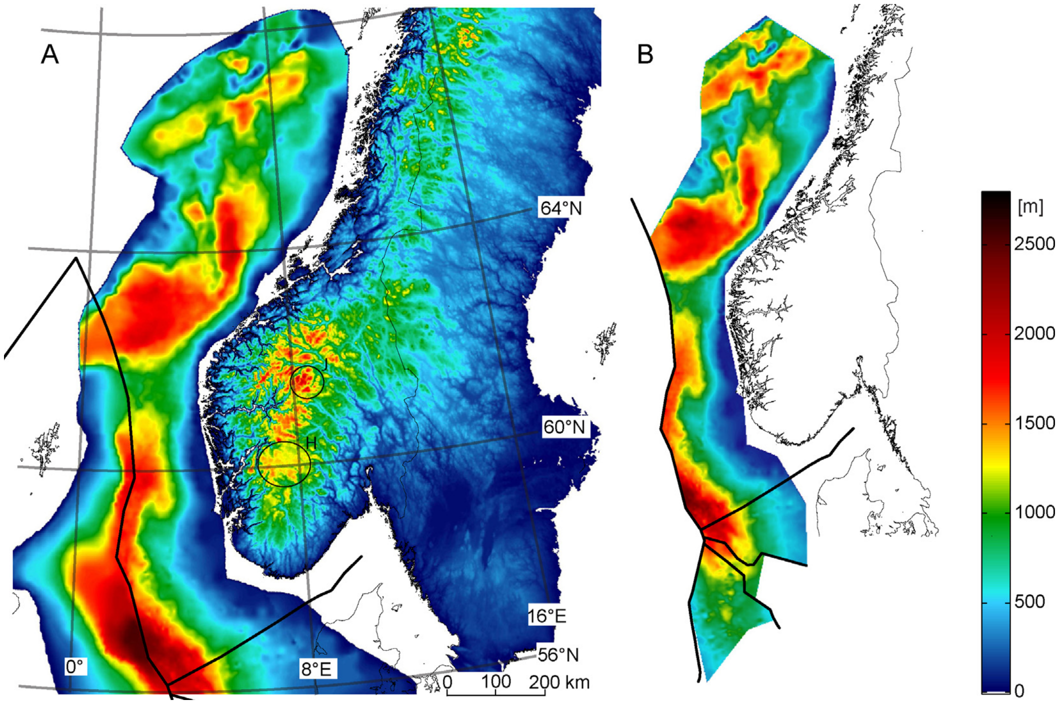

Fig. 1. (A) Present-day topography of Scandinavia illustrated by the ETOPO1 DEM dataset and matrix thickness of Cenozoic deposits offshore (Gołędowski et al., 2012 – Norwegian and Danish sectors of the North Sea, Norwegian Sea; Ziegler, 1990 – British sector of the North Sea; the sharp transition in matrix thickness between the Norwegian and British sectors results from merging of two datasets). H – Hardangervidda; J – Jotunheimen. (B) Matrix thickness used for landscape reconstruction (redrawn from Gołędowski et al., 2012).

are remnants of uplifted peneplains, which were created at sea level and lifted to their present elevation by Cenozoic tectonism of unknown origin (Reusch, 1901). This hypothesis assumes that the present-day Scandinavian topography did not persist since the creation of the Caledonides and that it was rejuvenated in Cenozoic times (e.g., Lidmar-Bergström and Näslund, 2002). Furthermore, the varying sediment flux to the basins is assumed to be mostly tectonic in origin (e.g., Jordt et al., 1995; Riis, 1996).

In contrast to this hypothesis, it has recently been suggested that the present-day landscape in Scandinavia is a persistent remnant of pre-Cenozoic tectonic events and long-term fluvial, glacial and periglacial erosion (Nielsen et al., 2009). The fluctuating and deteriorating Cenozoic climate is argued to be the main driver for varying sediment flux from western Scandinavia (Gołędowski et al., 2012; Nielsen et al., 2009). This latter hypothesis does not require Cenozoic tectonic uplift of the Scandinavian landmass. Furthermore, Steer et al. (2012) argued for significant Quaternary erosion not only within the fjords, but also at high elevation, in order to match the volume of sediment matrix delivered to the basins. This requirement for Quaternary erosion on the high-elevation surfaces is in conflict with the previously mentioned hypothesis involving elevated peneplains.

The difference between the two hypotheses for Scandinavia's landscape evolution comes down to a key question: Did the present topography develop from Cenozoic tectonic uplift of Mesozoic paleosurfaces from close to sea level or was it formed by glacial and periglacial erosion of a pre-Cenozoic fluvial remnant of the Caledonian mountains? It is impossible to answer this question solely on the basis of the sediment record owing to the lack of inland Mesozoic and Cenozoic sediments, and because tectonism and climate variations can lead to identical variations in sediment production rate (Molnar, 2004; Molnar and England, 1990; Montgomery and Brandon, 2002). However, in order to quantify the implications of the climate-driven erosion hypothesis in Scandinavia (Nielsen et al., 2009), we reconstruct a possible pre-Cenozoic fluvial landscape, using the sediment matrix volumes found offshore (Fig. 1B) and a computational landscape evolution model (Fig. 2). The reconstructed fluvial landscape is not unique, as it depends on unknown regional erosion patterns, but it allows us to (i) evaluate the height and morphology of a realistic pre-glacial landscape in Scandinavia, (ii) quantify the isostatic implications of the Cenozoic mass transfer and (iii) identify areas for thermochronological studies suitable for testing the erosion hypothesis of Nielsen et al. (2009).

2. The fluvial landscape reconstruction

2.1. Landscape description and modeling assumptions

Landforms like overdeepened glacial troughs, hanging valleys, cirques, and high elevation summit flats characterize the morphology of the present-day Scandinavian landscape. While the valleys

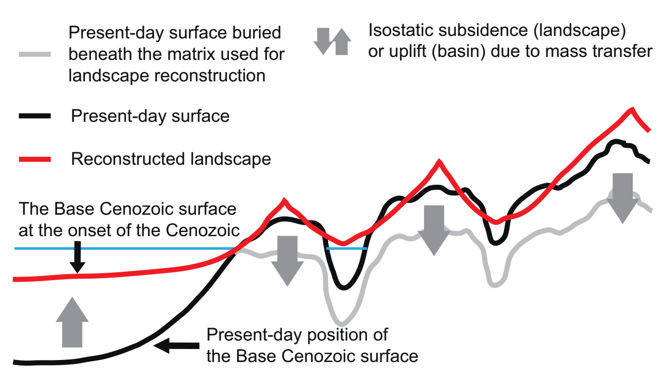

Fig. 2. Conceptual figure showing the relations between the rock mass transfer (from the basins onto the land), isostatic effects and reconstructed fluvial landscape. Not to scale.