Widespread glacial erosion on the Scandinavian passive margin

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ABSTRACT

The topography in Scandinavia features enigmatic high-elevation low-relief plateau regions dissected by deep valleys and fjords. These plateau regions have long been interpreted as relict landforms of a preglacial origin, whereas recent studies suggest they have been modified significantly by glacial and periglacial denudation. We used late Pliocene–Quaternary source-to-sink analyses to untangle this scientific conundrum. We compared glacier-derived offshore sediment volumes with estimates of erosion in onshore valleys and fjords and on the inner shelf. Our results suggest that onshore valley and fjord erosion falls 61%–66% short of the offshore sink volume. Erosion on the inner shelf cannot accommodate this mismatch, implying that the entire Scandinavian landscape and adjacent shelf have experienced significant glacial erosion.

INTRODUCTION

The characteristic high-elevation low-relief plateau regions in Scandinavia have traditionally been interpreted as remnants of a preglacial surface, with glacial erosion limited to overdeepening of existing valleys (e.g., Lidmar-Bergström et al., 2000; Japsen et al., 2018). On the contrary, others have proposed that both valleys and plateau regions have been modified by glacial and periglacial erosion, with plateau formation *in situ* at high elevation (Nielsen et al., 2009; Steer et al., 2012; Pedersen et al., 2016; Egholm et al., 2017; Andersen et al., 2018a, 2018b).

Earlier work has shown that fjord incision alone cannot account for the erosional volumes deposited offshore during glacial times, indicating several hundred meters of erosion on the plateau surfaces (Steer et al., 2012). However, others have since argued that this excess material can be accounted for by erosion of Mesozoic and Cenozoic sediments on the inner shelf (Hall et al., 2013) that are cropped by the glacial sediments in a prominent angular unconformity of Middle Pleistocene age (e.g., Sejrup et al., 1995). However, constraining the volume ascribed to inner-shelf erosion is diffi-

cult. Estimates are influenced by extrapolation of the subcrops onto onshore basement regions and any assumptions such extrapolations make about past topography (Riis, 1996). Particularly, inner-shelf erosion cannot be assumed to be uniform in this narrow zone along the coast, as it has recently been presumed (Hall et al., 2013).

We quantify inner-shelf erosion with an approach that is consistent with onshore-offshore profiles from the region and extends inner-shelf erosion estimates to the whole margin. This allows us to include inner-shelf erosion in quantitative source-to-sink analyses. In our approach, we consider flexural isostatic effects related to erosion and deposition as well as dynamic surface changes from mantle convection (Fig. 1C; Pedersen et al., 2016) that could result in exposure and erosion of preexisting shelf sediments. Quantifying the contribution from inner-shelf erosion to the late Pliocene–Quaternary sediment budget allows us to infer onshore erosion beyond the glacial troughs.

METHODS

Our comparison of the late Pliocene–Quaternary glacier-derived offshore sediment volume (V_{sed}) with estimates of onshore fjord and valley bedrock erosion (V_{fjord}) and inner-shelf sediment

erosion (V_{shelf}) allows us to assess the largely unknown onshore bedrock erosion volume beyond glacial troughs, $V_{onshore}$:

$$V_{onshore} = V_{sed}\left(1 - \varphi_{sed}\right) - V_{fjord} - V_{shelf}\left(1 - \varphi_{shelf}\right),\tag{1}$$

where φ_{sed} and φ_{shelf} represent porosities of glacier-derived offshore sediments and sediments eroded from the inner shelf, respectively.

The offshore sediment volume (Fig. 1B) includes late Pliocene–Quaternary sediments on the Norwegian margin (Naust Formation; Rise et al., 2005), sediment volumes of a similar age from the Norwegian part of the North Sea (Gołędowski et al., 2012), and the Quaternary sediment package from the Danish region (Binzer et al., 1994; Nielsen et al., 2008). Offshore regions north of Lofoten were excluded because the Scandinavian contribution is not well constrained. On the Norwegian margin, the outer parts of the Storegga slides were omitted, resulting in a negligible underestimation of the sink volume. In the North Sea, we included only the Norwegian and Danish sectors, corresponding to the northeastern rim of the basin (Fig. 1B). This conservative estimate is consistent with recent work on Quaternary sediment infill from the Scandinavian region (Ottesen et al., 2018), with other regions being dominated by infill from British river systems from the west and from the Baltic (Eridanos), the Rhine-Meuse (Europe), and Thames (UK) river systems from the south (e.g., Gibbard and Lewin, 2016; Lamb et al., 2018).

We use the concept of geophysical relief (e.g., Small and Anderson, 1998) as a proxy for onshore erosion in valleys and fjords (Fig. 1B). Calculations were based on a 1 × 1 km digital elevation model (GEBCO Compilation Group, 2019) using a previously calibrated

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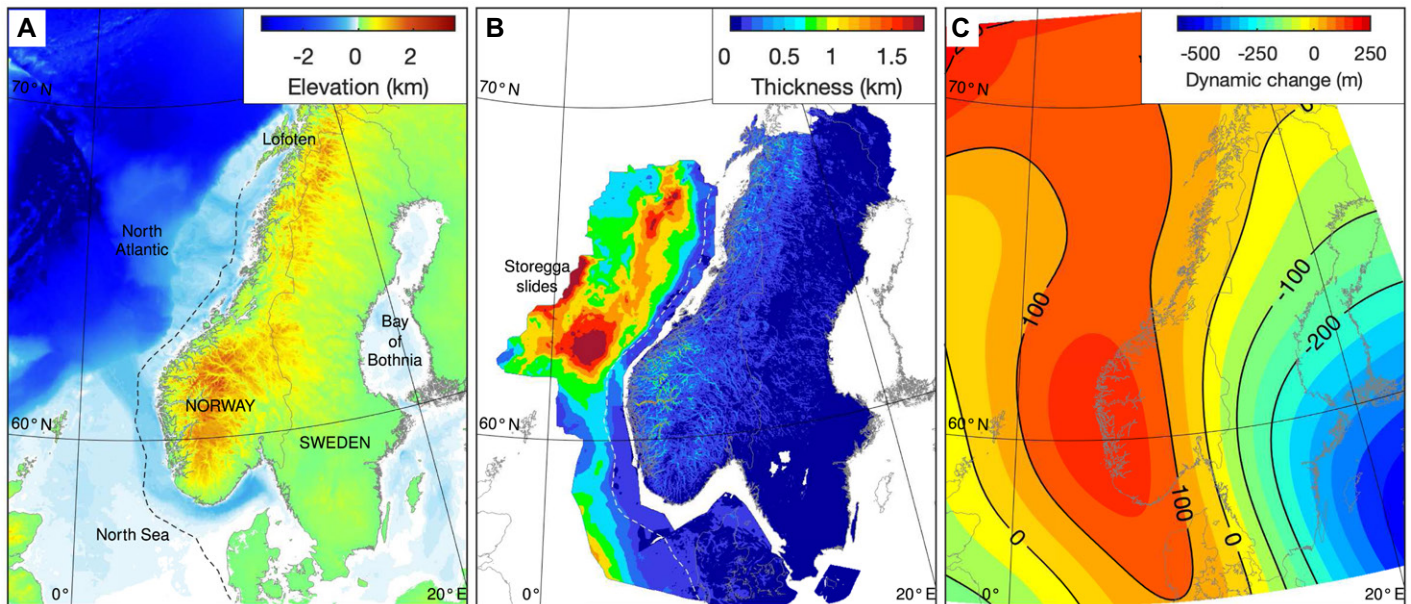
Figure 1. (A) Present-day topography and bathymetry of the Scandinavian region. (B) Offshore sediment thickness compared to estimated fjord and valley erosion from the onshore source region (see details in the text). (C) Dynamic surface changes due to mantle convection (30–0 Ma). Dashed lines in A and B mark base-Pliocene subcrop below Quaternary sediments, used to define the basinward extent of inner-shelf erosion (Figs. 2B and 2C).

radius of 2 km (Steer et al., 2012). To match the depositional sink, we excluded catchments in northern Norway that drain north toward the Barents Sea, as well as regions east of the Bay of Bothnia, where the former Scandinavian Ice Sheet drained east during glacial times, and where the Baltic (Eridanos) river system drained material to the southern and central North Sea Basin (e.g., Gibbard and Lewin, 2016; Lamb et al., 2018; Ottesen et al., 2018).

In order to assess erosion volumes on the inner shelf, we first reconstructed preliminary preglacial topography and bathymetry (Fig. 2). We removed the offshore late Pliocene–Quaternary deposits and filled in onshore valleys and fjords using our erosion estimates from geophysical relief. We calculated flexural isostatic adjustments from these load changes using the open-source gFlex version 1.0 model (Wickert, 2016). We adopted a Young's modulus of 70 GPa, Poisson ratio of 0.25, and densities of 1029 kg/m^3, 2300 kg/m^3, 2670 kg/m^3, and 3300 kg/m^3 for water, sediment, eroded bedrock, and mantle, respectively. Guided by studies of effective elastic thickness (T_e) in Scandinavia (Pérez-Gussinyé and Watts, 2005), we used constant T_e values between 10 and 25 km. Finally, we considered estimates of dynamic topography from global mantle convection models that suggest modest uplift in southwestern Norway in the late
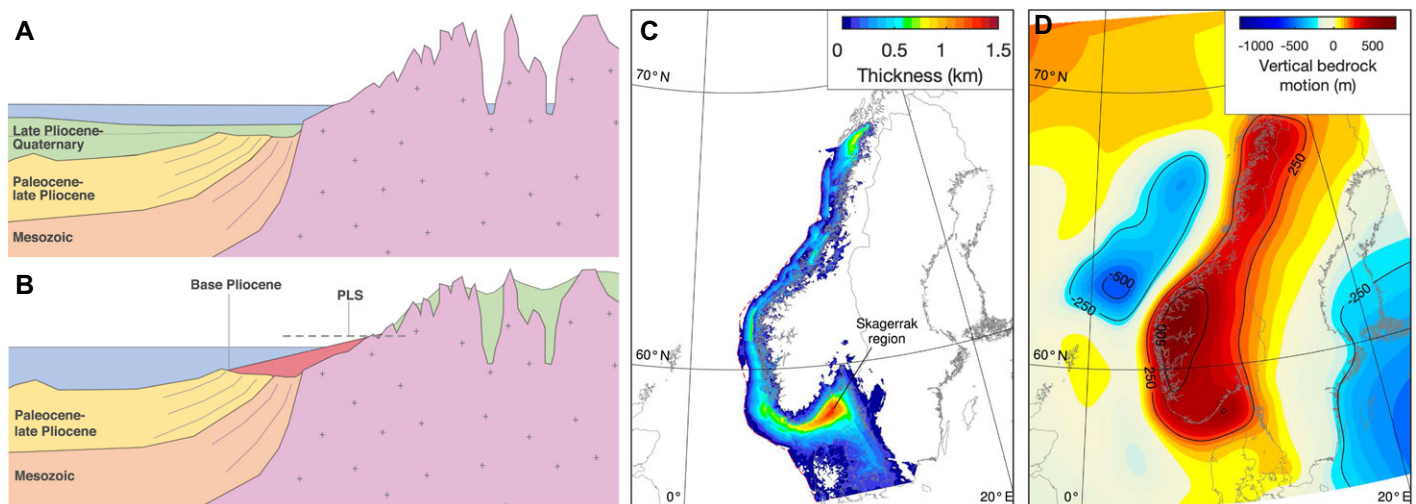
Figure 2. (A) Schematic section of the current margin architecture on the Scandinavian passive margin, with late Pliocene–Quaternary sediments overlying older Cenozoic and Mesozoic sediments that subcrop an angular unconformity of Middle Pleistocene age. (B) Schematic section of the reconstructed margin, with late Pliocene–Quaternary sediments replaced onshore in valleys and fjords, and reconstructed inner-shelf wedge of eroded sediment (see details in text). Panels A and B are not to scale. (C) Map view of reconstructed shelf wedge thickness (effective elastic thickness T_e = 15 km, paleo–sea level [PLS] = 150 m, with dynamic surface change). (D) Vertical bedrock motion from dynamic changes (Fig. 1C) and flexural isostatic adjustments owing to offshore deposition (Fig. 1B) and erosion (inner-shelf [C], valleys and fjords [Fig. 1B], and uniformly distributed onshore bedrock erosion volume, $V_{onshore}$, resulting in 152 m of uniformly distributed bedrock).

Cenozoic, thereby exposing preexisting shelf sediments to erosion (Fig. 1C; Pedersen et al., 2016). Because of the uncertainties associated with the amplitude of these dynamic changes (Pedersen et al., 2016), we present results with and without this component along with an alternative scenario proposing additional dynamic changes associated with mantle flow.

Based on the preliminary reconstructed preglacial topography and bathymetry, we reconstructed a shelf wedge of eroded sediment (Fig. 2C). This wedge is defined by linear interpolation, with its outer position corresponding to the isostatically corrected base Pliocene subcrop below the Middle Pleistocene angular unconformity (Sigmond, 1992; Japsen et al., 2007). We note that this approach neglects reworking of Pliocene units distinct from the Naust Formation, which are thin or absent in many places (e.g., Faleide et al., 2002). The inner delimitation of the wedge is defined by the intersection of the reconstructed topography with a maximum paleo–sea level that existed during the deposition of the cropped Mesozoic and Cenozoic sediments (Figs. 2A and 2B). Here, we assume that sea level was a maximum of ~100–150 m higher than today during the deposition of these older Mesozoic and Cenozoic sediments (Miller et al., 2011). Because the load of the reconstructed shelf wedge would result in isostatic subsidence of the preliminary reconstructed topography and bathymetry, the shelf wedge was redefined iteratively until its volume converged.

The porosity of the eroded shelf wedge is largely uncertain. However, values between 15% and 34% have been reported for Middle Jurassic–Lower Cretaceous units further offshore, and a similar range is assumed for the Cenozoic (Halland et al., 2014). We therefore present shelf wedge volumes using a porosity range of 15%–30%.

RESULTS

We estimate a total bedrock erosion in valleys and fjords of ~99 × 10³ km³ (Fig. 3; Table S1 in the Supplemental Material[1]), similar to previous work (Steer et al., 2012). Conversely, our compilation of offshore sediment volumes results in an estimated total volume of ~364 × 10³ km³ sourced from the Scandinavian region and the adjacent shelf (Fig. 3). This sink volume is ~55% larger than previously reported values (Steer et al., 2012) because we now include the Danish region and part of the North Sea Basin in
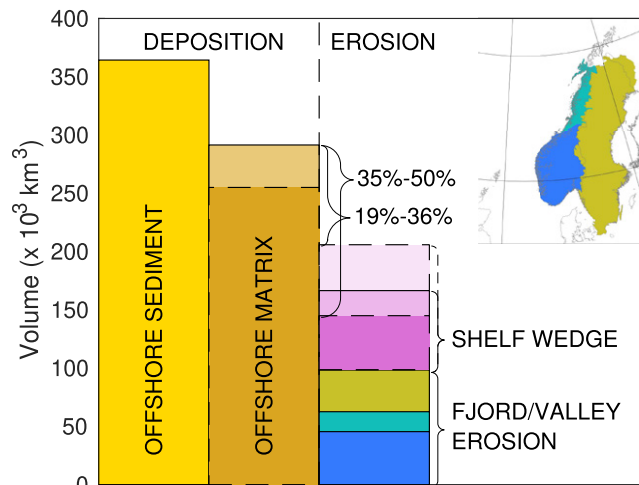
Figure 3. Sediment budget: offshore sediment volume (yellow), offshore matrix volume range (brown: 30% porosity, light brown: 20% porosity), and fjord and valley erosion (color-coded based on region; see inset) for the Scandinavian passive margin. The volume range of inner-shelf erosion is shown in pink colors (range is detailed in the text), with lightest pink representing inner-shelf erosion with an additional 200 m of dynamic change (Fig. S1G–S1I [see footnote 1]]) See the summary in Table S1.

addition to the Norwegian margin. The sediment volume converts to a matrix volume between 255 × 10³ km³ and 291 × 10³ km³, assuming a mean porosity of 20% (Storvoll et al., 2005; Dowdeswell et al., 2010) to a more conservative estimate of 30%, respectively. Compared with valley and fjord erosion, this results in a mismatch of ~61%–66%, suggesting that >60% of the sediment must have come from erosion outside of the fjords and large valleys.

The reconstructed shelf wedge has a maximum thickness >500 m along most of the Norwegian coast, with a maximum thickness >1300 m in the Skagerrak region, where the Norwegian Channel cuts deeply into older sediments (Fig. 2C). Our shelf-wedge volume estimates vary between 46 × 10³ km³ and 68 × 10³ km³ depending on the assumed sediment porosities (φ_{sed} and φ_{shelf}), paleo–sea level, T_e, and dynamic surface changes (Fig. 3; Table S1).

By including the volumes associated with inner-shelf erosion, we reduce the mismatch between erosion and deposition to 35%–50%. However, this still leaves a considerable portion of the sink (89 × 10³ km³ to 147 × 10³ km³) to have been eroded elsewhere. If we distribute this mismatch evenly over the contributing regions (Fig. 3, inset), it amounts to 117–194 m of erosion. The majority of this uncertainty range (~63 m) stems from porosity uncertainties (φ_{sed}, φ_{shelf}), with the remaining ~14 m stemming from our assumptions on paleo–sea level, T_e, and dynamic surface changes (Table S1).

Combined, dynamic topographic changes and isostatic deflections related to erosion and deposition result in significant vertical bedrock motions in Scandinavia, with >500 m of subsidence offshore and several hundred meters of uplift of onshore and inner shelf regions (Fig. 2D; Figs. S1–S3).

DISCUSSION

Our conceptual framework for quantifying erosion volumes on the inner shelf is based on well-established processes only, related to eustasy and isostatic changes from erosion and deposition, and with a flexible assumption on dynamic surface changes from mantle flow.

A previous conceptual approach has instead extrapolated the older Mesozoic and Cenozoic sediment packages onto an envelope surface constrained by block fields at high elevations (Riis, 1996). Such an approach relies on the assumption that the weathered mantles that cover parts of the plateau regions have a preglacial origin. This was suggested based on the occurrence of secondary minerals such as gibbsite and kaolinite that are attributed to weathering under a pre-Quaternary warm and humid climate (Rea et al., 1996; Strømsøe and Paasche, 2011). However, it has recently been demonstrated that a small amount of secondary minerals within blocky weathering mantles is consistent with formation under cool Quaternary climates and erosion rates of several meters per million years (Goodfellow et al., 2014; Andersen et al., 2018b). In addition, it is evident that most plateau surfaces in (southern) Norway display abundant evidence of glacial scouring; surface morphologies are dominated by exposed, streamlined bedrock dotted by lake basins (Andersen et al., 2018a, 2018b).

With our approach, we estimate inner-shelf erosion volumes that are similar to those presented by Hall et al. (2013), where material was modeled as being added uniformly to a narrow zone of fixed width along the coast. However, our expanded offshore sediment sink now warrants a different interpretation. Even with our conservative estimate, in which we distribute the mismatch uniformly throughout southern and central Norway and Sweden, we find that significant erosion (117–194 m) must have taken place outside the large valleys and fjords onshore in Scandinavia during glacial times.

Recent work suggests that such significant glacial erosion beyond large valleys and fjords is consistent with the occurrence of high

concentrations of cosmogenic nuclides at high elevations in Scandinavia (Egholm et al., 2017), even though these data have traditionally been interpreted as evidence for a preserved preglacial landscape. Concurrent numerical modeling of landscape evolution and cosmogenic nuclide concentrations (Egholm et al., 2017) indicates that high-elevation regions have experienced a gradual deceleration of glacial erosion rates over the Quaternary as ice is increasingly funneled through deepening glacial troughs. The effect is enhanced by erosion-driven isostatic uplift that moves the low-relief surfaces from warm-based to cold-based conditions (Steer et al., 2012). Such a gradual deceleration of erosion rates and the eventual development of cold-based nonerosive conditions reconciles erosion estimates of <5 m during the past million years from inverse modeling of cosmogenic nuclide data (Andersen et al., 2018a; Jansen et al., 2019) with hundreds of meters of erosion since glacial inception. The gradual development of cold-based conditions also explains the preservation of blocky weathering mantles formed at high elevations in Scandinavia within the late Quaternary.

We note that the dynamic surface changes utilized here may underestimate late Cenozoic surface uplift in the Scandinavian region. This is implied from studies of isostatic support of the present topography, suggesting dynamic uplift of as much as 400 m in westernmost Scandinavia (Pedersen et al., 2016). Therefore, we assess the effect of adding a mean of 200 m to the dynamic component throughout the region, resulting in close to 400 m of dynamic uplift in westernmost Scandinavia. This scenario increases the estimated inner-shelf erosion volume by ~60% (Fig. S1G–S1I), it reduces the mismatch between erosion and deposition to ~19%–36% (Fig. 3, lightest pink) and reduces the required erosion outside large valleys and fjords to 35–103 m. However, part of this dynamic uplift likely predates our offshore sink (Pedersen et al., 2016). In addition, past sea-level changes and other processes related to breakup of the North Atlantic could have caused transient surface uplift and inner-shelf erosion. Earlier unconformities related to such erosion events would have been erased by the Middle Pleistocene unconformity that we observe today. If part of the shelf wedge were eroded prior to the late Pliocene, the importance of shelf wedge erosion for our late Pliocene–Quaternary source-to-sink analyses would be proportionally smaller, resulting in a larger mismatch and a stronger case for onshore late Pliocene–Quaternary erosion beyond glacial troughs.

CONCLUSIONS

Here we have presented a sediment budget calculation in which we compare glacier-derived offshore sediment volumes from the late Pliocene–Quaternary with erosion by onshore valleys and fjords and older Mesozoic and Cenozoic sediments on the Scandinavian margin inner shelf. Our estimates show a large mismatch between the offshore sediment sink volume and onshore erosion sourced from valleys and fjords. The mismatch is ~85% larger than previous estimates (Steer et al., 2012), despite similar estimates of onshore erosion. Erosion of older Cenozoic and Mesozoic sediments on the inner shelf cannot entirely accommodate this mismatch as previously suggested (Hall et al., 2013). We conclude that the entire Scandinavian landscape, including high-elevation low-relief regions, must have experienced significant erosion during glacial times. A conceptual model of decreasing erosion on the plateaus as fjords deepen aids in reconciling this (Egholm et al., 2017). The high-elevation low-relief surfaces should therefore not be regarded as remnants of a preglacial surface.

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