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

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A B S T R A C T
The presence of Mesozoic and Cenozoic marine sediments at an altitude of 1.2 km near Scoresby Sund (central east Greenland) and Nuussuq Peninsula (central west Greenland), and even up to 2 km in the Kangerdlussuq 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 offshore 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%.

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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 (Oakley and Stephenson, 2008) and North America and between NE Greenland and Svalbard/Eurasia (Leever et al., 2011). Therefore, north Greenland displays...
We also attempt to evaluate the influence of the erosion processes on the evolution of local topography. We introduce the concept of erosion backward in time and present the results for the entire Greenland. A zoom of 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 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.
The Scoresby Sund fjord system and Disko Island are the two regions where the peripheral bulging could potentially affect inland topography, but the computed amplitude of the uplift is negligible. Thus, elastic bulging of the lithosphere caused by the ice loading contributes too little to be considered as one of the major mechanisms controlling the uplift of mountains around the Greenland ice sheet.
3. Influence of glacial erosion: general results

The topography obtained after removal of the ice sheet (Fig. 4B) is used as input topography for the numerical experiments of this section. Here we attempt to estimate the influence of the erosional carving along the fjord systems. To this end, we model the erosion processes backward in time (Fig. 5).

Erosion, especially glacial carving, locally removes material from the surface and unloads lithosphere activating the buoyancy forces from the deeper Earth (Fig. 5A–B). These forces, acting on the effectively elastic lithosphere, trigger isostatic elastic uplift of the lithosphere. The horizontal extent of such uplift is usually larger than the scale of the erosion localized, e.g., within fjords, and thus isostatic readjustment may result in topographic uplift of surrounding noneroded areas (Fig. 5C). Note that removing material by erosion will always reduce the average elevation of the subjected area, and uplift may be found only locally.

Quantifying erosional processes is possible only if the initial landscape is known. In our experiments we assume that, by numerically filling the eroded places with crustal material and adjusting it isostatically, we can estimate the elastic response and potential vertical movements of surface topography backward in time (Fig. 5D–F).

The numerical filling of the fjords and corresponding isostatic readjustment (the erosion backward in time) go iteratively. The procedure affects onshore regions between the main mountain chains and the modern shoreline. On each iteration step we find concavities (simply the points within the rectangular mesh with elevation below the average of the four neighbors) and add material (with density of crustal rocks 2800 kg/m³) that are required to equalize topography with the neighbors’ average. While the redistribution of material is processed on the topographic mesh, the associated isostatic response is calculated on the elastic plate and is assumed to be immediate. We repeat this process until no more impactful changes happen to the landscape.

To reduce the number of parameters in the model, we assume that the elastic property of the lithosphere is described by a thin elastic plate with uniform thickness for the entire model domain (Fig. 1). We compare calculations based on EET ranging between 15 and 30 km. Even though, in general, the results do not vary significantly (only several tens of meters in the local uplift) and do not alter the main conclusions, some regional-scale observations better match quantitatively to model with EET = 15 km (central west Greenland) and EET = 20 km (central east Greenland). For the sake of simplicity, we did not consider models with variable EET, which would introduce an additional degree of uncertainty into the models and did not change first-order conclusion. Instead, we compare local observations with model results inferred from models of uniform plate property of corresponding EET.

Fig. 6 presents results of calculations for the case of effective elastic thickness of the lithosphere of 20 km. A significant amount ofinflated material (Fig. 6A, up to 3.1 km) is observed mainly along the major fjords of Greenland and result in significant isostatic flexure of the lithosphere (Fig. 6B, up to 1.2 km in amplitude). We can consider the resulting smooth landscape as the approximation to the pre-erosional landscape of Greenland generated by the model (Fig. 6D).

As discussed above (e.g., Fig. 5), adding material to the upper surface not only elevates topography but may also result in a local decrease in elevation as shown by Fig. 7A. The results also show that the erosional processes do not create the main mountain belt in Greenland, as the pre-erosional mountains are of a similar elevation.

To assess the results, we compare our Greenland-scale model with observations on a regional scale. Fig. 7B presents a ratio of modern topography (Fig. 4B) to the elastic response caused by erosion (Fig. 6B).

Fig. 4. Results of a numerical experiment of removing the ice sheet load. (A) The elastic response indicates significant (0.8 km and higher) central uplift but insignificant (~20 m) peripheral bulging. (B) Bedrock topography of Greenland isostatically adjusted after removal of the ice sheet (cf. Fig. 1B). The calculations were performed using EET = 20 km and ETOPO1 topography and ice thickness. The variations of the parameters and DEMs do not affect the conclusions. This configuration is used as the initial position for calculations of the next parts of the study.
This ratio renders regions where isostatic movements are in the same order as the elevation of the topography. It highlights regions where uplift may be potentially caused by glacial erosion and allows us to choose two areas to discuss in detail in the next sections (Fig. 7B). Other areas also demonstrate the high ratio, but they are either of insignificant topography (areas south from the western square and north from the eastern square on Fig. 7B), or subjected to complex tectonic evolution during Cenozoic (northern Greenland; Oakey and Stephenson, 2008; Leever et al., 2011). Note that to ensure a general approach and to avoid influence of unknown boundary conditions on the numerical models, we do not perform special regional modeling but zoom into the results of the calculations of this section and apply them to the two chosen regions.

Thus, by modeling the effect of glacial erosion on the whole of Greenland, we have been able to estimate the topography and isostatic evolution and to present a model for the pre-erosion landscape. We also show that two particular regions are potentially more influenced by this mechanism than the rest of Greenland.

![Fig. 5. Illustration of how erosion reshapes topography (A–C) and the model approach of this study, erosion backward in time (D–F). We consider a simple three-layer lithosphere (not to vertical scale) with an upper layer (yellow) passively sitting on top of an elastically strong part of lithosphere (orange) that is in turn underlined by an inviscid asthenosphere (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 are assumed as areas with concave shape (D) that we numerically fill with bedrock material (E) and then calculate the downward motion caused by the additional load (F). We assume that absolute values of vertical motions on (C) and (F) are approximately equal.](image)

![Fig. 6. Results of modeling erosion backward in time: (A) amount of material used to smooth the topography and to fill concavities (infilled material), (B) Amplitude of the elastic response to the additional loading (EET = 20 km). Areas with elastic response <20 m are blanked. (C) Resulting topography, which we treat as approximation to pre-erosional landscape.](image)
4. Influence of ice sheet and glacial erosion: close up on central west Greenland

The topography and geology of central west Greenland displays a highly incised enveloping surface with basalts covering Mesozoic marine sediments elevated high above sea level (Japsen et al., 2010). We compare the results of our global model with the regional study published in Bonow et al. (2006), with particular interest in profile B–B′ of their study. This profile (Fig. 8A) goes along the entire Nuussuaq Peninsula. Bonow et al. (2006) pointed to the Mesozoic marine sediments at an elevation of more than 1 km and presented the eastern part of the profile as a remnant of a paleo-plateau formed approximately at sea level (Fig. 8C). Why this plateau is now uplifted by almost 2 km and tilted westward by ~1.2 km remains enigmatic.

The topographic sampling performed in the regional study of Bonow et al. (2006) is much more precise than the data set used in our model (SRTM30). Despite this resolution gap, the topographic signature of the paleo-surface along Nuussuaq Peninsula is easily mapped in our model (Fig. 8C).

Fig. 8C shows that removing the ice sheet changes the elevation of the eastern part of the profile by ~100 m, similar to predictions in Bonow et al. (2006). The erosion, however, has a much stronger influence on the topography evolution. The material added within our model restoring erosion backward in time is illustrated in Fig. 8C (blue fill). By restoring up to 1 km of erosion backward in time, the profile is smoothed toward a plateau. However, the most significant downward motion of profile is caused by the regional isostatic response to filling (backward in time) the fjords adjacent to Nuussuaq Peninsula, Uummannaq and Vaigat, where the amount of material adds up to 3 km (Fig. 8A).

By reversing the backward in time model we estimate the role of glacial erosion and ice loading within the evolution of landscapes of Nuussuaq Peninsula and the surrounding area. Significant glacial erosion results in carving the paleo-plateau and uplifting it by up to 0.8 km (out of a total of 2 km). Additionally, uneven glacial erosion and ice loading contribute to the eastward tilt of the chosen profile by 0.5 km (out of a total of 1.2 km).

The western part of the profile shows the presence of marine sediments at a high elevation (1.2 km, Fig. 8B). The total erosion-related uplift in that area (the difference between green and blue lines on Fig. 8C) is only 200 m. However, this particular area of the global DEM (SRTM30) used in the global model for Greenland is rather inaccurate. Thus, the low (200-m) rise of the peak with marine sediments probably reflects data resolution used in numerical simulations. All other dominating peaks in the area have risen by ~700 m, which is more than half of the elevation of the marine deposits.

The results of this section show that ice loading and glacial erosion contribute significantly to reshaping the landscapes of central west Greenland. The results presented in this section are based on DEM SRTM30 and an effective elastic thickness of 15 km. Variations of data (using ETOPO1 and/or different elastic thicknesses) give similar results with quantitative effects within a 10% variation.

5. Influence of glacial erosion on the evolution of central east Greenland

The topography of central east Greenland is dominated by prominent fjord systems: Scoresby Sund, Kong Oscar, and Kejser Franz Joseph Fjords (Fig. 9A). The largest, Scoresby Sund, is ~400 km long, up to 60 km wide, and in some areas cuts more than 2-km-high paleosurfaces (Fig. 2A) to a depth of 1.5 km below sea level. Medvedev et al. (2008) pointed out that the mountains between fjords are almost as high as the adjacent main mountain chain but are not supported by thickened roots (Schmidt-Aursch and Jokat, 2005) and that the high elevation of these mountains may be a result of significant erosion. The same
mechanism was suggested to explain Mesozoic marine sediments uplifted up to 1.2 km in the fjord area (Fig. 2B, Henriksen, 2003). The erosional unloading of this region has resulted in up to 1.1 km isostatic uplift (Medvedev et al., 2008). In the present study we revisit the area, mainly considering evolution of the upper surface using the results obtained while modeling the entirety of Greenland. The result of the global model zoomed into the area indeed shows that the elastic isostatic response, 0.4–1 km, may indeed explain the amount of uplift in the areas of Mesozoic marine sediments (Fig. 9B). However, the model assumes filling up the concave shapes even on a large scale; thus the pre-erosional landscape of the areas of marine sediments is well above sea level, even after isostatic readjustment is applied. Although the pre-erosional elevation in those areas is not high (mainly below 0.5 km), we cannot expect that marine sediments would be accumulated in such areas. To explain the uplift of marine sediments within our simple model, we have to find an alternative approach.

The model presented in this study is based on elastic plate response to loading and unloading caused by glaciations and erosion. We also assume that the isostatic response is immediate (essentially assuming that asthenosphere underlying the lithosphere is inviscid). Thus, our model does not have explicit time-dependence. Moreover, the model is additive in time and space: effects caused by loads separated by time and space can be calculated separately, and the sum of responses is equal to the response of the summarized load. Thus, we can suggest the model in which some parts of the Scoresby Sund area were eroded earlier than others.

In the modified model (Fig. 9C, D) we assume that the landscape of the central east margin covered by marine sediments was formed earlier than the surrounded regions. This assumption is supported partially by the Swift et al. (2008) study, which shows that a portion of landscapes in the area was developed before breakup of Greenland and Eurasia.

Fig. 9(C and D) presents the results of the model in which the area characterized by Mesozoic marine sediments (within the yellow line on Fig. 9) subjected to erosion backward in time only if below sea level. The rest of the model (entire Greenland) is subjected to the same procedures as before (e.g., Fig. 6). The elastic response in the area, even though still significant, becomes smaller (up to 0.7 km on
Fig. 9. Results zoomed to central east Greenland. (A) The modern day topography. (B) Model results with color coding of the pre-erosional topography with black isolines of elastic response in kilometers. (C) Results for the model with the special treatment of the marine sediments with black isolines of elastic response in kilometers. Note that most of the marine sediments are below sea level on (C). (D) Elevation changes caused by erosion within the modified model. The yellow line outlines the locations of marine sediments along the east coast of Greenland (Henriksen, 2003) and in Kangerdfluussuaq area (Myers et al., 1998). White square in (A) shows location for analysis presented in Fig. 10, white stars indicate locations of photographs in Fig. 2. Geographical locations on (A): SS = Scoresby Sund, JL = Jameson Land, KO = Kong Oscar fjord, KFJ = Kajser Franz Joseph fjord.
Fig. 9C vs. 1.2 km on Fig. 9B). However, the resulting pre-erosional topography is almost entirely below sea level within the area of marine sediments (with maximum topography of 0.5 km on Fig. 9D vs. up to 1 km on Fig. 9C). The load from the fjord infill in the surrounding areas is strong enough to bring the margin with marine sediments under water within our erosion backward in time model. Henceforth, erosion (considering real time evolution) results in uplift of marine sediments up to 300–600 m (Fig. 9D).

Results presented in this section show that erosion of the central east Greenland margin may result in the uplift of the Mesozoic marine sediments of the area well above sea level. The preferred model requires that the landscape of the most outer part of the margin was formed prior to the internal part.

6. Discussion

In our calculations, based solely on geometrical definitions of cavities and immediate elastic response of the lithosphere, we cannot constrain the time of evolution. Post-processing of mass redistribution can give us a time scale for the model. The model allows us to calculate the masses involved in the erosion process and compare them with the amount of offshore sediments, which we have attempted to average from published profiles of offshore Greenland (e.g., Chalmers et al., 1993; Chalmers, 2000; Hamann et al., 2005; Tsikalas et al., 2005; Japsen et al., 2006; Berger and Jokat, 2009). Even though the data on the amount of off-shore sediments is sparse, we may conclude that the masses eroded from central east Greenland are much larger than the amount of sediments accumulated in adjacent offshore areas. Similar conclusions may be drawn for western Greenland, but with less certainty, as the difference is not that significant. Two obvious mechanisms may explain this inequality: (1) the eroded material travels long distance; and (2) the landscape was (partially) formed before breakup of the surrounding oceans (Fig. 1A). The latter mechanism is supported by geomorphological and stratigraphical studies of Swift et al. (2008) on central east Greenland. However, even quantitative analysis needs more data on offshore sediments.

The model presented in this study is highly sensitive to the resolution of the mesh used to calculate the topographic changes and the DEM. In the models we use SRTM30 and ETOP01 data sets (~1-km resolution) and the mesh resolution of 1.5 km is dense enough to catch the features of DEM. However, higher resolution topographic data would record more dramatic topography, which then gives the model more cavities to fill and amplifies the effect of isostatic response.

To test the sensitivity to topographic resolutions we calculate the total volume trapped between the topography and the convex envelope in several sample localities in the Scoresby Sund area using different DEMs. Fig. 10 demonstrates significant differences in topography of one sample area using SRTM30 and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer, a joining venture of METI and NASA) data (prepared by the NASA LP DAAC, USGS/EROS Center). In the areas of comparison, high resolution data reveals 30 to 49% more space between the DEM and the enveloping surface. The most significant contribution to that difference brings higher topography variations (peaks are higher and valleys are deeper) within the higher resolution DEM (cf. Fig. 10A and B). Thus, the erosion-related (un)loading performed in this study and based on the global DEM (Fig. 10A) may be significantly smaller than in reality.

We already discussed some specific problems of low resolution of our model when the marine sediments on the western part of the Nuussuaq Peninsula profile (Fig. 8B) were addressed. These marine sediments are located on the peak that simply does not exist in the DEM used here (SRTM30 in this case). Hence, this significant uplift of marine sediments cannot be discussed within the model.

Simplifications of our model in addition to an absence of the high resolution global DEM for Greenland (especially concerning thickness of the ice sheet and fjords depth) preclude us to use higher resolution. Nevertheless, the local tests (Fig. 10) show that estimates of eroded masses, and thus erosional uplift, presented in this study are conservative.

In our numerical experiments we only consider the influence of ice load and erosion caused by ice. Even though we demonstrated that these mechanisms play a significant role in land-forming processes along Greenland margins, other mechanisms may contribute. One of those processes is a significant thickness of 55 Ma mafic intrusions recorded in the locations considered in our study (e.g., Henriksen, 2008; Fig. 2B). Intrusions of 5–10% into several kilometers thick marine sediments may result in uplift counted in hundreds of meters. The concentration of intrusions roughly corresponds to the areas of sediments remaining above sea level in Fig. 9C.

The results of our calculations (Figs. 6 and 7) show that glacial erosion in northern Greenland has a potentially high influence on landscape forming. That part of Greenland, however, experienced collision with North America (Ellesmere Island, west) and Eurasia (Svalbard, east) in the latest Mesozoic to early Cenozoic when Greenland moved northward (Tessensohn and Piepjohn, 2000). Thus, the landscape of that nonpassive margin of Greenland was subjected to active deformation, and the analysis presented in our study (based solely on the erosion process) may be misleading.

Fig. 10. Examples of topography derived from two different data sets: (A) SRTM30 (resolution 30 arc sec or 0.5–1 km) and (B) from Aster data set (resolution 1 arc sec, approx. 30 m). We use SRTM30 and ETOP01 in our calculations because of lack of global data with high resolution (especially the lack of ice-thickness data). Vertical exaggeration is 10 times. Location of this example area is outlined in Fig. 9A. The color-scale of these figures is the same as on all other topographic figures.
The other part of the Greenland margin that represents enigmatic uplift is the area south of Scoresby Sund (Kangerdlugssuag region; Fig. 9). Whereas the geology of Scoresby Sund and northward is dominated by widespread sedimentary rocks covered by a thin layer of basalt, the area south of the fjord has only a thin layer of Cretaceous to Paleogene marine sediments covered by a kilometer-thick basalt layer. These southern marine deposits rest as much as 1 km higher than the northern deposits (Myers et al., 1998). This is enigmatic, partly because of the considerable load of overlying basalts, which should have loaded the marine deposits even deeper, but also because the region is little incised, so that erosional uplift only amounts to 0.4 km for the region while the sediment rests at an elevation of up to 2 km (Fig. 9B or C). Clearly an alternative and dominant source of uplift is needed here. These high altitude marine deposits sit directly on the Iceland hot spot track, where Kangerdlugssuag passed above the present day position of the Iceland plume at 30 Ma (Lawver and Muller, 1994). The age fits roughly the apatite fission track ages of the region (Hansen, 1996); and thus, this mid-Cenozoic uplift is likely related to the hotspot interaction with the Greenland lithosphere, although the exact mechanism of such interaction and resulting uplift is not yet understood.

7. Conclusions

We quantified the effects of ice-related processes on shaping margins and the internal part of Greenland. These effects include the influence of the load of massive ice sheets on the Greenland topography and the influence of significant erosion caused mainly by glacial carving. Our results show:

- Whereas the isostatic response to the load of the Greenland ice sheet is significant, more than 800 m in some areas, within central Greenland peripheral flexural bulging is an inefficient mechanism in generating topography along Greenland's margins.
- Glacial carving may introduce major vertical motions on the Greenland margin and be a major contributor to landscape forming. Our study allowed outlining the areas where this mechanism is potentially important.
- We demonstrate how regional observations may be explained using the global model of Greenland evolution and considering the erosion backswing in time. In particular, we consider to which degree erosion may contribute to uplift and tilting of Neuussuaq Peninsula (central west Greenland) and how Mesozoic marine sediments could have been uplifted in the central east Greenland margin.
- Our numerical experiments with different resolutions of topographic data show that the estimation of uplift is conservative.
- We point out some regions with significant vertical motions that cannot (Kangerdlugssuag region with Cretaceous marine sediments at ca. 2 km altitude and only 0.4 km erosional uplift) and should not (e.g., northern Greenland, which is subjected to rather recent tectonic deformations) be analyzed within our purely erosional model.
- Our model allows considering the mass balancing processes within and around Greenland; however, this type of study requires more data on the offshore sediment structure around Greenland. The first-order observations show that the volume of offshore sediments in the mouth of the Scoresby Sund fjord system is largely insufficient to balance the amount of eroded material inland. This could suggest either that the topography of the fjord is older than the removed Cenozoic offshore sediments and may be linked with other Mesozoic basins around the continental shelf or that a large proportion of sediments were lost by drifting away from the shelf.

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