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Influence of ice sheet and glacial erosion on passive margins of Greenland

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ABSTRACT

The presence of Mesozoic and Cenozoic marine sediments at an altitude of 1.2 km near Scoresby Sund (central east Greenland) and Nuussuaq Peninsula (central west Greenland), and even up to 2 km in the Kangerdlugssuaq region (south-central east Greenland), illustrates significant uplifts of Greenland's margins. The magnitude of these uplifts somewhat contrasts with the absence of major tectonic activity along Greenland margins during the Cenozoic. In this study we test to which degree these vertical motions can be explained by glacial processes. We analyze the influence of the ice sheet loading in the central part of Greenland and the carving of the fjord systems on the evolution of the topography by numerically modeling these processes backward in time. In our experiments, we start with the modern topography and ice thickness and evaluate the pre-glacial topography calculating the flexural isostatic response to unloading the ice sheet. By restoring *erosion backward in time* and calculating the flexural isostatic effects, we estimate the influence of *glacial carving* (hereafter, the carving of the Earth surface by glacial-related erosion) and evaluate the pre-erosional topography of Greenland. Our analyses show that (1) the load of the ice sheet causes up to 850 m subsidence of the bedrock topography of the central part of Greenland. (2) The peripheral bulging caused by this ice loading has a negligible effect on amplitude of the uplifted Greenland margins. (3) Glacial carving and corresponding development of the large fjord system has a significant influence on vertical motion of passive margins of central (east and west) Greenland and can explain up to 1.2 km uplift. (4) The models show, however, that much of Greenland's topography is not caused by ice-related processes, and thus origin of these older mountain chains remains enigmatic. (5) Masses eroded from the regions of significant glacial erosion are larger than the recognized amount of sediments within adjacent off-shore basins, meaning that either the topography of those margins formed before breakup of Greenland or that sediments can be moved far away by the ocean. We also illustrate that our estimations are conservative because of low resolution of the DEMs used for calculations. Higher DEM resolution may increase effects of glacial carving by ~40%.

1. Introduction

The interplay between the thick ice sheet, glacial erosion, and bedrock surface of Greenland is intriguing simply because of the size of the affected area and the volumes of ice and rock involved. Thus, we can expect tectonic scale amplitude of response to such interaction. Fig. 1A illustrates the major masses of ice stored within the Greenland Ice Sheet now. We also can observe the traces of previous activity of ice shaping the margins of Greenland by carving out the fjord systems (Fig. 1B).

Greenland displays a distinct topography with a central depression, surrounded by a near-continuous mountain chain along its coast. The nature of these mountains is enigmatic, given that the mid-Paleozoic orogeny of east Greenland was the last major orogenic event in Greenland (Wilson, 1966; Henriksen, 2008). After that time, the Caledonian mountains first eroded and the topography was first filled with continental deposits; and later in the Permian to Mesozoic, the future margins of Greenland were mostly submerged, as recorded in well-exposed marine deposits now uplifted to mountains (Haller, 1971; Japsen and Chalmers, 2000; Henriksen, 2003, 2008). The western and eastern margins of Greenland record continental rifting, particularly in the late Jurassic to early Cretaceous prior to the Paleogene breakup of the North Atlantic. The breakup is marked by thick layers of basalt, well exposed in central west and east Greenland. During the early Cenozoic, northern Pangea broke up leaving Greenland as a huge microcontinent between North America and Eurasia (Fig. 1A; Bullard et al., 1965; Mosar et al., 2002). During this event, Greenland was displaced northward relative to the adjacent plates (Tessensohn and Piepjohn, 2000), resulting in transpressional deformation (fold and thrust belts) between NW Greenland (Oakey and Stephenson, 2008) and North America and between NE Greenland and Svalbard/Eurasia (Leever et al., 2011). Therefore, north Greenland displays

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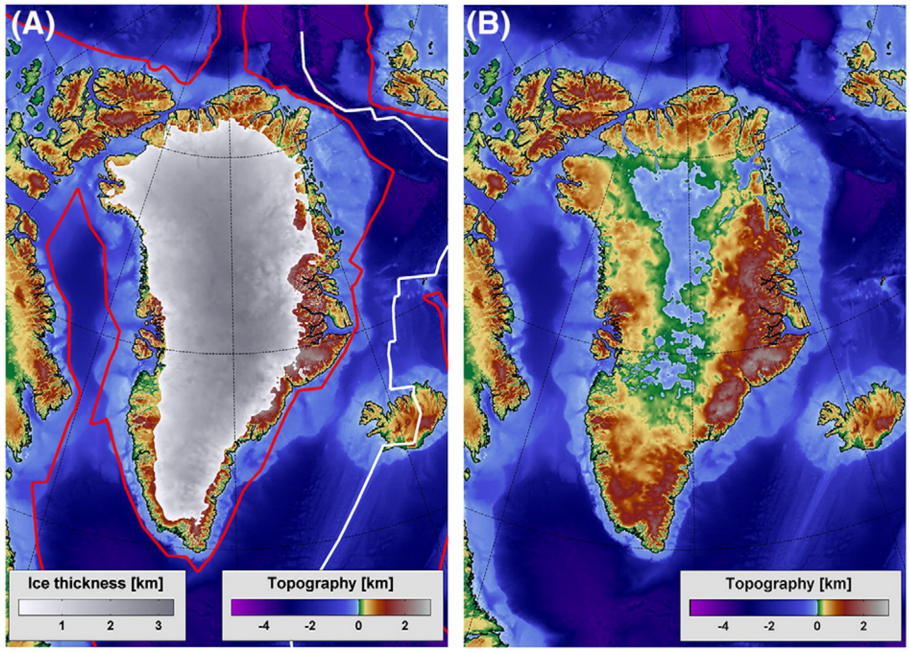

Fig. 1. Map view of the study area. (A) Topography of the region with ice sheet thickness indicated by gray scale (the ice sheet thickness of more than 100 m is presented). Red lines present continent–ocean boundary, and white line separates plates (after Muller et al., 2008). Note that some of the large sedimentary fans, building out from the mount of fjords, extend on to oceanic crust. (B) Bedrock topography.

active margins in the Cenozoic, whereas the margins south of these northern corners are truly passive. In the mid-Cenozoic, opening west of Greenland ceased. About the same time, central east Greenland passed above the Iceland Hotspot, and the Jan Mayen microcontinent rifted off central east Greenland (Fig. 1A; Lawver and Muller, 1994; Gaina et al., 2009).

The modern landscapes of the peripheral part of Greenland are characterized by large fjord systems formed by glacial erosion (e.g., Odell, 1937), locally cutting more than 3 km down from the paleosurfaces. Fig. 2 shows examples from the Scoresby Sund area in central east Greenland. Bonow et al. (2006) presented a study of paleoplateau in the western Greenland, which was cut and tilted during Cenozoic. Erosion processes can be a major mechanism to enhance relief (Gilchrist and Summerfield, 1990; Molnar and England, 1990; Gilchrist and Summerfield, 1991). Combined effect of localized erosion and diffused action of flexural isostasy may result in nonuniform evolution of the topography. A series of recently developed models of flexural isostasy attempts to explain the importance of the surface denudation and resulting isostatic uplift for different geological structures (Pelletier, 2004; Stern et al., 2005; Champagnac et al., 2007; Medvedev et al., 2008; Champagnac et al., 2009; Steer et al., 2012).

In this study we expand the local model of Medvedev et al. (2008) onto the entire Greenland realm (Fig. 1). Medvedev et al. (2008) demonstrated how the carving of fjords and valleys of central east Greenland explains up to 1.1 km of uplift, which also is the maximum elevation of marine Mesozoic sediments of the area. By similar modeling, we test to what degree this process is applicable to the entire Greenland. Considering a region that is much larger than the one discussed in Medvedev et al. (2008), we remove the influence of boundary effects and analyze the degree of ice influence on the different parts of Greenland within the same model.

We first test how the loading of the ice sheet changes the topography of the region. Then we introduce the concept of erosion backward in time and present the results for the entire Greenland. A zoom of our results onto the east and west margins of central Greenland gives numerical estimations of the influence of ice load and carving on the evolution of local topography. We also attempt to evaluate the balance of the erosional products outside the fjords with the topographic cavities inland, checking if one can find correlation in time and space between erosion and deposition.

2. Influence of load from Greenland ice sheet

The Greenland Ice Sheet exceeds 3 km in thickness and covers most of Greenland (Fig. 1A). The bedrock topography of Greenland (Fig. 1B) resembles that of a typical response of an elastic plate subjected to a load in its central part (Fig. 3). The significance of this effect is numerically investigated in the case of Greenland by removing the equivalent weight of the ice sheet and numerically calculating the flexure of the lithosphere from the corresponding isostatic response.

The numerical model utilizes Matlab-based numerical suite ProShell (Medvedev et al., 2008). The model uses two grids, one for the surface load integration and another for calculation of the elastic response. Resolution of topographic grid is 1.5 km, whereas elastic calculations were mainly performed using 7.5-km grid resolution. We checked different resolutions to ensure durability of modeling. We also checked the model results for a range of elastic thickness (EET) values: 15, 20, and 30 km. The ice density used is 930 kg/m^3 and mantle density is 3300 kg/m^3.

The input topographic data used in this work are taken from three different digital elevation models (DEMs): ETOPO2 (developed by the US National Geophysical Data Center), ETOPO1 (Amante and Eakins, 2009), and SRTM30 (Becker et al., 2009) —although we do not discuss results obtained using ETOPO2 as its resolution is too low. Results based on different DEMs were compared for durability. All the global data sets are not exact, especially in the remote areas like the one discussed here. Data on ice thickness is taken from ETOPO1 and from Bamber et al. (2001). In many places within our model domain, the data sets show significant differences (with topography differences up to 600 m and ice thickness data of up to 200 m). We performed careful comparison of results to ensure that our conclusions do not depend on a particular choice of data set.

The results of the calculations show that the central part of Greenland responds significantly (up to ~850 m, Fig. 4A) to the unloading of the ice cap, whereas the associated peripheral bulging is only a few meters (<20 m). Most of the peripheral bulging occurs offshore.