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Evolution of topography of post-Devonian Scandinavia: Effects and rates of erosion

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ABSTRACT

The mechanisms and timing of mountain growth in Scandinavia remain enigmatic given that the region has not been involved in active orogenesis since the Devonian and in any large-scale tectonic activities after the NE Atlantic breakup during the early Cenozoic. In this study we combine analysis of the vertical motions of the region caused by (dominantly) glacial erosion during the Quaternary with Apatite Fission Track (AFT) analysis of rocks from the area. Using numerical models, we first quantify how fluvial and glacial erosion carved out the fjords and valleys to a depth of 2 km below the paleosurfaces. This erosional episode represents a major local weight loss and results in up to a 0.8-km uplift of rocks and up to a 0.5-km rise of local topography. These estimates only marginally depend on the effective elastic thickness of the lithosphere and thus are robust. We show then that no correlation exists between sample altitude and published AFT data, but that a correlation does exist between AFT age and the depth below our constructed pre-glacial summit surface. This correlation demonstrates the robustness of the numerical erosional model, quantifies average erosion rates during Carboniferous–Cretaceous at <10 m/My, and outlines the regions of western Scandinavia (Lofoten and Bergen areas and Møre–Trøndelag fault complex) with atypical Mesozoic–Cenozoic evolution, probably related to regional tectonic activities.

1. Introduction

The origin of mountains along the North Atlantic coastlines remains enigmatic. It is a matter of continuing debate if these mountains are topographic remains from the Caledonian mountain belt (*e.g.*, Nielsen et al., 2009) or if they emerged in the Cretaceous or later (*e.g.*, Japsen et al., 2012). Here we address parts of this issue by estimating the influence and intensity of erosion from the late Paleozoic.

The Caledonide Orogeny (450–420 Ma) was the consequence of the continent–continent collision of Laurentia and Baltica (Cocks and Torsvik, 2002) and represents the most recent grand-scale mountain-building process in Scandinavia. Collapse and rifting processes began to dismember the Caledonides shortly after their formation (Andersen, 1998). The Skagerrak-centered large igneous province 297 Ma eruption event in NW Europe covered vast areas, estimated to at least 0.5 million km^2 and thus affected the thermal history of southern Scandinavia (Torsvik et al., 2008). The prolonged continental rifting process between the North American–Greenland craton and Eurasia (with several rift phases dated from late Paleozoic until early Cenozoic; Faleide et al., 2008) led to ocean formation in the North Atlantic at ~56 Ma. The area has not been involved in large-scale tectonic processes since.

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The evolution of the post-Devonian Scandinavian topography was studied using subregional stratigraphic landscape analysis and field observations of paleosurfaces (Bonow et al., 2007; Gabrielsen et al., 2010a; Lidmar-Bergstrom et al., 2000, 2007, 2013; Reusch, 1901; Riis, 1996). The amplitude of vertical movements inferred from such observations, however, is debatable (see for example discussion in Gabrielsen et al., 2010a,b; Nielsen et al., 2010b; Olesen et al., 2013). Extending the geometry and timing of such paleolandscapes to all of Scandinavia also remains speculative. Our study method is based on numerical analysis of modern topography and trends in thermochronological data. The method lacks the details of those above, but in contrast remains robust and unbiased thereby permitting super-regional application.

Erosion processes can be an important mechanism to enhance relief (Gilchrist and Summerfield, 1990, 1991; Molnar and England, 1990). The combined effect of localized erosion and the diffused action of flexural isostasy may have resulted in a nonuniform evolution of the topography. This is the focus of recently developed models of flexural isostasy, which study isostatic uplift resulting from surface denudation in different geological structures (Braun et al., 2013; Champagnac et al., 2007, 2009; Medvedev et al., 2008, 2013; Pelletier, 2004; Steer et al., 2012; Stern et al., 2005). Regional studies show that the development of the fjord system in Scandinavia strongly enhances the topography in the region (Gołędowski et al., 2013; Nielsen et al., 2009; Steer et al., 2012).

Several methods have been used to test the validity of numerical models. Ice-related erosion partially explains the uplift of Mesozoic marine sediments along passive margins of eastern Greenland (Medvedev et al., 2008, 2013) as well as the evolution of paleoplateaus in western Greenland (Bonow et al., 2006; Medvedev et al., 2013). An alternative test of models of pre-glacial topography looked at the mass balance between assumed connected onshore erosion and offshore sediments (Steer et al., 2012). However, even considering uncertainties, analysis showed that the Scoresbysund region in east-central Greenland lacks offshore sediments (Medvedev et al., 2008, 2013), whereas a model of Scandinavian erosion below the paleosurface demonstrates an excess of offshore sediments (Dowdeswell et al., 2010; Steer et al., 2012). In the Scandinavian realm, the area of our study, stating that the cause of the sediment masses in the North Sea is entirely owing to the erosion of the Norwegian mountains is challenging, as other regions (notably, the Baltic and Central European river basins) are known to also have contributed significant masses into North Sea sediments (*e.g.*, Anell et al., 2010). Here, we utilize an entirely different approach whereby we test the erosional models for Scandinavia against published Apatite Fission Track (AFT) data from that region.

A comprehensive database of AFT studies in Scandinavia is compiled in Hendriks et al. (2007; continuously updated). These data were previously applied to analyze geological evolution on a subregional scale (Hendriks et al., 2010; Redfield et al., 2004, 2005a,b). Nielsen et al. (2009) analyzed the evolution of Scandinavian topography using a copious set of AFT data, modeling the paleolandscapes based on the thermal history inferred from the AFT samples. The downside of such an approach is the lack of widely accepted theoretical background for interpretation of AFT data onto the thermal and exhumation history. That type of interpretation is the subject of continuing discussions (*e.g.*, Chalmers et al., 2010; Green et al., 2011; Hendriks et al., 2010; Nielsen et al., 2010a; Redfield, 2010). In contrast, in this study, we model paleolandscapes using the topographic data; and test this model statistically against AFT data, particularly against trends (or breaks of trends) in AFT ages. This has the benefit that the erosion rates leading to the modern landscape are also resolved. Our study is further augmented by the recently published AFT data set (more than 50 samples) from the Bergen area (Ksienzyk et al., 2014).

In this study we first present erosion backward in time as a numerical method to reconstruct pre-glacial/pre-fluvial landscapes. Applying this method to the Scandinavian topography gives us vertical motions caused by glacial and fluvial erosion over a younger period. Secondly, we combine our numerical erosional model and AFT data in an analysis to estimate early erosion rates and to test for consistency between AFT-based erosion estimates and our hind-casted, pre-incised paleic surfaces.

2. Numerical model of fluvial and glacial erosion

2.1. The method

Continental erosion, especially glacial carving, locally removes material from the surface and unloads the lithosphere activating the buoyancy forces from the Earth interior (Fig. 1A–B). These forces, acting on the effectively elastic lithosphere, trigger isostatic uplift of the lithosphere. Caused by a significant elastic strength of the lithosphere, the horizontal extent of such uplift is usually larger than the scale of the erosion localized, *e.g.*, within fjords; thus, isostatic readjustment results in topographic uplift of surrounding noneroded areas (Fig. 1C). Note that removing material by erosion will always reduce the average elevation of the subjected area, and surface uplift can occur only locally. Thus erosion cannot be a main mechanism for mountain building.

We use a simple quantitative approach by numerically filling the eroded places with crustal material and calculating the additional load. The resultant modeled surface is an approximation of the pre-erosional topography, and simplifications behind the numerical approach does not tie this process to a specific period of time. This allows us to estimate the elastic response and potential vertical movements of surface topography backward in time (Fig. 1D–F). The numerical model utilizes Matlab-based numerical suite ProShell (Medvedev et al., 2008, 2013). Two grids are utilized in the model, one for the surface loads integration and another for calculation of the elastic response. The resolution of the topographic grid is 0.8 km, whereas elastic calculations were mainly performed using a 5-km grid resolution. The topographic data is taken from an SRTM30 digital elevation model (Becker et al., 2009).

The iterative treatment includes several numerical procedures. In each iteration step we find concavities (simply the points within the rectangular mesh with elevation below the average of the four neighbors) and add the material (with density of crustal rocks 2800 kg/m^3) that is required to equalize topography with the neighbors' average. While the redistribution of material is processed on the topographic mesh, the associated isostatic response (using a mantle density of 3300 kg/m^3) is calculated on the elastic plate and is assumed to be

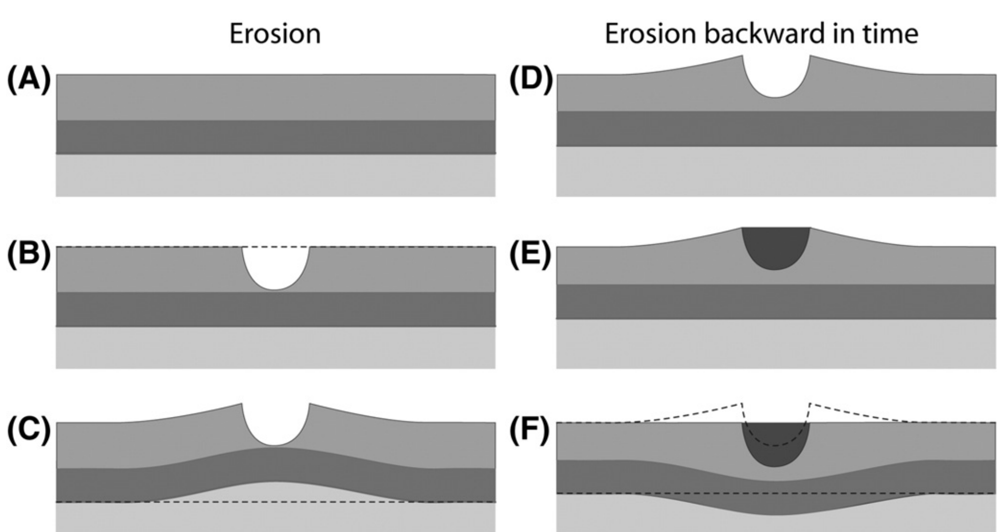

Fig. 1. Illustration of how erosion reshapes topography (A–C) and the model approach used in this study, erosion backward in time (D–F). We consider a simple three-layer lithosphere (not to vertical scale) with an upper layer (gray) passively sitting on top of an elastically strong part of lithosphere (darker gray) that is in turn underlined by an inviscid asthenosphere (light gray). The initial surface (A) is subjected to localized erosion (B) that unloads lithosphere and thus results in isostatic uplift (C). In the erosion backward in time, the localized eroded areas, found to be concave in shape (D), are numerically filled with bedrock material (E) and then used in the calculation of the downward motion caused by the additional load (F). We assume that absolute values of vertical motions in (C) and (F) are approximately equal. Modified after Medvedev et al. (2013).