# Quantitative Comparison of Offshore Sediment Volumes and Onshore Erosion Potential in Norway in the Neogene and Quaternary.

Master Thesis

Åsne Rosseland Knutsen

Department of Earth Science

University of Bergen

June 2018

# Abstract

The geodynamic evolution of the Scandinavian topography is the cause of a controversy with several competing hypotheses. Western Scandinavia is characterized by dramatic fjords and high-altitude low-relief surfaces, which is interpreted by mainly two end-member hypotheses. The first hypothesis interpret that the landscape has been eroded down to sea level in Mesozoic, uplifted in Cenozoic and has then been eroded by fluvial and glacial erosion. On the other side of the controversy, is the ICE (isostasy-climate-erosion) hypothesis, which interpret the landscape to be remnants of the Caledonian orogeny, where the topography has been exposed to climate-dependent erosion and isostatic uplift. The motivation for this thesis is therefore to attempt to expand our knowledge and understanding of the hypotheses that are trying to explain the Scandinavian topography.

I this thesis, the attempt is to quantitatively compare the Pliocene-Pleistocene offshore sedimentation volume, deposited in the North Sea and along the Norwegian margin, with onshore erosional potential in Norway. This is done by reconstructing the topography, bathymetry and the shelf. Reconstruction of the shelf is based on a new concept, where sediments are re-placed, in a wedge kind of shape, between the Miocene-Pliocene boundary in the west and up to relative sea level at the coast. Estimates of onshore erosional potential consists of fjord and valley erosion, calculated with the geophysical relief method, and inner shelf and coast erosion, which is based on the difference between reconstructed topography and reconstructed shelf.

There are several components causing an uncertainty to the results. The reconstructions and volume estimates are tested with varying paleo sea level (PSL) values, porosity and radius for the geophysical relief calculations, which result in a wide range of mismatch volume. When including the assumed realistic values for the uncertainties, there is still some sediment volume offshore that cannot be explained with onshore fjord and valley erosion, and inner shelf and coast erosion. This gives the indication that there must have been erosion coming from somewhere else, e.g. high-altitude low-relief surfaces. Furthermore, due to the high PSLs needed to get an onshore-offshore balance, this indicate that there has been some dynamic uplift along the coast.

## Acknowledgements

I would like to thank my supervisor Ritske S. Huismans for the opportunity of this thesis.

To my co-supervisor Vivi K. Pedersen, thank you for all the guidance throughout these two semesters. You have helped me stay motivated, with a positive attitude and a helping hand whenever I needed it.

To my friends – thank you for the many study breaks, and all the memorable moments throughout my years as a student.

Last, I would like to thank my family and boyfriend for the support, and for always believing in me.

# Table of Content

# 1. Introduction

The Scandinavian landscape is characterized by a general high topography, spectacular fjords and high-altitude low-relief surfaces. However, the geodynamic evolution of western Scandinavia has caused some controversy with various competing hypotheses. The Norwegian continental margin is one of several glaciated passive margins (GPM), which have been studied by many authors (e.g. Japsen, 1998, Lidmar-Bergström et al., 2000, Nielsen et al., 2009, Hall et al., 2013), in order to establish timing, patterns and rates of glacial erosion and deposition (Hall et al., 2013). This is important for understanding the long-term landscape development, uplift mechanisms (in Cenozoic), and also the burial and erosion history of hydrocarbon traps (Hall et al., 2013). In this thesis, I will contribute to this on-going discussion, with a quantitatively comparison of offshore sedimentation volume, deposited the last 4 Ma, with onshore erosional potential. Here the onshore erosional potential consists of both onshore bedrock erosion and erosion of older sediment in coast-near regions of both old (4 - 0 Ma) and present shelf.

The distinct high-altitude low-relief surfaces found on the Norwegian continental margin have initially been interpreted as remnants of a Mesozoic peneplain uplifted in Cenozoic (hypothesis 1, classical model; e.g. Lidmar-Bergstrom et al., 2000). However, there have recently been other suggestions for the development of the south-western Scandinavian topography. One of these is the ICE (isostasy-climate-erosion) hypothesis, suggesting that the topography may be a result of prolonged climate-dependent erosion and isostatic uplift of remnant topography of the Caledonian orogeny (hypothesis 2, ICE-hypothesis; e.g. Nielsen et al., 2009). Another hypothesis was recently proposed by Pedersen et al. (2016), which suggests a combination of the above end-member hypotheses.

These hypotheses are based on observations that are possible to interpret in various ways, which is also the reason why it is so difficult to find one hypothesis that everyone agrees on. The observations mostly come from offshore studies, which show an increased sedimentation during the Cenozoic, over-burial of coast-proximal tilted sedimentary strata, and an angular unconformity at the base of Quaternary (Riis, 1996, Japsen, 1998). These key observations have initially supported the classical interpretation, but the ICE-hypothesis suggests that the observations may equally well be explained by Cenozoic rifting (Nielsen et al., 2009, Gołędowski et al., 2012, Steer et al., 2012). Onshore observations used to support the various hypotheses include the landforms that are displayed on GPMs. These consist of both glacial (deep fjords, glacial valleys and cirques) and non-glacial landforms (stepped surfaces, residual hill masses and fluvial valleys; Hall et al., 2013). Other onshore observations are cosmogenic nuclide data (Egholm et al., 2017), which are used to determine the recent erosion history of the high-altitude low-relief surfaces, and thermochronological studies (e.g. Nielsen et al., 2009), that among other things, can be used in testing landscape evolution models (Gołędowski et al., 2013).

One example of previous work that has tried to disentangle the controversy of the Scandinavian topography is by Steer et al. (2012). Here the classical model and the ICE-hypothesis are tested for their ability to quantitatively match the onshore erosional volume with offshore sedimentation. According to the classical model, there should be no extra onshore erosion outside fjords, which means that the offshore sedimentation should match the onshore erosional volume. However, the results from the mismatch test indicated that erosion from fjords alone, could not explain all the offshore sedimentation from Late Pliocene and Quaternary (Steer et al., 2012) Therefore, according to Steer et al. ( 2012), there must have been significant erosion coming from somewhere else, e.g. the high-altitude low-relief surfaces. The study therefore indicates that the high-altitude low-relief surfaces have been modified significantly during the recent glaciations, which questions their role as an old uplifted peneplain.

This view on the recent evolution of the high-altitude low-relief surfaces has been challenged by Hall et al. (2013). Here they suggest that glacial erosion of the coast and inner shelf of the Norwegian GPM, has provided a huge sediment volume that can resolve the mismatch found by Steer et al. (2012), between onshore fjord erosion and the Pliocene-Pleistocene offshore sedimentation (Hall et al., 2013). In addition, this study finds no evidence that mountain glaciers have contributed to the formation of the high-altitude low-relief surfaces (Hall et al., 2013). It is here suggested that these surfaces are slowly eroded pre-glacial features that have been little modified by glacial erosion (Hall et al., 2013). Hall et al. (2013) recognize that the mass transfer of sediment volume from the inner shelf, coast and escarpment to the outer shelf, generated ca. 400 m of flexural isostatic uplift (Riis, 1996), causing western Norway to uplift and the GPM to tilt towards the Baltic. However, according to Hall et al. (2013), the main driver for uplift of the Norwegian GPM in the late Cenozoic is not due to glacial erosion as suggested by Nielsen et al. (2009), but rather due to tectonics (Redfield and Osmundsen, 2013).

## 1.1 Objectives

The main objectives of this thesis are i) to estimate volumes of recent fjord and valley erosion on land, and ii) to approximate an erosion volume of older sediments on the inner shelf and in coast-near regions. The reason for this is to be able to match the offshore sedimentation volume, deposited in Pliocene-Pleistocene, with onshore erosional volume. To get these volume estimates, reconstructions of the topography and bathymetry are made, using the present topography and bathymetry, the geophysical relief method, and deflection. Estimations of shelf erosion is based on a new concept defined in this thesis, which give a conservative estimate of how much sediments have been removed since 4 Ma ago. The goal is not to reconstruct the true onshore topography, but rather to estimate eroded volumes. This thesis is thereby a continuation of the idea presented in Steer et al. (2012), and its novelty lies in the inclusion of the sediment volumes that have been eroded on the inner shelf and in coast-near regions.

# 1. Introduction

## 1.2 Geological history

The Scandinavian topography has been developed over many hundred million years (Fossen, 2008). The most recent mountain-building process in the region of Scandinavia was caused by the continent-continent collision between Laurentia and Baltica (450-420 Ma; Soper et al., 1992, Cocks and Torsvik, 2002).

As a result of the collision, big thrust sheets were pushed over Norway (Fossen, 2008). Some of Norway's high mountain tops are remnants of these sheets, even though the power of erosion has removed most parts of the thrust sheets since collision ended at about 400 Ma (Fossen, 2008). On the western coast of Norway, there are found minerals that can only develop under high pressure (Fossen, 2008). This indicate that the minerals were subdued to around 100 - 125 km, which imply that the mountain chain, called the Caledonian orogeny, was as large as today's Himalaya (Fossen, 2008).

After millions of years of slow collision, collapse and rifting processes started immediately after the formation of the Caledonian orogeny (Nielsen et al., 2009). These processes caused the development of sedimentary basins on the continental shelf of north-western Europe, east Greenland and onshore western Scandinavia (Dunlap and Fossen, 1998, Fossen and Dunlap, 1999, Andersen et al., 1999, Mosar, 2003). At about 62 Ma, in early Paleogene, the rifting process led to a left-lateral translation in the North Atlantic area and the Artic oceans, in addition to a phase of magmatism (Nielsen et al., 2007). This led to ocean formation in late Paleocene, where the drifting placed the remnants of the Caledonian orogeny in widely separated locations (Andersen et al., 1991, Skogseid et al., 2000). Erosion processes have been working on for a long time, and therefore it is no surprise that the present-day topography is generally low in most of these locations. However, this do not apply to the onshore European realm of the Caledonian orogeny (Nielsen et al., 2009). This include the western Scandinavia, where there is a mountain range, which at present-day have peak elevations of above 2000 m both in northern and southern Norway (Nielsen et al., 2009). The origin of the high topography in western Scandinavia is highly debated with a range of competing hypotheses (e.g. Pedersen et al., 2016). This controversy will be the focus of the next section, where the main hypotheses are presented.

## 1.3 Background

There are several hypotheses for the post-Caledonian geodynamic evolution of western Scandinavia, including the evolution of the topography. The characteristics of this topography are high-altitude low-relief surfaces, that are dissected by deep and narrow fjords (Steer et al., 2012). The different hypotheses stem from diverse observations, where people put a different weight on the different key observations. In the following, various hypotheses will be presented, including the various explanations for some key observations.

### 1.3.1 Hypothesis 1: Classical model

The classical model indicate that the Scandinavian topography is about 25 Ma old (Japsen and Chalmers, 2000). The high-altitude low-relief surfaces are interpreted to be remnants of a Mesozoic peneplain, which have been uplifted in Cenozoic. The observed increase in offshore sedimentation rate is thereby explained by tectonic events that took place in Neogene (Japsen and Chalmers, 2000).

One of the key observations for the classical peneplain model, are autochthonous block fields that are found in several meters thickness on the summits of the Scandinavian mountains (Nesje et al., 1988). According to Riis (1996), the interpretation of these block fields is undoubtedly connected to geological processes, such as frost, ice, wind and water acting on the elevated low-relief surfaces. The occurrence of block fields at many summits indicate that there has been a limited amount of glacial erosion of these summits (Riis, 1996). Thus, these surfaces are interpreted to be preserved remnants of the old peneplain surface, that has been protected by a cold-based ice cover.

According to Japsen and Chalmers (2000), there is no doubt that there has been uplift around the North Atlantic, but the timing is unclear. An increase in offshore sedimentation indicate that there has been an uplift onshore, which again indicate increased onshore erosion. The uplifting event in the Paleogene, proposed to be caused by emplacement of magma from the Iceland plume (e.g. Clift et al., 1998), cannot explain all the offshore sedimentation volume or the geological structures in the North Sea. There are found sediments from Pliocene that are both uplifted and eroded (Riis, 1996, Japsen and Chalmers, 2000), which indicate that there have been two distinct uplifting events, one in the Paleogene and one in the Neogene (Japsen, 1997). The second uplifting event during the Neogene and Quaternary is not that easy to explain (Japsen and Chalmers, 2000). According to Japsen and Chalmers (2000), the isostatic rebound from glacial erosion during Quaternary is an important element to explain the uplift of the Scandinavian mountains, but they state that it is still unclear if that can explain all the uplift that has happened.

### 1.3.2 Hypothesis 2: ICE (Isostasy - Climate - Erosion) hypothesis

The second hypothesis discussed here is the ICE-hypothesis, which suggest that the topography in western Scandinavia is remnant topography from the Caledonian orogeny (Nielsen et al., 2009). It is suggested that the Caledonian orogeny survived the Mesozoic by slow climate-dependent erosion and isostatic uplift (Steer et al., 2012).

According to the ICE-hypothesis, the erosion from glacial and periglacial erosion around and above the Equilibrium Line Altitudes (ELA) may explain the high-altitude low-relief surfaces (Egholm et al., 2009, Steer et al., 2012). The many cirques observed in western Scandinavia (Rudberg, 1994), indicate that there have been a glacial headward erosion that has been documented to produce low-relief surfaces around and above ELAs (Oskin and Burbank, 2005, Egholm et al., 2009). This glacial erosion pattern is often referred to as the glacial buzzsaw (Egholm et al., 2009).

The ICE-hypothesis suggest that climate, rather than tectonics, explain the large sediment volume found in the North Sea. At late Eocene - early Oligocene there was a change in the sedimentation in the North Sea, where thick units of coarser sediments were deposited (Nielsen et al., 2009). The sediment units were prograding from the north-east, which is previously interpreted to have been caused by tectonic uplift in western Scandinavia (Nielsen et al., 2009). However, Nielsen et al. (2009) found that the timing of these changes coincides with the temperature fall and sea level fall that is globally recognized for late Eocene - early Oligocene (Zachos et al., 2001, Miller et al., 2005). Confirming that, climate can explain the thick sediment units found in the North Sea (Huuse et al., 2001, Huuse et al., 2002, Nielsen et al., 2002, Nielsen, 2003).

1. Introduction

An important element in the ICE-hypothesis is the work by Steer et al. (2012), balancing the onshore erosional volume with offshore sedimentation from Late Pliocene and Quaternary. In this work, estimates for the onshore erosional volume, i.e. fjord erosion, were calculated by computing the geophysical relief, which is the elevation difference between a smooth surface that connects the highest point in the landscape and the present-day topography (Small and Anderson, 1998, Champagnac et al., 2007, Anell et al., 2010). Before comparing the volumes, the offshore sedimentation volume is corrected for porosity (20 %; Dowdeswell et al., 2010) to convert it into a volume of erosion (Steer et al., 2012). Steer et al. (2012) found that the onshore fjord erosion only represents 35 - 55% of the offshore sediment matrix volume, indicating that there must have been significant erosion from somewhere else, e.g. high-altitude low-relief surfaces.

Another important element for the ICE-hypothesis is the correlation between topographic height, Buoguer gravity, anomaly and crustal thickness (Nielsen et al., 2009). In general, elevated topography is usually supported by a crustal root (Nielsen et al., 2009). According to the ICE-hypothesis, a thickening buoyant crust is expected to compensate for all present-day topography (Pedersen et al., 2016), meaning, the correlation indicate that the mountain range is close to isostatic equilibrium. Nielsen et al. (2009) used receiver function measurements to calculate the crustal thickness in southern Norway, and this gave the indication that there is a crustal root under today’s topography. The geophysical data that were presented in Nielsen et al. (2009), therefore strongly suggests a long-term erosion of the topography. The relative contributions of crustal isostasy, in addition to dynamic topography, in controlling the topography are studied further by Pedersen et al. (2016), and will be presented in the next section.

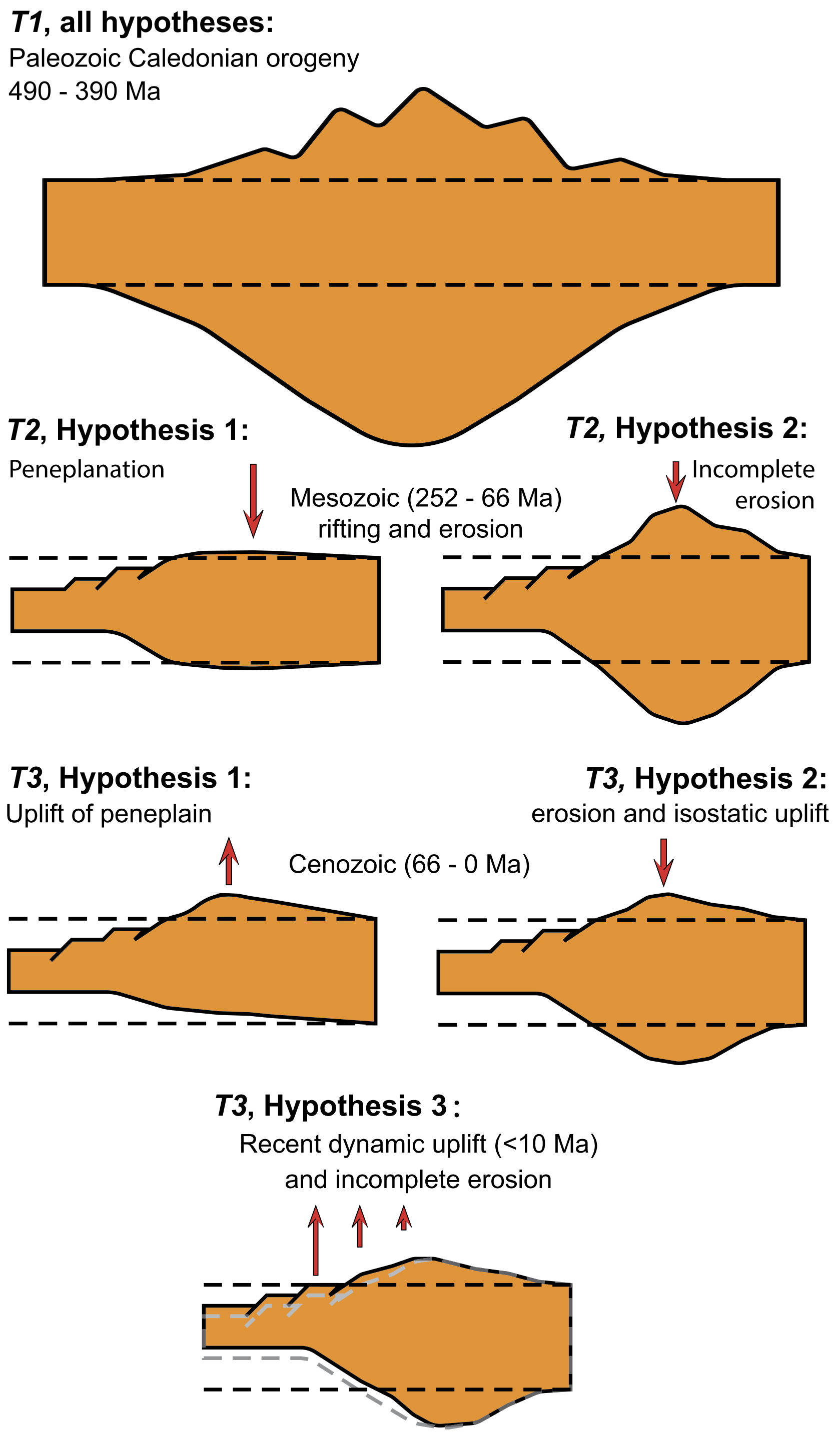



***Figure 1.1**: Schematic models of the different hypotheses of the geodynamic evolution of western Scandinavia at three different times (T1, T2, T3). The dashed line represents the crustal thickness with no compensated topography, while the arrows represent change in surface elevation (Pedersen et al., 2016).*

### 1.3.3 Hypothesis 3: Combination of Classical Model and ICE-hypothesis

A third hypothesis was recently proposed by Pedersen et al. (2016), where they test whether a combination of the two previous hypotheses may explain the recent evolution of the present topography (figure 1.1). This study quantifies the contribution of crustal isostasy and dynamic topography in how these have been controlling the present-day topography (Pedersen et al., 2016). This combination hypothesis is based on quantitative estimates of crustal thickness, crustal density and the flexural strength of the lithosphere (Pedersen et al., 2016).

The previous end-member hypotheses (hypotheses 1 and 2) predict very different crustal compensation of the present-day topography (Pedersen et al., 2016). The classical peneplain model requires complete erosion of topography, meaning no crustal root present (Pedersen et al., 2016), while for the ICE-hypothesis a thick buoyant crust is expected to compensate for all present-day topography (figure 1.1; Pedersen et al., 2016). Instead, hypothesis 3 suggests that there has both been dynamic uplift, which is consistent with hypothesis 1, and incomplete erosion, which is consistent with hypothesis 2 (Pedersen et al., 2016). The results from this study display a large degree of isostatic support of topography, which do not match with the classical model (Pedersen et al., 2016).

# 2. Flexure of the Lithosphere

Flexural isostasy is a stress balance that also considers horizontal elastic stresses, meaning it is at least a two-dimensional stress balance (Stüwe, 2007). It may be used to interpret surface topography in terms of both hydrostatic balance and elastic features (Stüwe, 2007).

Deflection represents the degree of displacement of a lithospheric plate under a load (figure 2.2). The theory to describe deflection started by approaching a simple model of a perfect buoyant compensation of loads with of a lithosphere with no strength, overlying a mantle of known density (Wickert, 2015). Two models for this theory called isostasy, where proposed by Airy (1855) and Pratt (1855). According to the Airy model, lithospheric blocks all have the same density but different thickness (figure 2.1a), while the Pratt model states that blocks float to the same depth but have different densities (figure 2.1b; Mussett and Khan, 2000).

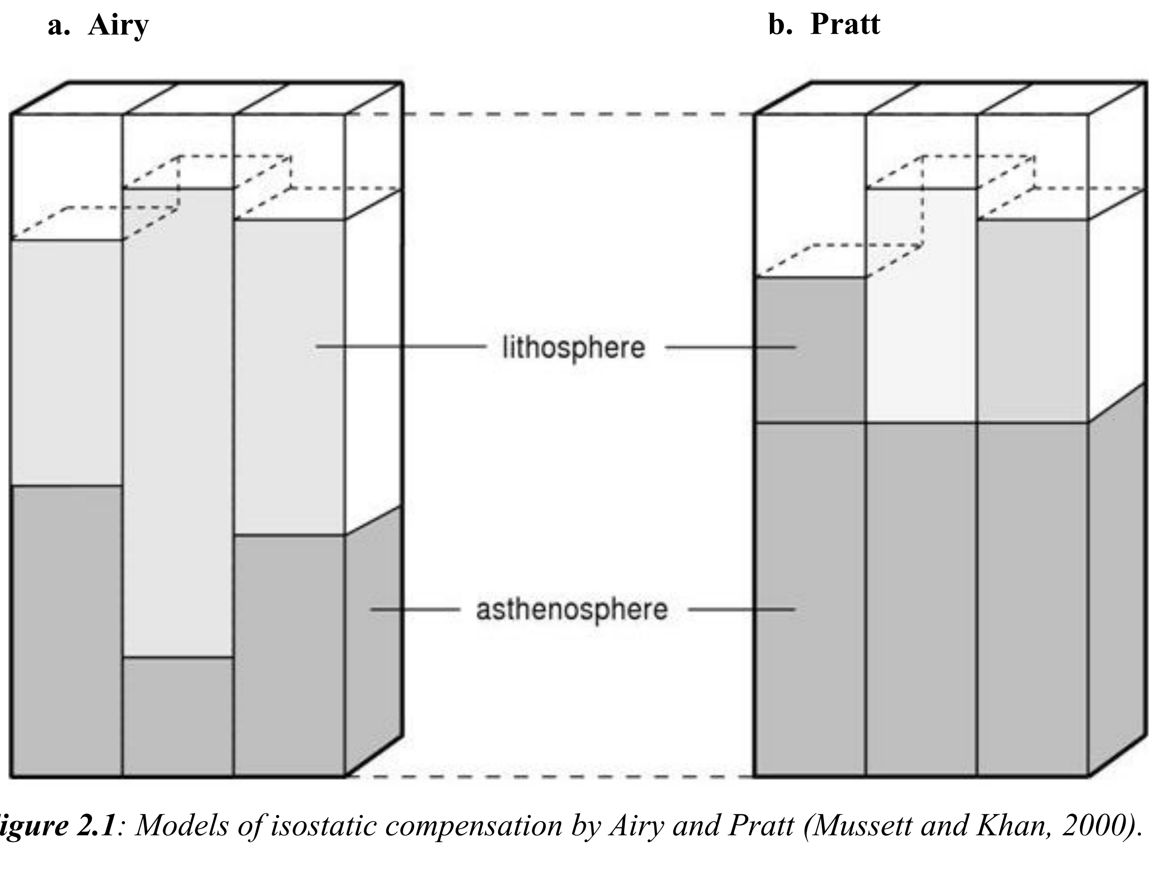



***Figure 2.1**: Models of isostatic compensation by Airy and Pratt (Mussett and Khan, 2000).*

A more realistic solution for isostatic deflection also take account for flexure of a lithospheric plate of a finite strength, called effective elastic thickness (EET; see section 3.5; Wickert, 2015). In this thesis, deflection is calculated using gFlex v1.0 (Wickert, 2015) and is important for understanding how the offshore sedimentation volume (4 - 0 Ma) and the onshore erosional material (from fjords, valleys and inner shelf), affect the lithospheric plates (see section 3.4).

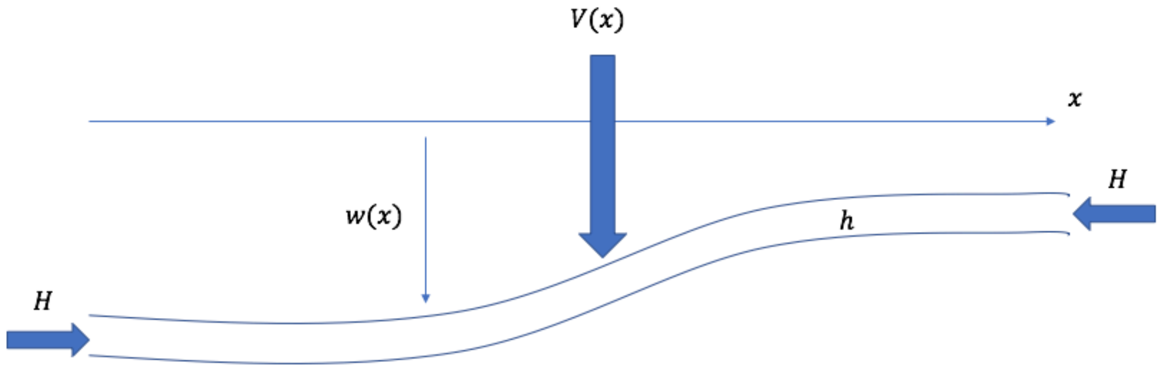



***Figure 2.2***: *Schematic model of a thin, lithospheric plate being deflected because of a variable vertical force per unit $V(x)$, and a constant horizontal force H per unit length. $w(x)$ is the deflection and h is the thickness of a thin, elastic lithospheric plate (Fowler, 2005).*

The lithosphere is, in this thesis, assumed to act as an elastic plate. Studies of bending and flexure of the lithosphere as a result of loading by e.g. mountain chains and volcanoes give estimated elastic properties of the lithosphere (Fowler, 2005). In addition, the rate of recovery/rebound when a load is removed, depend on the viscosity of the underlying mantle as much as the elastic properties (Fowler, 2005). From the fourth-order differential equation, we can determinate deflection of an elastic plate as a function of a horizontal distance, x:

$$D\frac{d^4w}{dx^4} = V(x) - H\frac{d^2w}{dx^2} \tag{2.1}$$

where $w(x)$ is the deflection of the plate, $V(x)$ is a vertical force per unit length applied to the plate, $H$ is a constant horizontal force per unit length applied to the plate and $D$ is the flexural rigidity of the plate, which is defined by:

$$D = \frac{Eh^3}{12(1-\sigma^2)} \tag{2.2}$$

where $E$ is Young's modulus, $h$ is the EET (see section 3.5), and $\sigma$ is Poisson's ratio (Fowler, 2005).

# 3. Data and Method

In this thesis, the main focus is to quantitatively compare offshore sediment volume from the northern North Sea and the Norwegian margin, with onshore erosional potential in Norway. The onshore erosional volume consists of both onshore bedrock erosion and older sediment from the inner shelf and coast-near regions. Estimations of these onshore erosional volumes are calculated with the use of reconstructed topography, bathymetry and the shelf.

Data sets used in my reconstructions are i) present day topography and bathymetry, ii) an offshore sediment thickness map for the time period 4 - 0 Ma, iii) an EET map, and iv) the Quaternary subcrop map "Norway with Sea Areas" (Sigmond, 1992). The offshore sediment thickness map has been provided by Gołędowski et al. (2012), and is calculated from two-way-time (TWT) structure maps and velocity maps compiled from velocity values in wells. The EET map has been provided by Pérez-Gussinyé and Watts (2005), and is based on gravity anomalies (Bouguer coherence) and topography.

Based on these data I have estimated i) potential bedrock erosion in fjords and large valleys onshore, as a result of mainly glacial erosion, and ii) the amount of older sediments that may have been eroded from coast-near regions, including the present shelf. The sediment volume that is reconstructed on the shelf and in the coast-near regions is, in this thesis, referred to as the shelf wedge (figure 3.3). Figure 3.1 show an overview of the workflow of the thesis, including uncertainties, which lead to the varying results. The following sections will describe the different components of the workflow.

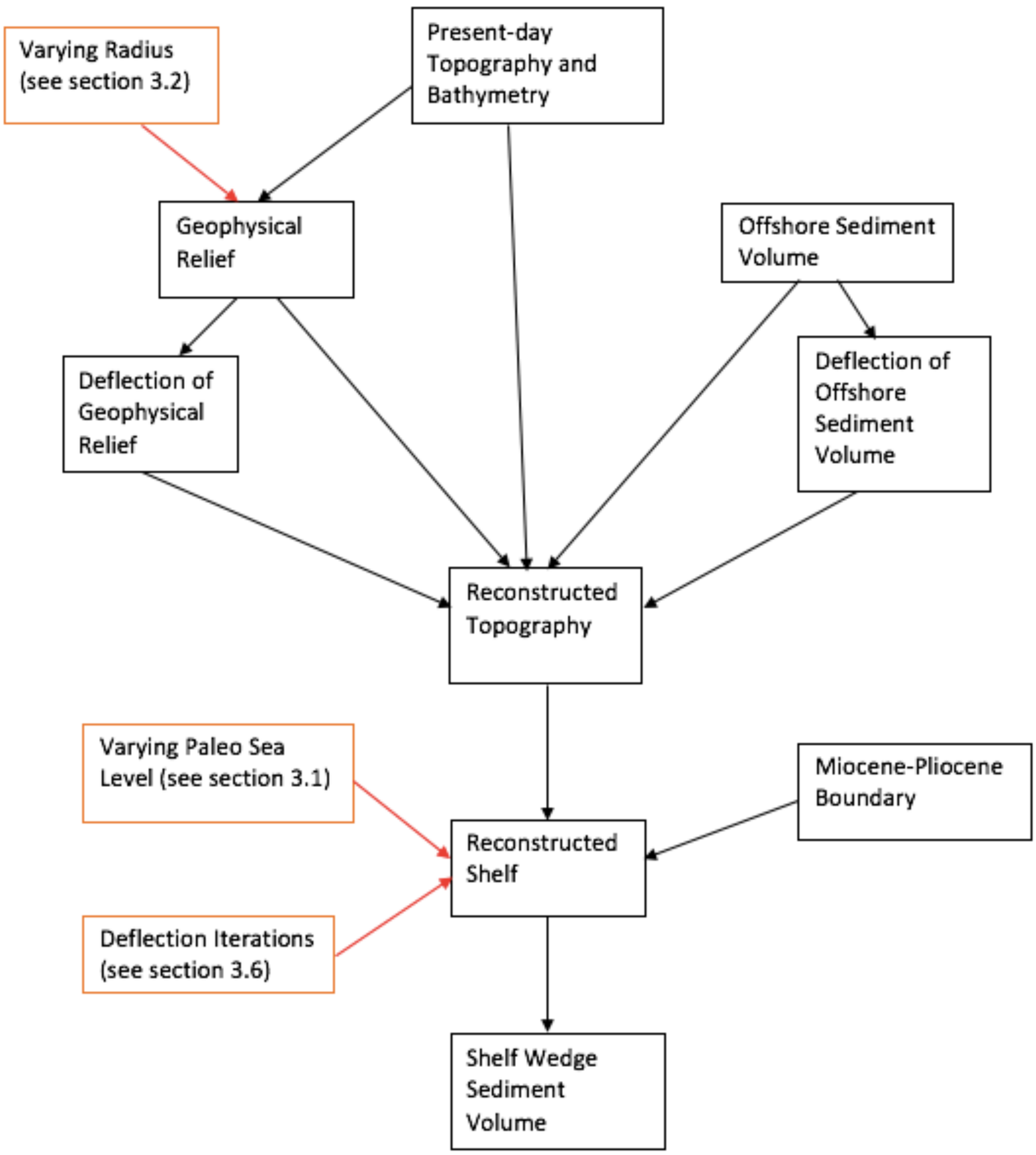



***Figure 3.1***: *Overview of processes, uncertainties and data used to calculate different sediment volumes for the volume mismatch test. The red boxes are parameters that cause an uncertainty in the results.*

## 3.1 Definition of Reconstructed Topography, Bathymetry and Shelf

The idea behind the reconstruction of topography and bathymetry from 4 Ma (figure 3.1), is to 1) remove the offshore sediment volume from the last 4 Ma from present-day bathymetry (figure 3.5), 2) fill in the present fjords and large valleys onshore (see section 3.2), and 3) take into account deflections that would arise from these mass redistributions (offshore deposition and onshore erosion) because of flexural isostasy (see section 3.4). This is shown with the simple equation:

$$Reconstruction\ of\ topography = TOPO + GR - SED_{Offshore} + w_{GR} - w_{SED} \tag{3.1}$$

where $TOPO$ is present-day topography, $GR$ represents fjord and valley erosion calculated using geophysical relief method (see section 3.2), $SED_{Offshore}$ is offshore sedimentation from the last 4 Ma, while $w_{GR}$ and $w_{SED}$ represents deflections calculated for fjord and valley erosion, and offshore deposition. This approach gives a reconstruction of how the topography and bathymetry might have looked like before glacial erosion of the fjords and large valleys, and offshore deposition took place. However, this first exercise excludes the effect of potential erosion of older sediments that has occurred during the last 4 Myr, i.e. the shelf wedge.

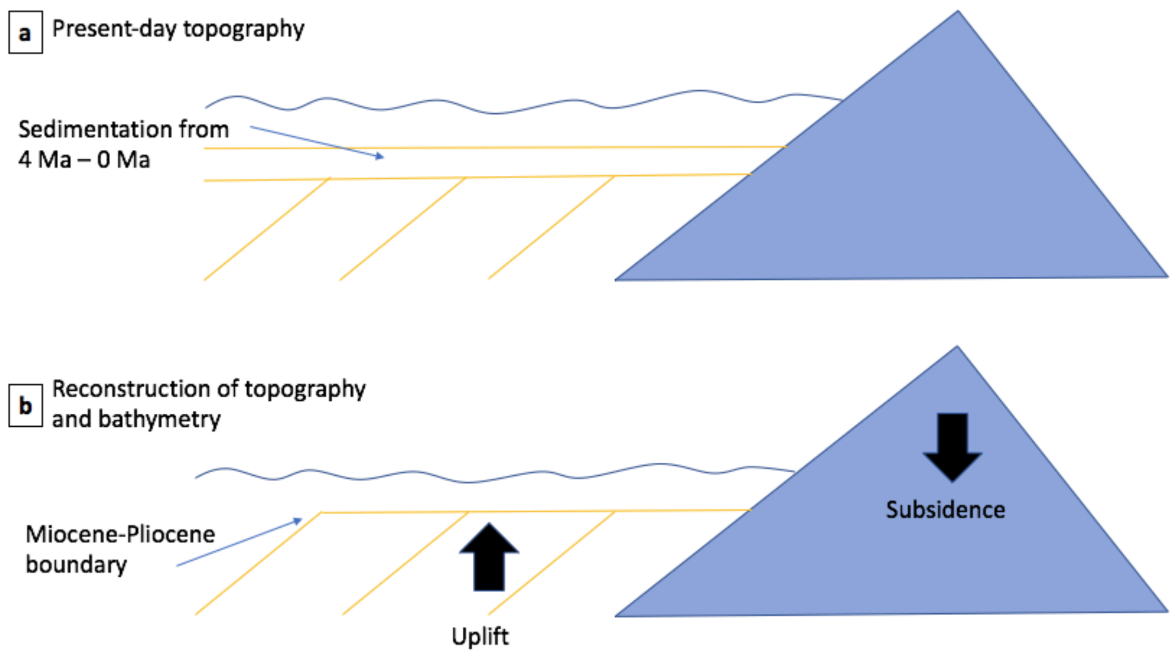



***Figure 3.2****: Schematic models of present-day topography and bathymetry (**a**) and the reconstruction (**b**). The figure illustrates what happens when the offshore sedimentation volume is removed and fjord and valley erosion is re-placed onshore.*

The first step in the process of defining the shelf wedge, was to define its westernmost edge and the depth of this edge (figure 3.3). The westernmost edge is defined as the Miocene-Pliocene boundary corresponding to an age of approximately 5 Ma, and the depth of the edge is based on the reconstructed bathymetry (figure 3.2b). The Miocene-Pliocene boundary was digitized from the Quaternary subcrop map “Norway with Sea Areas” (Sigmond, 1992). As this boundary does not go all the way around southern Norway on the published map, and is unclear in other studies (Japsen, 1998), the study area is limited to the Norwegian margin specifically. Also, the study area excludes areas north of Lofoten, since offshore sediment volume sourced from this area is not included.

Next step was to find the eastern boundary at a chosen PSL onshore. Here it is assumed that sediments could have been deposited up to maximum relative sea level in the period of sediment deposition, in a wedge kind of shape. This wedge has then later been eroded and has thus contributed to the offshore sedimentation volume. From these boundaries, linear interpolation was used to get the reconstructed shelf. The shelf wedge (figure 3.3), which represents the sediments that are re-placed on the shelf, is found by taking the difference between reconstructed shelf and the reconstructed topography and bathymetry. The shelf wedge represents older sediments deposited over a long period (since Mesozoic), and thus should be corrected for porosity. Observations studied in Hall et al. (2012), indicate that the shelf wedge sediments consists of Jurassic shales (Nielsen et al., 2009), Late Cretaceous chalk (Japsen, 1998) and Neogene sediments. Due to the large age span and different rocks and sediments, the porosity are set to vary between 20 - 60 %. However, some studies of reservoir rocks, have found porosities of 19 - 34 % (Halland et al., 2014), which suggests that a large part of the older sediments have porosities in that range. This method for reconstruction of the shelf, is a minimum, conservative approach in recreating the coastal and inner shelf sediment volume of 4 Ma, and does not consider large tectonic movements as assumed by Riis (1996).

In this thesis, different PSLs that vary between 200 m and 800 m above present-day sea level have been tested for the reconstruction of the shelf. The reason for these variations is that both dynamic topography (Pedersen et al., 2016) and eustatic, global sea level changes (Miller et al., 2005) could influence the former relative sea level, which make PSL uncertain. According to Miller et al. (2005), PSL seem to vary between 0 m and ±200 m in the Cenozoic, relative to today. Therefore, in this thesis it is assumed that the relative sea level has been at least 200 m above present-day sea level. The dynamic topography is more uncertain. However, according to Pedersen et al. (2016), there might have been around 300 - 400 m of dynamic uplift in southern Norway.

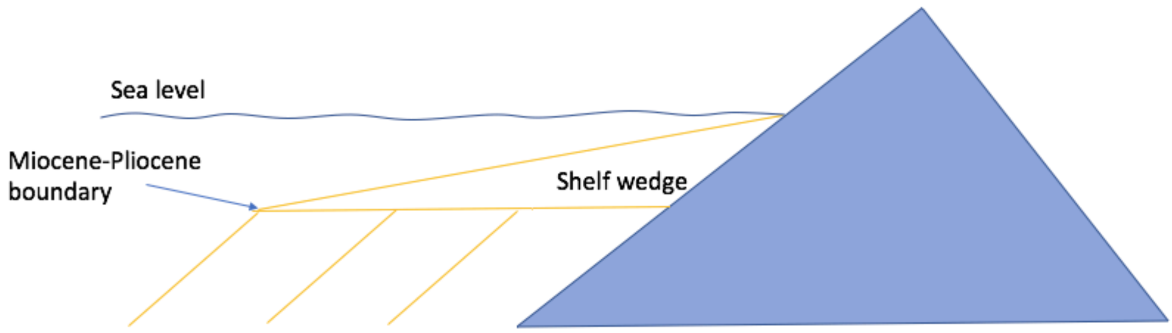



***Figure 3.3**: Schematic model of reconstruction of the shelf, where a sediment load is placed back on the shelf. The shelf wedge is placed between the Miocene-Pliocene boundary and the chosen PSL boundary onshore.*

## 3.2 Geophysical Relief

The geophysical relief method (Small and Anderson, 1998, Steer et al., 2012) is used in this thesis to estimate fjord and valley erosion. This method defines a surface through the highest parts of an area, and the difference between this surface and the present-day topography represents the geophysical relief, i.e. fjord and valley erosion. This approach uses a sliding window to detect the maximum value inside every grid of the window. The geophysical relief is then found by interpolation (linear method) between these points. Input parameters needed in this approach are present-day topography data set (figure 3.4), utm coordinates, and radius in km for the sliding window. As indicated in the overview (figure 3.1), the radius is a varying parameter (figure 4.3), which change the resulting erosion volume considerably. An increase in radius results in an increase in fjord and valley erosion volume. The most plausible radius would only fill in fjords and valleys, and no other onshore area. Therefore, in this thesis, the geophysical relief method is calculated with radius of 1 - 10 km, to test which radius give the most realistic volume of fjord and valley erosion.

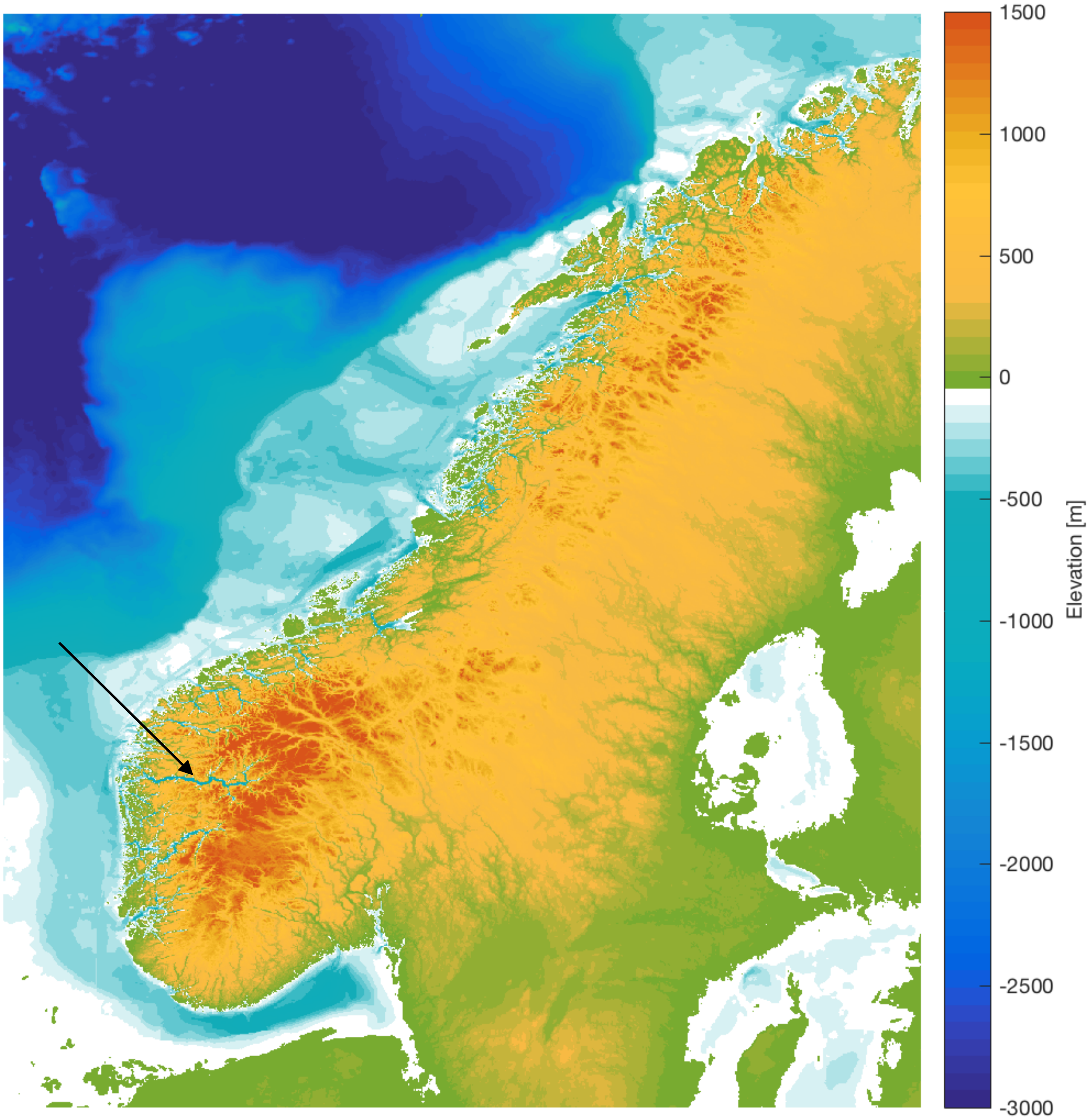



***Figure 3.4***: *Present-day topography and bathymetry of Scandinavia. The figure present the fjords, which are by the geophysical relief method later filled with rock volume. The arrow is pointing at Sognefjorden, which is Norway's largest fjords.*

## 3.3 Offshore Sediment Volume and Porosity

The offshore sediment volume consists of sedimentation from the last 4 Myr, deposited in the northern North Sea and along the Norwegian margin during the Pliocene and Quaternary (figure 3.5). This volume is from a thickness map that have been calculated from 2D seismic reflection profiles and well data from the North Sea and the Norwegian shelf (Gołędowski et al., 2012). As mentioned earlier, the thickness map was calculated from TWT structure maps (from the seismic profiles) and velocity maps (from velocity values in wells) (Gołędowski et al., 2012). In the mismatch comparison, the matrix part of the sediment volume represents the volume that is attempted to be re-placed onshore and on the shelf. This gives the equation:

$$\begin{aligned} &Offshore\ Sediment\ Matrix\ Volume \\ &\quad = Onshore\ Fjord\ and\ Valley\ Erosion \\ &\quad + Shelf\ Matrix\ Erosion \\ &\quad + Onshore\ Erosion\ Outside\ Fjords\ and\ Valleys \end{aligned} \tag{3.2}$$

where $Offshore\ Sediment\ Matrix\ Volume$ is the offshore sediment volume corrected for porosity (shallow glacial sediment porosity), $Onshore\ Fjord\ and\ Valley\ Erosion$ represents the onshore erosional volume calculated using the geophysical relief method, $Shelf\ Matrix\ Erosion$ is the shelf wedge volume corrected for porosity (older buried sediment porosity) and $Onshore\ Erosion\ Outside\ Fjords\ and\ Valleys$ represents the mismatch, which is assumed to be onshore erosion from outside fjords and valleys.

The volume deposited offshore between 4 - 0 Ma is about 221.9 x $10^3$ $km^3$ (Gołędowski et al., 2012). Correcting for porosity, which is estimated to be about 20 - 30 %, based on sediment density data from offshore well logs (Dowdeswell et al., 2010), converts the sediment volume into a volume of rock. The offshore sediment matrix volume then varies between $1.55 \times 10^5$ $km^3$, with a porosity correction of 30 %, and $1.77 \times 10^5$ $km^3$, with a porosity correction of 20 %.

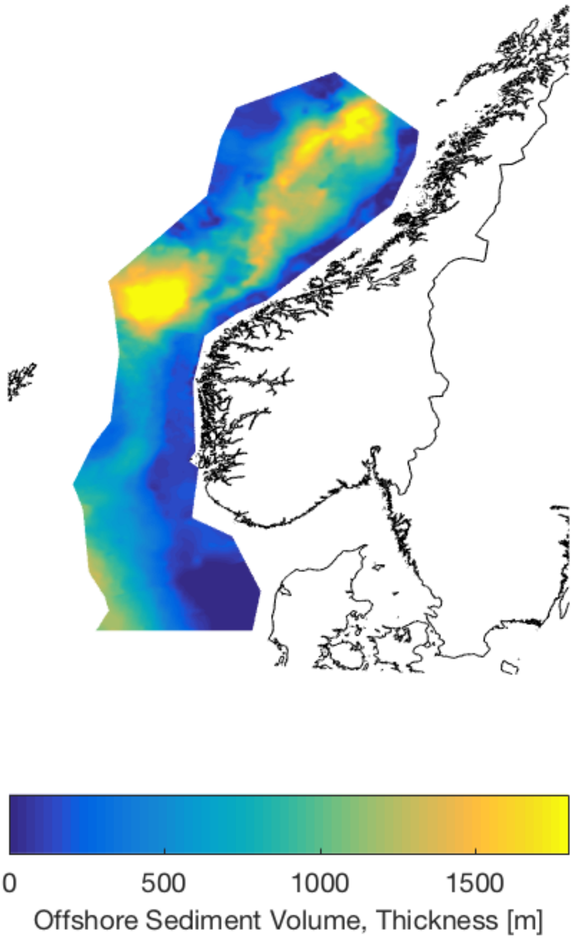



***Figure 3.5****: Offshore sediment volume shown relative to the Norwegian coastline. This shows the sediment volume that is not corrected for porosity.*

## 3.4 gFlex v1.0

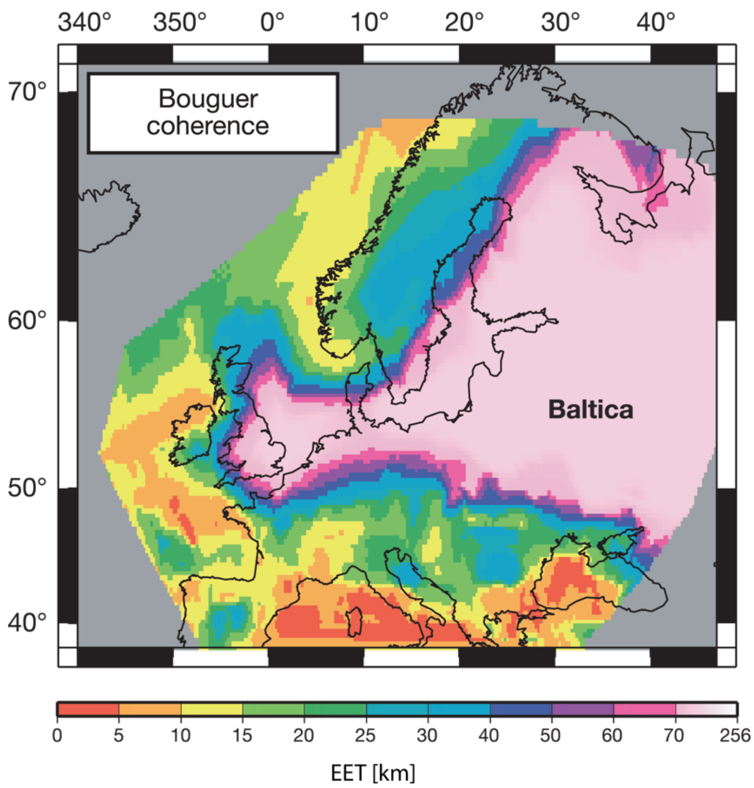
gFlex v1.0 is an open-source model used to simulate the flexural isostatic response to an imposed load (Wickert, 2015). The model can produce analytical and finite difference solutions for lithospheric flexure in both one and two dimensions (Wickert, 2015). As mentioned in the paragraph on flexure of the lithosphere, in this thesis the lithospheric plate is assumed to act as an elastic plate where deposition and erosion result in loads that bend the elastic plates. The time-dependent aspect is not considered in this thesis, in addition to the viscous component, which is ok to leave out on the timescale considered here (>100 000 yrs). It is however important for the individual glacial cycles and changes in ice volume, but not for the long-term changes due to erosion and deposition.

The various erosion and deposition volumes are used as input for calculating the respective deflection for these loads in gFlex v1.0. All data sets must be down sampled, because of the amount of time used in gFlex v1.0. Other input parameters required are Poisson's ratio (0.25), Young's modulus (70 GPa), EET (see section 3.5) and density of the load. A density of 2200 kg/m$^3$ is used for both the offshore sediment deposited during the last 4 Ma and the older shelf wedge sediments (Mussett and Khan, 2000), and a density of 2670 kg/m$^3$ (Pedersen et al., 2016) for the onshore bedrock.

## 3.5 Effective Elastic Thickness

The EET varies spatially due to the age, temperature and composition of the lithosphere. In order to take these effects into consideration, the spatially varying EET map from Pérez-Gussinyé and Watts (2005), determined from Bouguer coherence of northern Europe, is used (figure 3.6). Spatial variations in EET are not well understood, which is mostly because different methods gives very different results (Pérez-Gussinyé and Watts, 2005). Pérez-Gussinyé and Watts (2005), use both the 'Bouguer coherence' method (onshore) and the 'free air addmittance' method (offshore) for a grid of gravity anomalies (Pérez-Gussinyé and Watts, 2005). Both methods are based on present-day topography and gravity anomaly data, which give the current strength of a thick, cooled lithosphere (Grotzinger and Royden, 1990). Pérez-Gussinyé and Watts (2005) conclude that the strength of an old lithosphere is much larger than that of a young lithosphere.

a.




b.

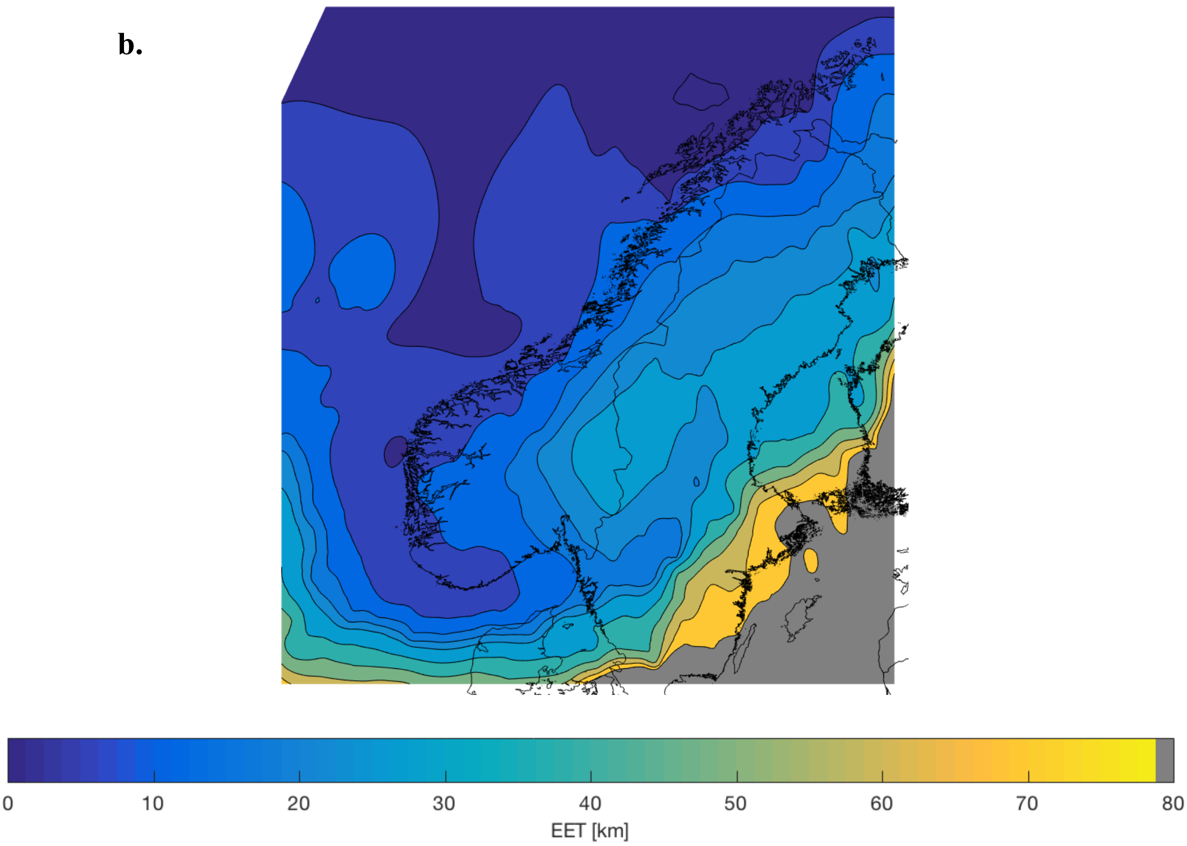



***Figure 3.6***: *Both figure **a** and **b** display EET obtained using the Bouguer coherence method. Figure **a** is a more detailed figure with EET of Europe, modified from Pérez-Gussinyé and Watts (2005). Figure **b** display EET of Scandinavia, where the grey colour represents values >80 km.*

## 3.6 Volume vs. Deflection Iterations

The shelf wedge calculated during reconstruction of the shelf, affects the flexural isostasy and contributes to the deflection. By iterating due to the contribution of deflection, the load from the shelf wedge causes there to be room for more sediments, because of the increased deflection. This iterative approach for the shelf wedge deflection, may converge after about three iterations. Small changes in the deflection cause complex changes in the way that the reconstructed shelf is being defined. There are places where the shelf wedge is very thin, and this seems to lead to local variations in the topography, as seen on the last iteration with PSL of 800 m above today's sea level (figure 3.7). Therefore, in further calculations, three iterations are used, because of the complex changes that happen with four or more iterations.

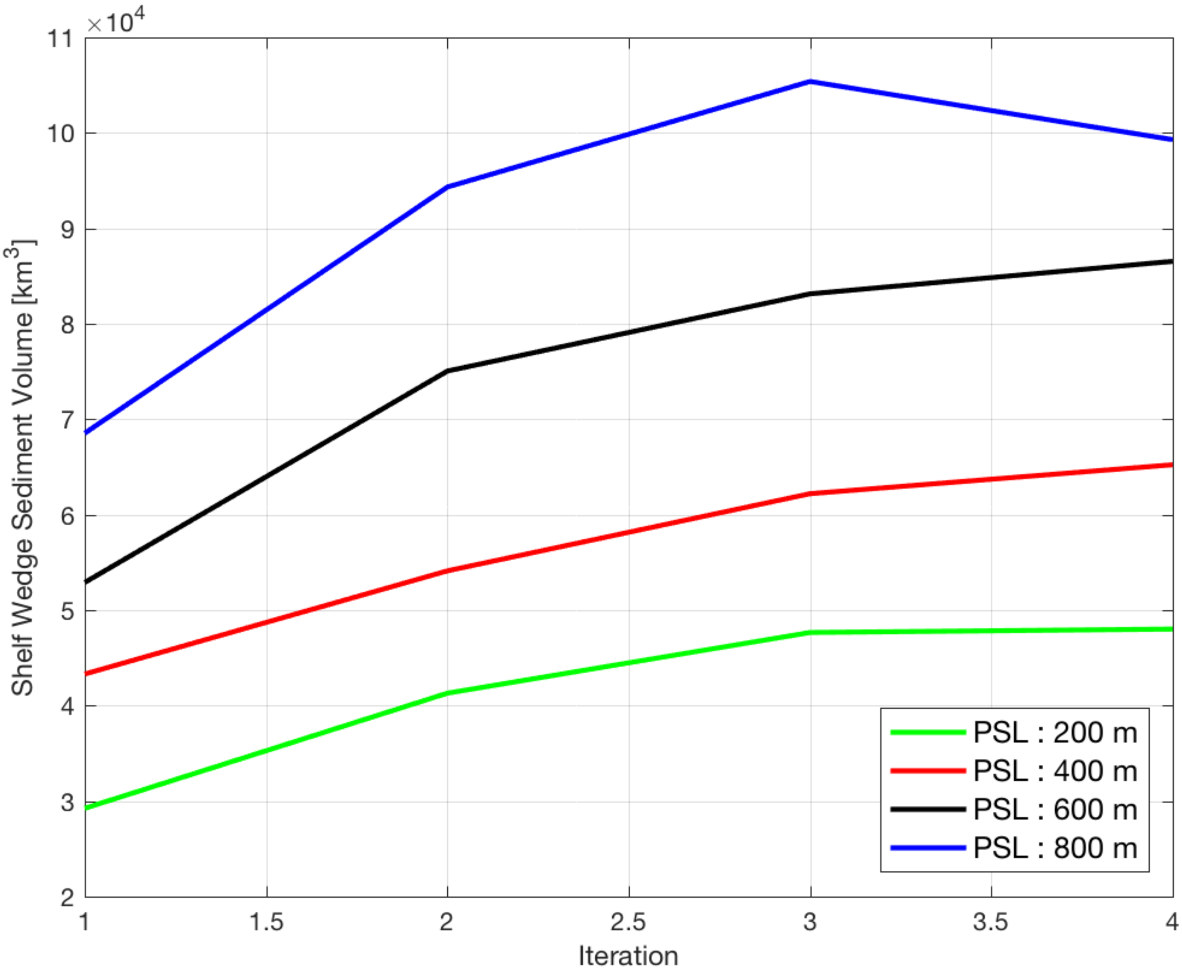



***Figure 3.7**: Shelf wedge volume vs. deflection iterations. The figure show the shelf wedge volume from four different PSLs, changing, mostly increasing, with every iteration of deflection.*

## 3.7 Inclination

In reconstructing the 4 Ma pre-glacial landscape, the inclination of the shelf changes due to deflection of fjord and valley load, shelf wedge load and the offshore sediment load. To get an idea of the inclination of the reconstructed shelf, it is here calculated on a cross section across the reconstructed shelf (estimated with PSL of 200 m; figure 4.11). The inclination is calculated with the Finite Difference Method (Stüwe, 2007) and basic trigonometry. I use the central difference method, expect for the first and last step, where forward- and backward difference methods are used:

$$\frac{dh}{dx} = \frac{h_{i+1} - h_{i-1}}{2\Delta x} \tag{3.3}$$

which is the central method, where $h$ is the height at every point and $\Delta x$ is $(x_{i+1} - x_i)$, where $x$ represents the distance. And:

$$\frac{dh}{dx} = \frac{h_{i+1} - h_i}{\Delta x} \tag{3.4}$$

which is the forward difference method, and the last Finite Difference equation is the backward difference method:

$$\frac{dh}{dx} = \frac{h_i - h_{i-1}}{\Delta x}. \tag{3.5}$$

When I have these points, I can calculate the angle between every point across the section. As mentioned, this is done with simple trigonometry, which gives the equation:

$$\tan\alpha = \frac{h}{x} \tag{3.6}$$

where $\alpha$ is the inclination.

3. Data and Method

# 4. Results

In this chapter, the reconstructed topography, bathymetry and shelf will be presented, in addition to calculations that have led to these results. First, the reconstructed topography and bathymetry for 4 Ma, with the uncertainties associated with this reconstruction, will be described. This is the starting point from where the reconstruction of the shelf can be estimated. Again, there are some uncertainties, such as PSL and porosity, which will be evaluated in more detail throughout the results chapter. Section 4.3 will focus on describing the inclination of the reconstructed shelf, while the final section in this chapter will focus on the main results that describe the comparison of offshore sedimentation with onshore erosional volume and shelf wedge volume (eq. 3.2).

## 4.1 Reconstruction of Topography and Bathymetry

As mentioned in section 3.1, the idea behind the reconstruction of topography and bathymetry, is to i) re-place fjord and valley erosion products, ii) remove the offshore sediment volume, and iii) consider flexural isostatic deflections because of fjord and valley erosion and offshore deposition.

### 4.1.1 Geophysical Relief

Fjord erosion has been calculated with the geophysical relief method (Small and Anderson, 1998, Steer et al., 2012), where linear interpolation is used between the highest points inside a sliding window with varying radius. However, the value for the radius is uncertain. Therefore, it is here tested with radius varying from 1 km to 10 km (Steer et al., 2012). As mentioned in section 3.2, an increase in radius results in an increase in fjord and valley erosion volume (figure 4.1). However, at a certain radius, the geophysical relief method fill in more than just the fjords and valleys, which lead to an overestimation. Therefore, the difficulty is to find the radius that give the most plausible fjord and valley erosion pattern. In Steer et al. (2012), the optimal radius was found to be 2 km, based on a comparison with an alternative approach for estimating fjord and valley erosion.

Figure 4.1 displays where and how much (in meter thickness) fjord erosion volume is filled in and around the fjords for a range of radius. Figure 4.2, shows the geophysical relief in more detail around Sognefjorden for a radius of 2 km. Here, most of the erosional material is found in the fjord itself, with around 2 km of sediments filled in.

**a.** **b.** **c.** **d.**

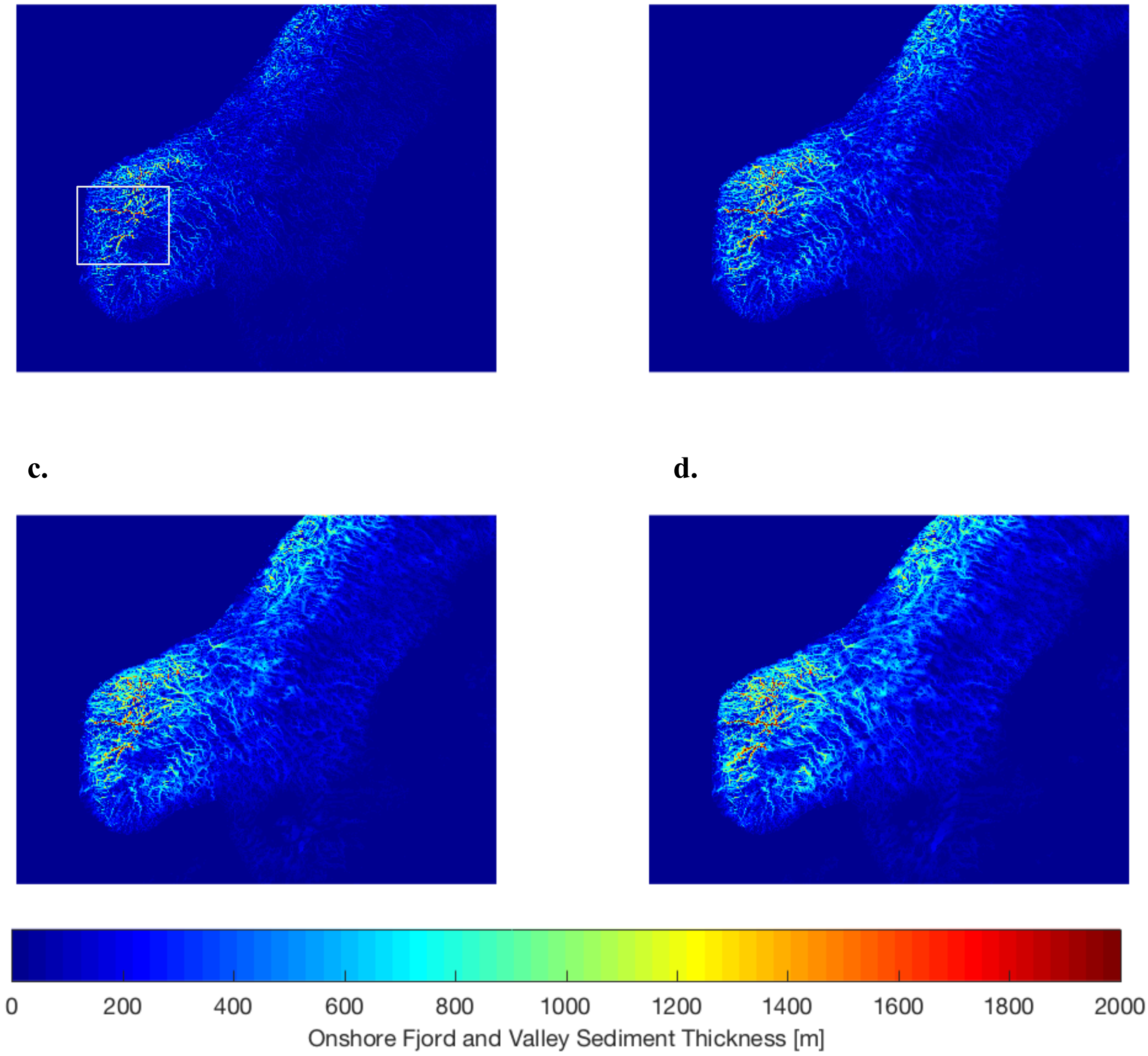



***Figure 4.1****: Fjord and valley erosion in southern Norway, calculated with the geophysical relief method, where the radius varies from 2 - 8 km (**a:** radius = 2 km, **b**: radius = 4 km, **c**: radius = 6 km, **d**: radius = 8 km). The erosional volume increases with increasing radius. White square in figure **a** is presented in figure 4.2.*

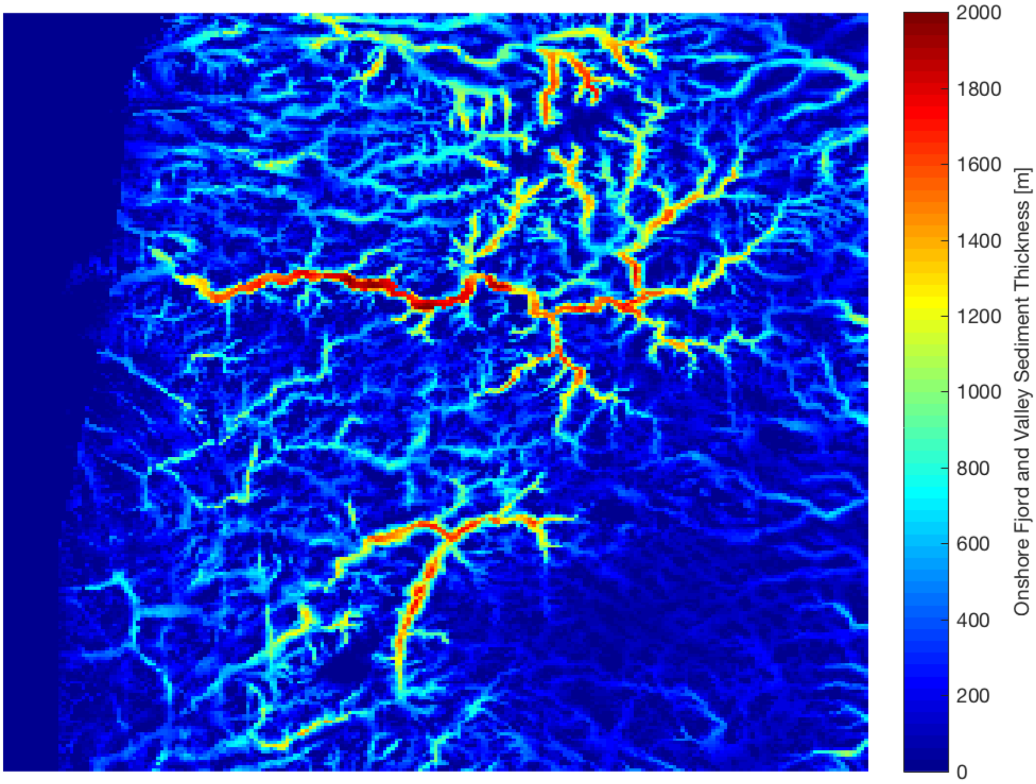



***Figure 4.2**: Fjord and valley erosion of Sognefjorden and Hardangerfjorden, calculated with radius of 2 km.*

The total volumes of fjord and valley erosion calculated with a sliding window radius, varying from 1 - 10 km are shown in figure 4.3, where the erosional volume increases with every calculation, as is also shown in figure 4.1. Figure 4.3 also display the offshore sediment volume with no correction of porosity, in addition to correction for both 20 % and 30 % porosity. The erosional volume from fjord and valley erosion is estimated to vary from $0.33 \times 10^5$ km$^3$, with radius of 1 km, to $1.65 \times 10^5$ km$^3$, with a radius of 10 km. If the fjord erosion alone were to match the offshore sedimentation volume, a radius of about 8 - 9 km is required, in addition to a porosity of ca. 30 % for the offshore sediments. The radius of 2 km, found to give the most realistic result for fjord and valley erosion in the Norwegian region by Steer et al. (2012), give a total fjord and valley erosion volume of $0.66 \times 10^5$ km$^3$. This corresponds to about 44 - 50 % of the offshore sediment matrix volume (figure 4.3).

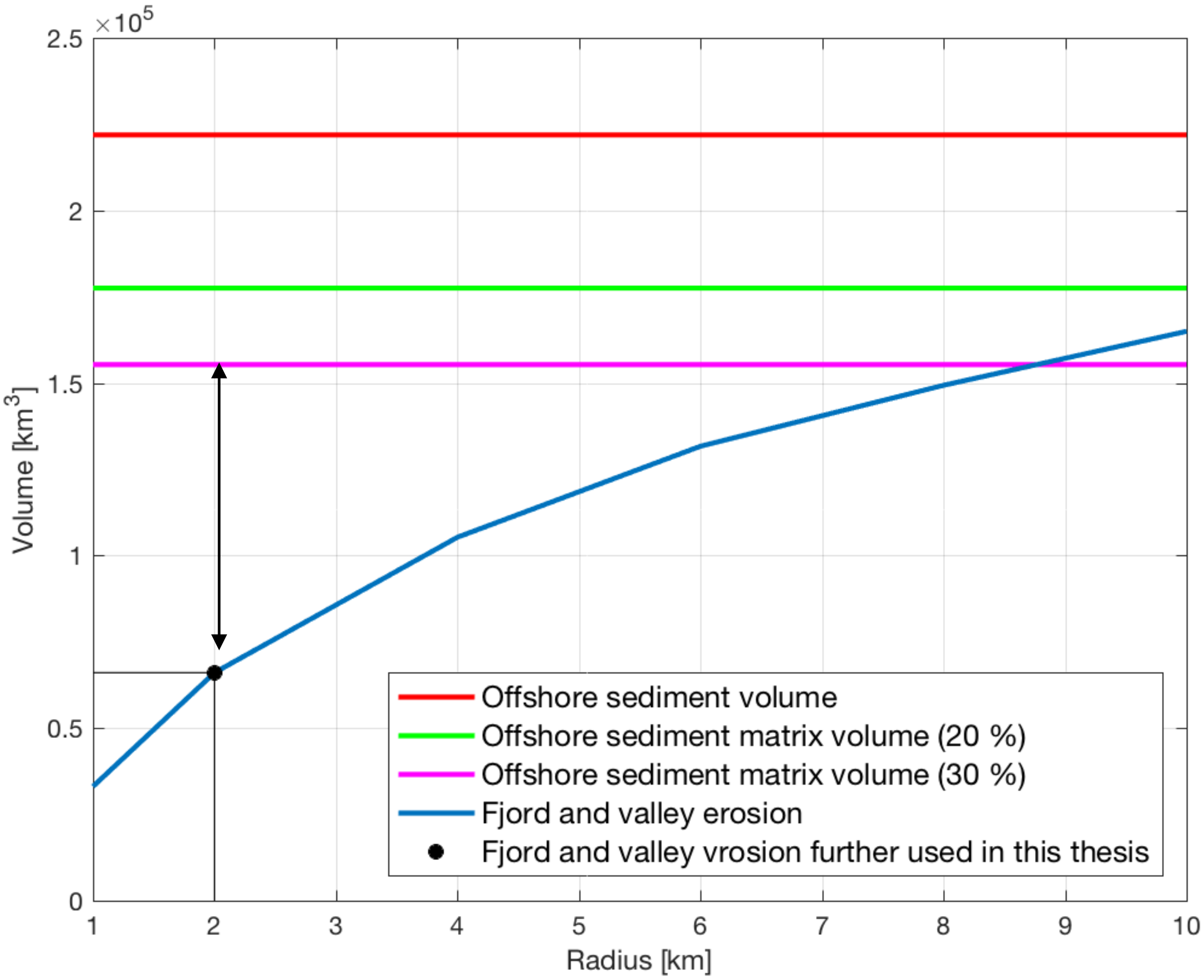



***Figure 4.3****: Fjord and valley erosion estimates of western Scandinavia compared to offshore sedimentation volume and offshore sediment matrix volume. Blue line represents fjord and valley erosion and the red line represents total offshore sediment volume, while the green and purple lines represents offshore sediment volume corrected for porosity. The black dot show the fjord and valley erosion volume calculated with a radius of 2 km. Volume mismatch (with 30 % porosity) is represented with arrow.*

### 4.1.2 Deflection

Figure 4.4 show the amount of deflection that the offshore sediment load and the onshore fjord and valley erosion load will give rise to. The results of deflection are defined as negative for both loads. Must therefore add $w_{GR}$, to get subsidence onshore as a result of re-placing the eroded rock volume, and subtract $w_{SED}$ to get uplift offshore because of removal of the sediment load in reconstructing the topography and bathymetry. The loads are not balanced because of the volume mismatch, where the offshore sediment load is much larger, but also due to the EET values. The EET values are generally lower offshore (figure 3.6), which give a more local response that does not affect the onshore very much, whereas the onshore EET values are larger, giving a more distributed response.

**a.** **b.**

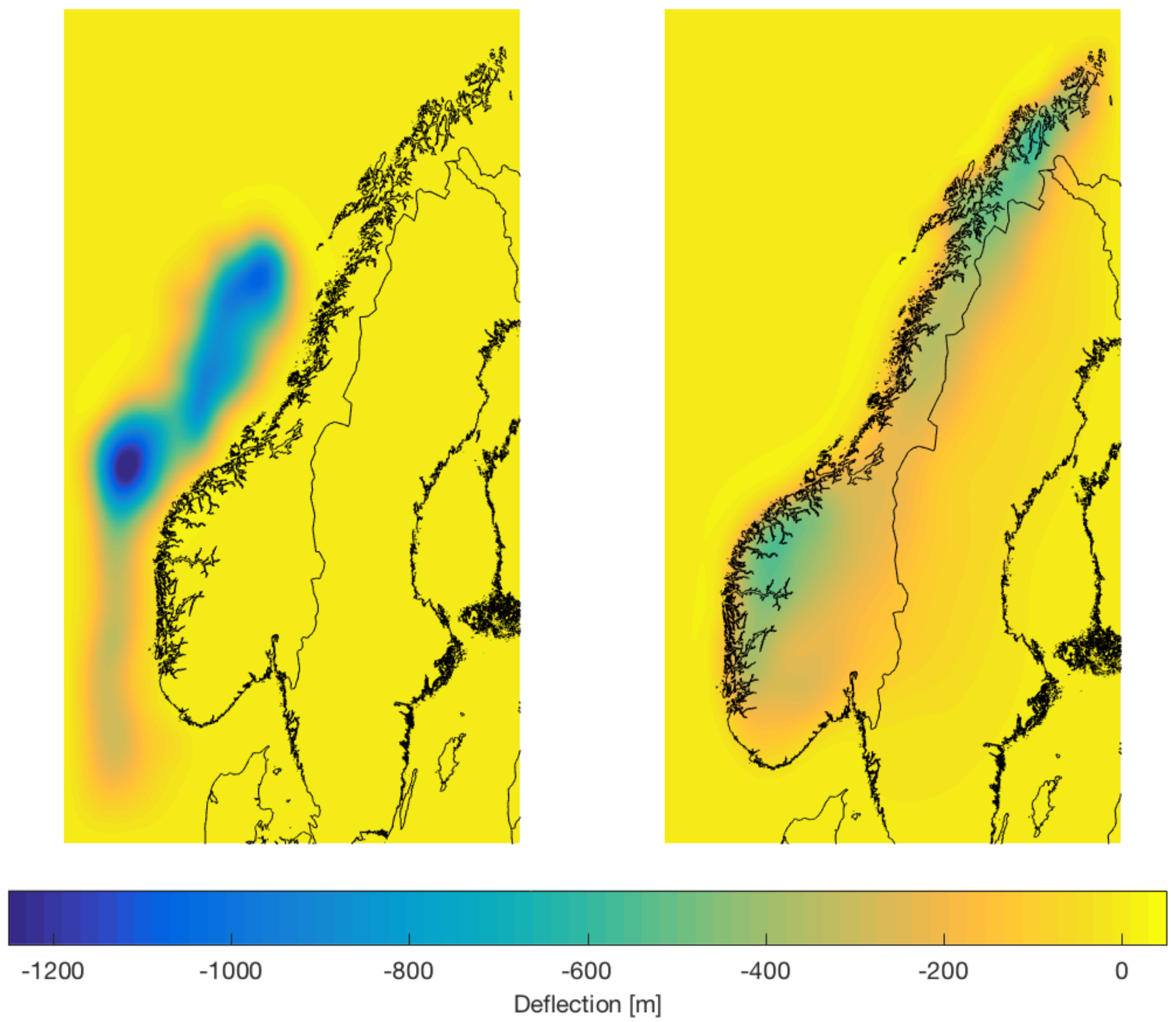



***Figure 4.4***: *Deflection of offshore sediment load* ***(a)*** *and fjord and valley erosion load* ***(b)****. The effect of the offshore sediment load is much larger than the effect of fjord erosion (calculated with a radius of 2 km) due to difference in sediment volume.*

### 4.1.3 Reconstructed Topography and Bathymetry

Since the fjord erosion estimates have an uncertainty related to the chosen radius, this also affect the onshore load and the resulting deflection. Figure 4.5 demonstrate the reconstructed topography calculated with a radius of 2 km which is the radius used in further comparisons, and 8 km, which is the radius needed for fjord and valley erosion to match the offshore sediment volume (figure 4.3). The general thickness of the re-placed erosion material increases due to an increasing radius and so does the corresponding deflection. Some fjords are still visible when fjord and valley erosion is calculated with a radius of 2 km. When increasing the radius of the sliding window, the result is that rock material would be filled in in more than just the fjords and valleys.

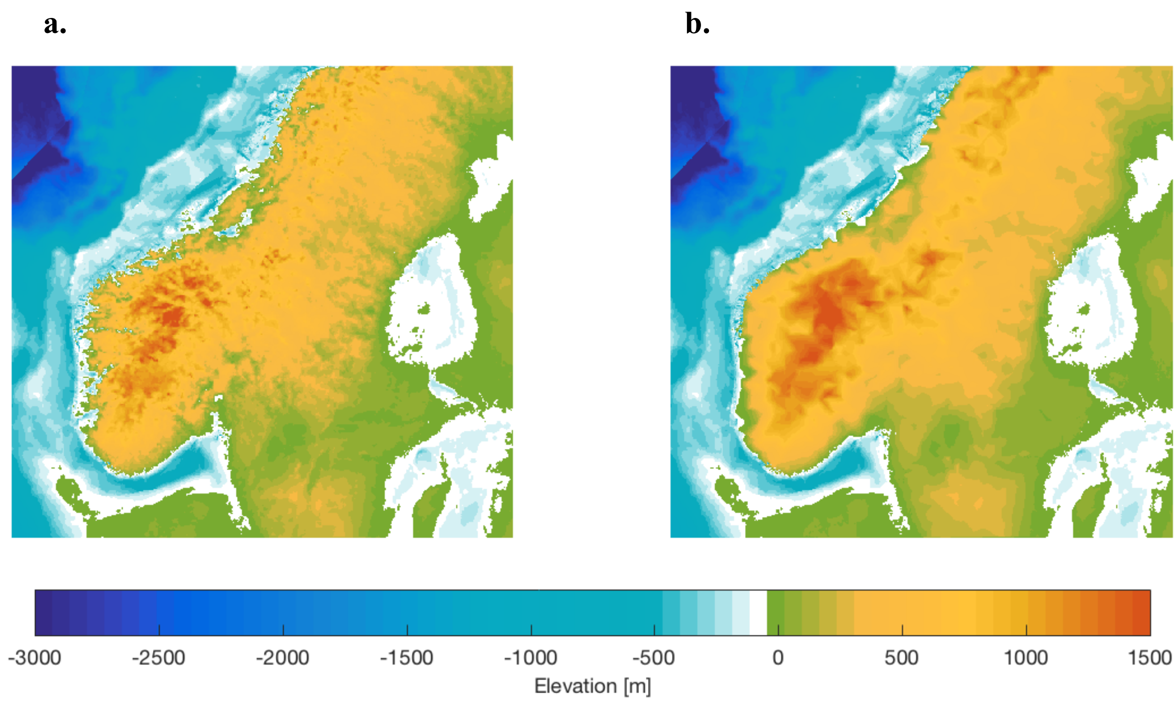



***Figure 4.5**: These figures show the reconstructed topography when re-placing the eroded material defined with a radius of 2 km (**a**) and 8 km (**b**), and including the deflection which is affected by the increase in fjord erosion volume. Figure **b** show the reconstructed topography where fjord and valley erosion match the offshore sedimentation volume.*

Figure 4.6 shows present-day topography and bathymetry compared to the reconstructed topography and bathymetry. The offshore sediment volume is removed, fjords and valleys are filled in with eroded rock volume and the flexural isostatic deflections of onshore erosion and offshore sedimentation are considered (figure 4.6b). Because of the removal of the offshore sediment load, there have been an offshore uplift of around 600 - 800 m, and in some areas 1200 m (figure 4.4a). Figure 4.6b show that the coastline has changed, where some of the coastal areas are under present-day sea level. This is related to the onshore subsidence, which also cause a reduction in elevation of the high topography.

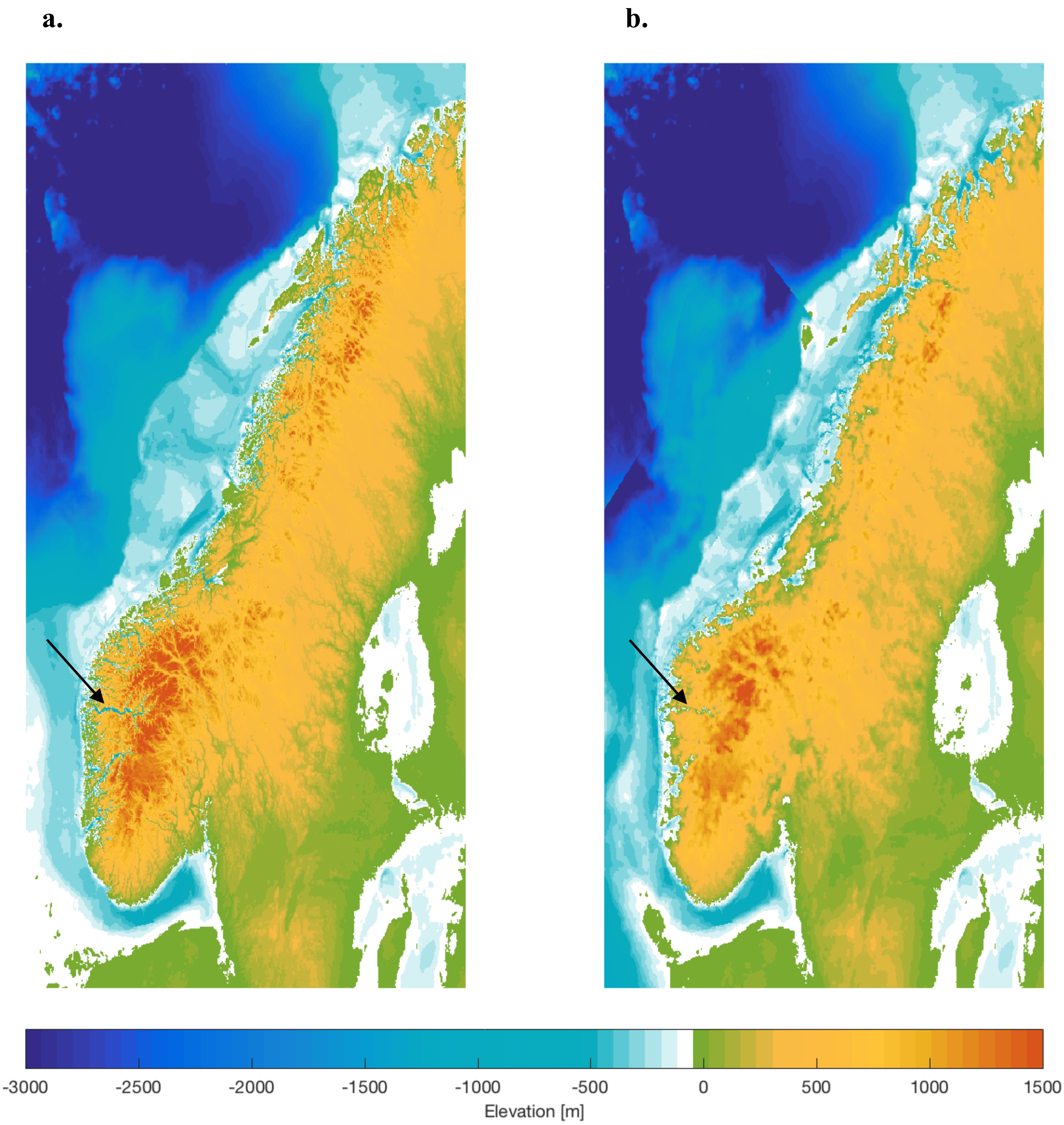



***Figure 4.6**: Comparison of present-day topography and bathymetry (**a**) and reconstruction of topography and bathymetry (**b**). The arrows are pointing at Sognefjorden, where figure **a** show negative values of about -1200 m, while in figure **b** the fjord is filled in, and show values of about -300 - 100 m (calculated with radius of 2 km).*

The difference between present-day topography and bathymetry, and the reconstructed topography and bathymetry show more clearly the exact fjord and valley erosion that have been re-placed, in addition to the removal of the offshore sediments. Most fjords and valleys are filled up with a thickness of about 300 - 500 m, while the larger fjords such as Sognefjorden and Hardangerfjorden are filled with a thickness of 1000 - 1500 m (figure 4.7). Figure 4.7 show where the offshore sediment volume from 4 - 0 Ma is removed from, and demonstrate overall negative values of around -500 m.

Figure 4.8 show the same difference as in figure 4.7, but with focus on the onshore in southern Norway, and a colour map that highlight the negative changes (positive values are saturated at 500 m). The high-elevation, low-relief surfaces in today's topography, such as Hardangervidda, are in figure 4.8 presented with negative values of about -100 m to -300 m. Some parts of the coastline are also shown with negative values. This means that the regions have experienced uplift as a result of fjord and valley erosion. On the high-elevation low-relief surfaces, the flexural isostatic uplift due to erosional unloading in adjacent fjords is larger than the local erosion.

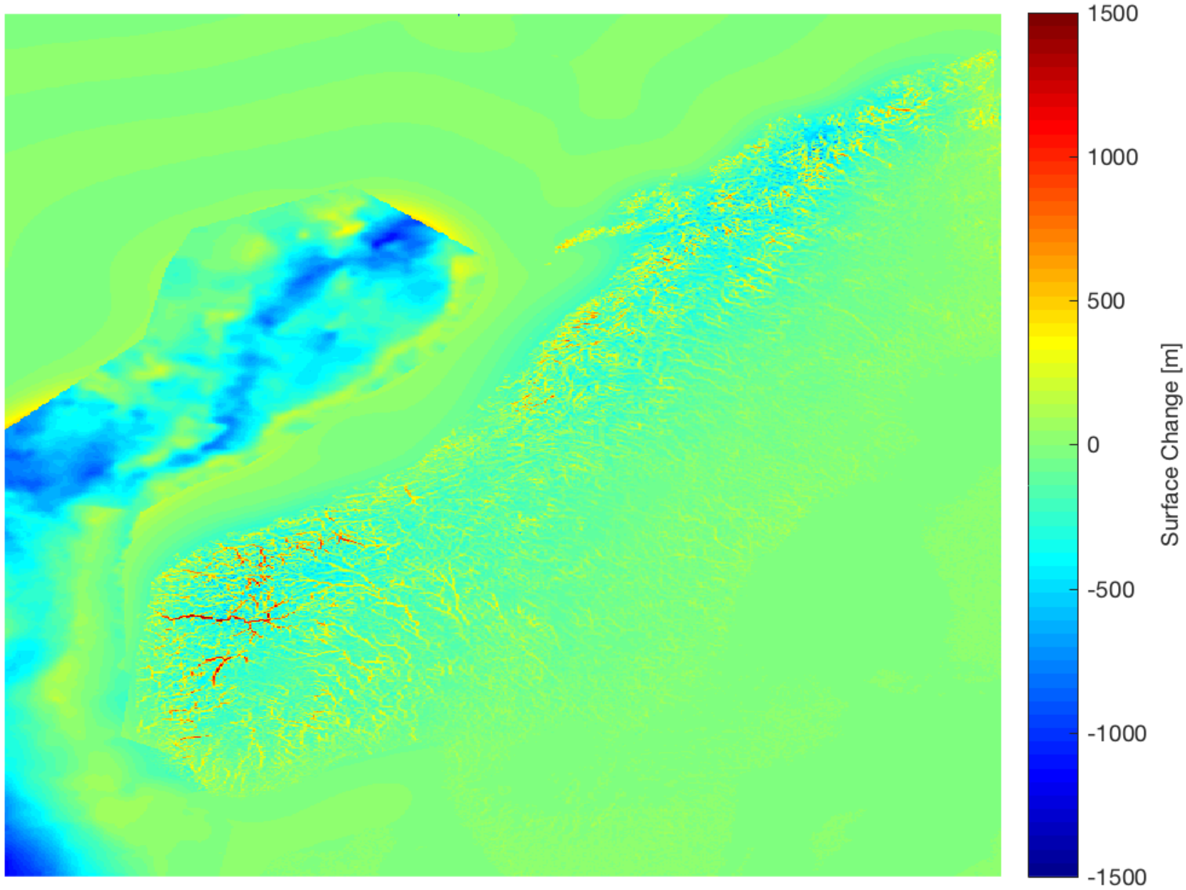



***Figure 4.7****: Difference between present-day topography and reconstructed topography, showing the surface changes.*

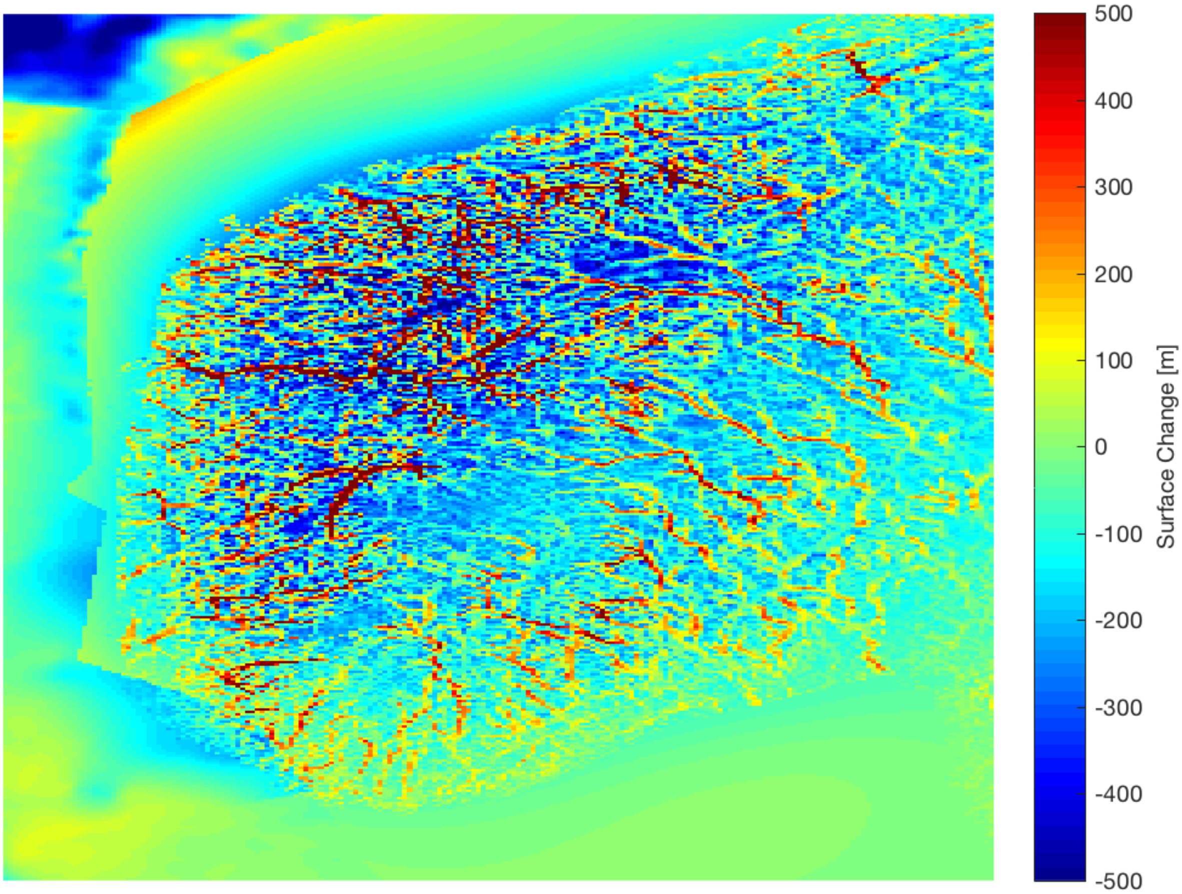



***Figure 4.8****: Southern Norway displayed with the difference between present-day topography and reconstructed topography. Yellow and red areas represent the areas where fjord erosion volume is re-placed, giving positive values. Blue areas, i.e. Hardangervidda, have negative values, which mean that these areas are about 100 - 300 m lower than the present-day topographic surface.*

## 4.2 Reconstruction of the Shelf

The reconstruction of the older sediments that have been eroded in coast-near regions and on the continental shelf is generated using the reconstructed topography, values for PSL, and the position of the Miocene-Pliocene boundary. The reconstruction is done in several steps for varying PSLs and three iterations of deflection (see section 3.6). In figure 4.11a, the reconstructed shelf is displayed, estimated with a PSL of 200 m. As the sediments are placed between the Miocene-Pliocene boundary at the seafloor and 200 m above present-day sea level on the topography, the sediment thickness is increasing towards the coastline (figure 3.3 and 4.11a). As mentioned in section 3.1, the concept used to reconstruct the older sediments that have been eroded in coast-near regions (the shelf wedge), gives a conservative estimate of how much sediments have been removed since 4 Ma ago. It is assumed that the old sediments could have existed in regions previously below sea level, considering eustatic sea level changes and changes due to dynamic topography, i.e. not including any tectonic component. The difference between the reconstruction of older sediments that have been eroded in coast-near regions and on the continental shelf, and the reconstructed topography and bathymetry, give us the shelf wedge (figure 4.9)

### 4.2.1 Shelf Wedge Volume

The range of PSL values considered here, and the number of iterations used in the deflection calculation, will result in different reconstructions of the shelf, and therefore different shelf wedge volumes. Figure 4.9 display different shelf wedges calculated with PSL varying from 200 m to 800 m above present-day sea level, and all using three iterations. As mentioned in section 3.6, the shelf wedge volume roughly converges after three iterations in the deflection calculations. Figure 4.9 and 4.10 show an increase in shelf wedge volume with increasing PSL. The calculated shelf wedge volumes, when not corrected for porosity, vary from $0.47 \times 10^5$ km$^3$ with PSL at 200 m to $1.05 \times 10^5$ km$^3$ with PSL at 800 m.

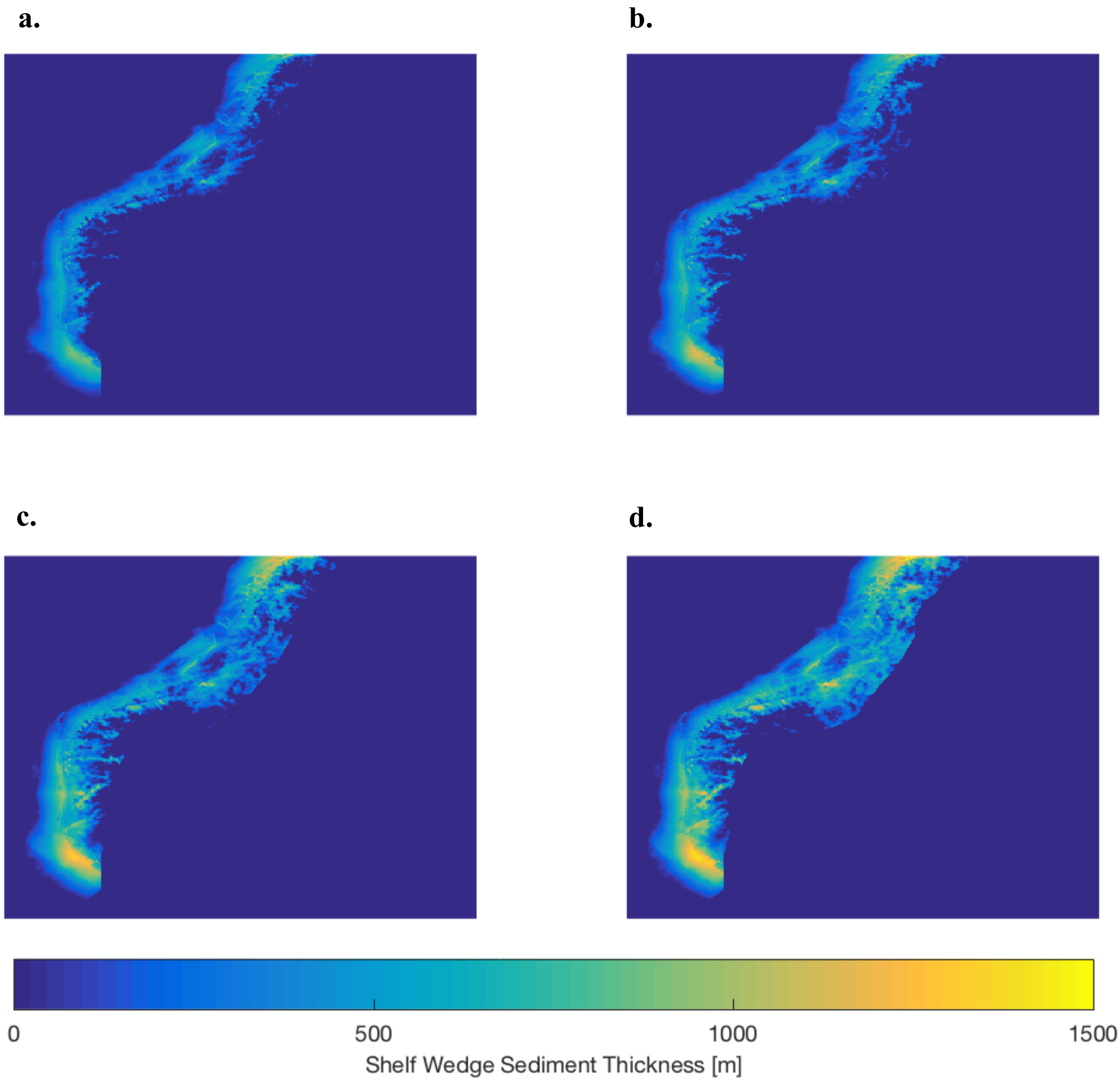
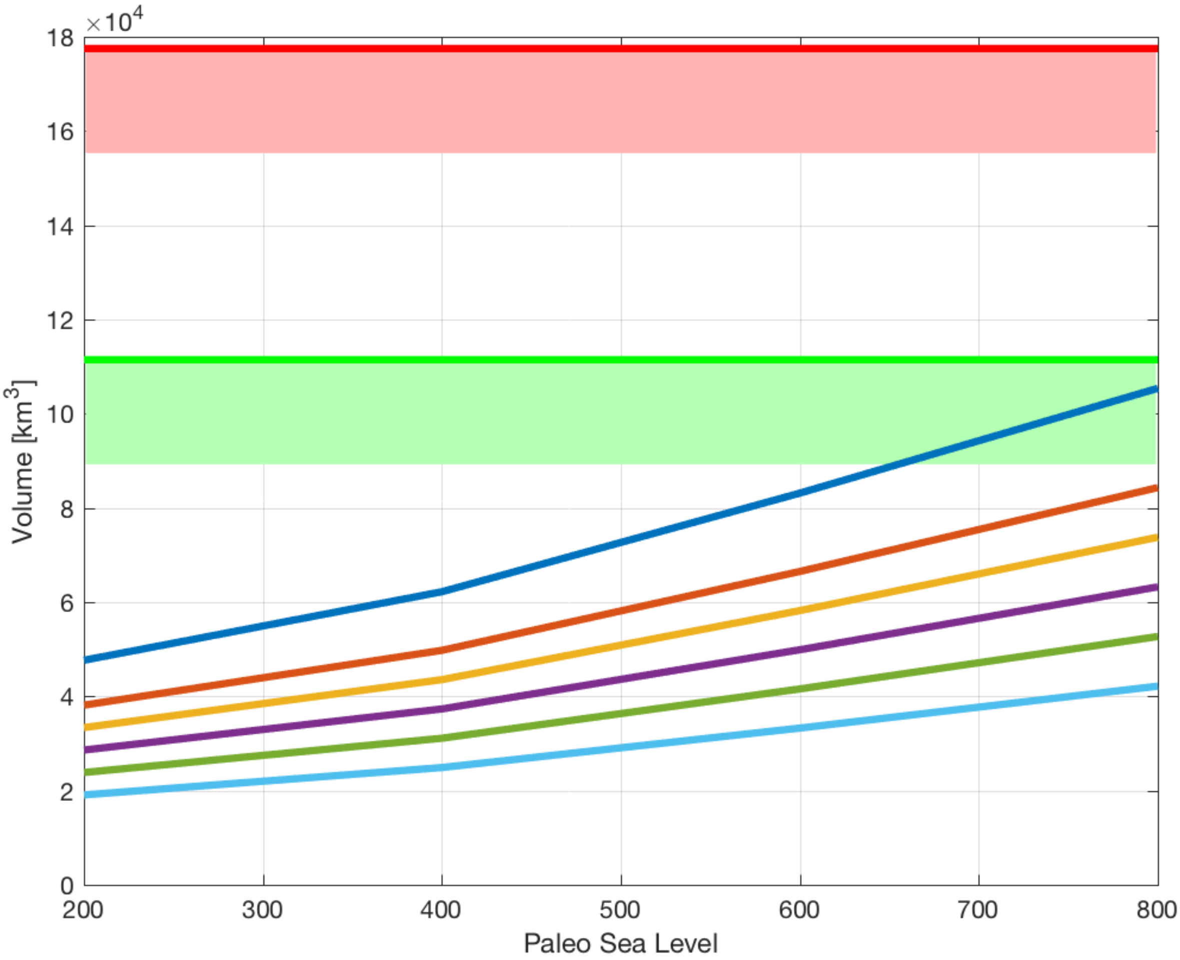



***Figure 4.9***: *Comparison of the different shelf wedge volumes due to increasing PSL (**a**: PSL = 200 m, **b**: PSL = 400 m, **c**: PSL = 600 m, **d**: PSL = 800 m). The higher the PSL, the larger the area of the shelf wedge gets. Larger area and volume, also increases the deflection.*

The shelf wedge matrix volume depends on the porosity assumed for the old sediments, and decreases accordingly with porosity assumptions between 20 - 60 % (figure 4.10). Figure 4.10 also displays the offshore sediment matrix volume for an assumed porosity range between 20 - 30 %, including the volume difference between the offshore sediment matrix volume and the fjords and valley erosion volume (calculated with radius of 2 km). A PSL value higher than 650 m above present-day sea level is required to be able to match the onshore erosional material (fjord and valley erosion + erosion of older sediments in coast-near regions) to the offshore sediment matrix volume. However, including the porosity of the eroded older sediments, the PSL needs to be significantly higher.



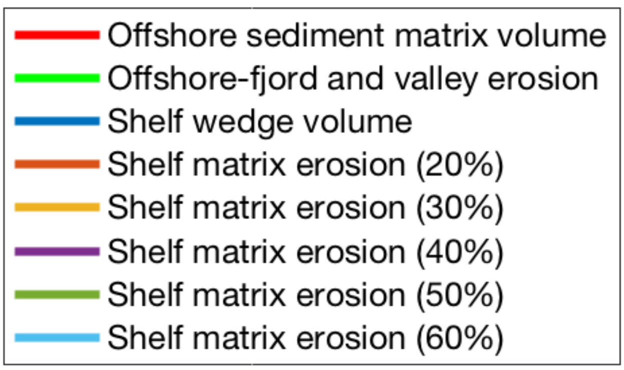




***Figure 4.10**: Shelf wedge volume and shelf matrix erosion versus PSL. Red line and gradation represent the offshore sediment volume (4-0 Ma) with correction of porosity between 20 % and 30 %. The green area is the offshore sediment volume subtracted fjord and valley erosion (radius = 2 km), with the same porosity corrections.*

## 4.3 Inclination of Shelf

Often the inclination of the sediment layers that make up the shelf is exaggerated to accentuate the structures. In previous work by Gołędowski et al. (2013), they have reconstructed the shelf, and found that the inclination decreased significantly compared to the present-day offshore surface. In this study, calculated inclinations of the surfaces of the reconstructed shelf, would give similar results as Gołędowski et al. (2013), although to a less degree since Gołędowski et al. (2013) reconstruct for the whole Cenozoic.

The inclination estimates from the reconstructed shelf (figure 3.3), have been calculated along one profile located in western Norway, near Hardangerfjorden. Figure 4.11b show a cross section of the shelf, going from around 250 m below present-day sea level and up to 200 m above present-day sea level, while figure 4.11c display the inclination values, where the majority of the values give inclinations of 0.2° and 0.3°. The largest inclination estimates are calculated with PSL of 800 m, and give values of inclinations between 0.3° and 0.4°.

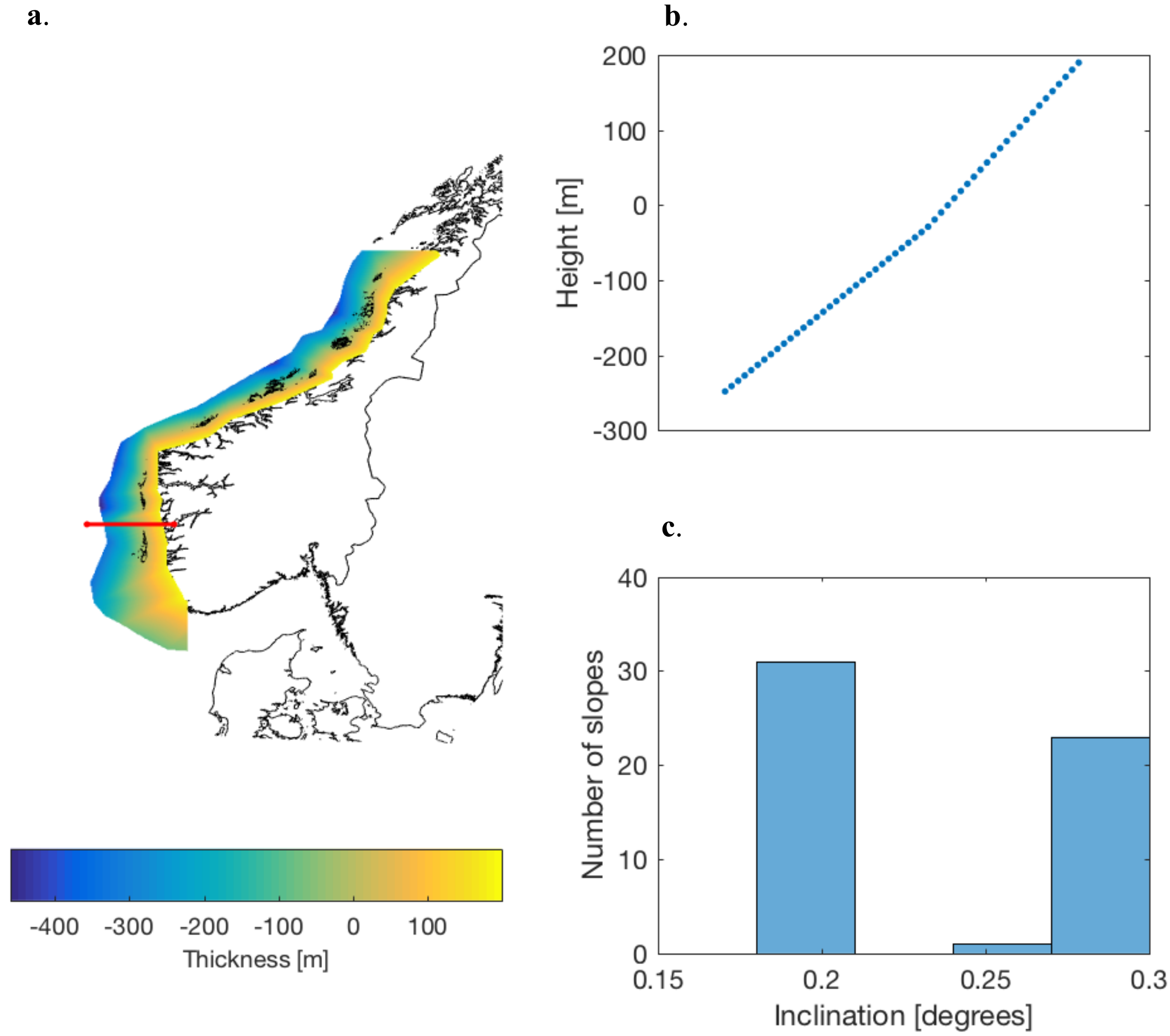



***Figure 4.11**: Figure **a** show the reconstructed shelf in thickness meters, with a red line that represents the cross section shown in figure **b**. The inclination is calculated between each point on the profile. Shown in figure **c**, is a histogram of the inclinations that are between 0.1° and 0.3°.*

## 4.4 Volume Mismatch

Equation 3.2 explains the different components that is used to do a volume mismatch test. Offshore sediment matrix volume from the last 4 Ma defines the rock volume that is in this thesis, attempted to be re-placed onshore (figure 4.12). Onshore erosion volume is the combination of shelf matrix volume, fjord and valley erosion volume, and onshore erosion outside fjords and valleys. As mentioned earlier, the estimated volume of fjord and valley erosion has been calculated with radius of 1 - 10 km (figure 4.3). However, in this mismatch test, the focus is on the fjord and valley erosion volume calculated with a radius of 2 km, which give an erosional volume of $0.66 \times 10^5$ $km^3$.

The shelf wedge volume is estimated with PSL values of 200 - 800 m, and later corrected for porosity using 20 - 60 % to get the shelf matrix erosion volume. With a PSL of 200 m and porosity of 20 % (Halland et al., 2014), this give an erosional volume of $0.38 \times 10^5$ $km^3$. The shelf wedge presented in figure 4.13 is calculated with a PSL of 200 m, and show the outline of where the shelf wedge would be when calculated with PSL of 800 m.

The volume mismatch is also shown in figure 4.10, where fjord and valley erosion (radius of 2 km) is subtracted from offshore sediment matrix volume, and compared to estimates of shelf wedge matrix volume of various PSLs. Table 4.1, display the volume mismatch for a PSL of 200 m and 600 m, with offshore sedimentation porosity corrections of 20 - 30 %, and shelf wedge porosity corrections of 20 - 60 %. The table show that the lowest mismatch value, of 7 %, is achieved with PSL of 600 m, 30 % correction of porosity for offshore sedimentation volume and a porosity correction of 20 % for the shelf wedge volume.

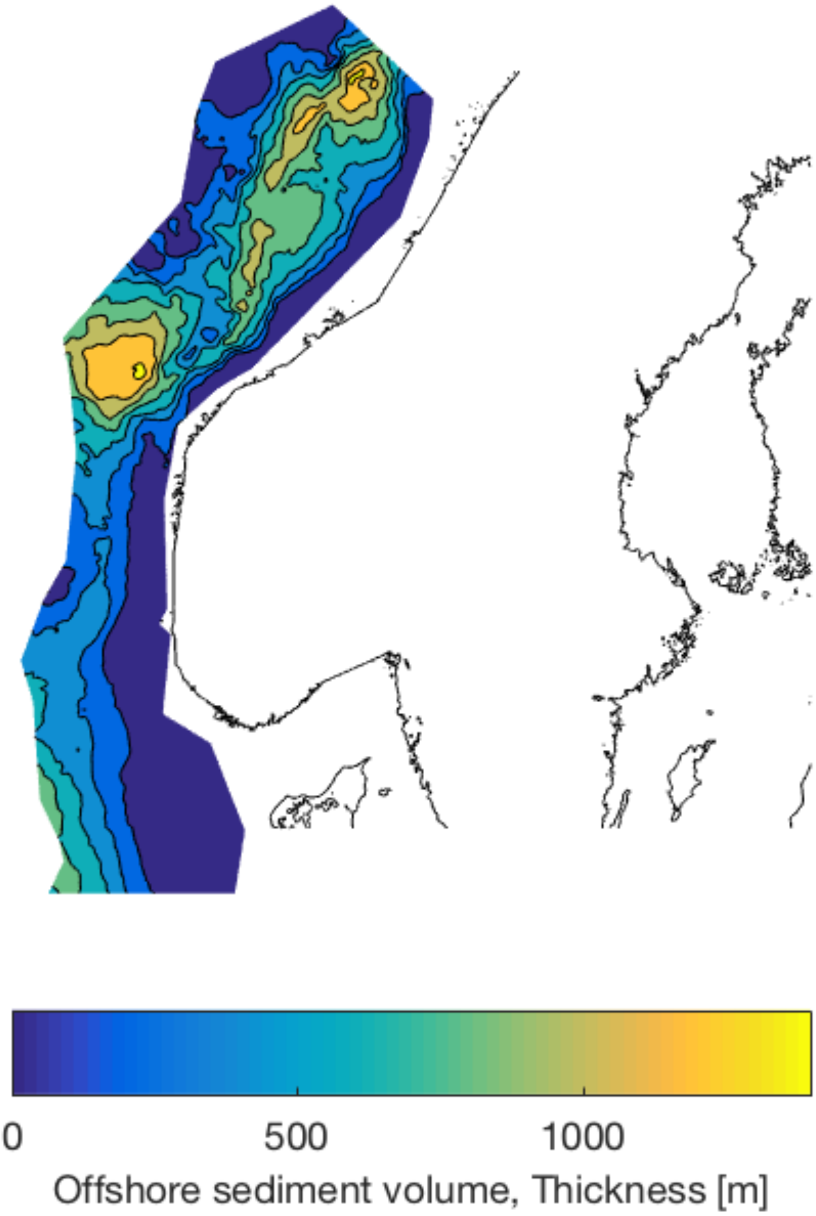



***Figure 4.12**: Total offshore sediment matrix volume (4 - 0 Ma) on Norwegian continental margin.*

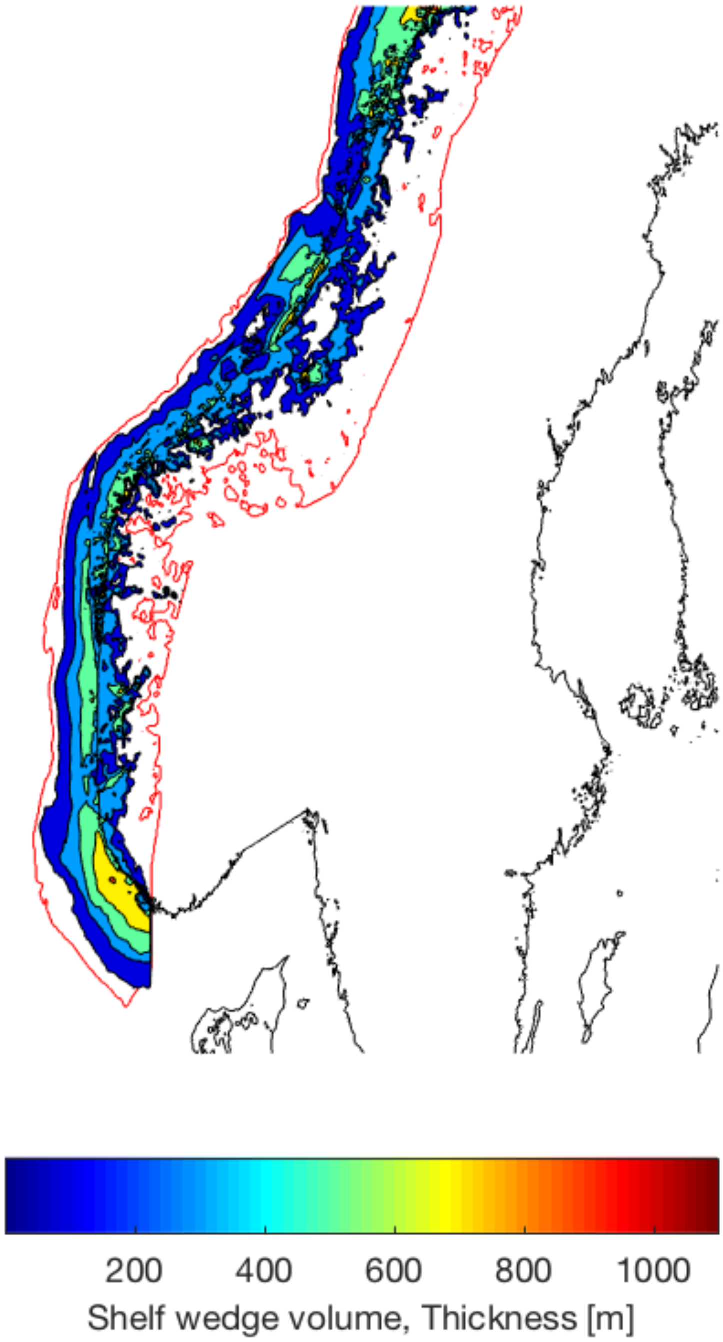



***Figure 4.13***: *Shelf wedge volume displayed with PSL of 200 m along the Norwegian coastline. The red line represents the outline of the shelf wedge calculated with PSL of 800 m.*

| **PSL (m)** | **Offshore - Porosity (%)** | **Shelf Wedge - Porosity (%)** | **Volume Mismatch (%)** |
|---|---|---|---|
| 200 | 20 | 20 | **34** |
| 200 | 20 | 30 | **37** |
| 200 | 20 | 40 | **39** |
| 200 | 20 | 50 | **42** |
| 200 | 20 | 60 | **45** |
| 200 | 30 | 20 | **25** |
| 200 | 30 | 30 | **28** |
| 200 | 30 | 40 | **31** |
| 200 | 30 | 50 | **34** |
| 200 | 30 | 60 | **37** |
| 600 | 20 | 20 | **18** |
| 600 | 20 | 30 | **23** |
| 600 | 20 | 40 | **28** |
| 600 | 20 | 50 | **32** |
| 600 | 20 | 60 | **37** |
| 600 | 30 | 20 | **7** |
| 600 | 30 | 30 | **12** |
| 600 | 30 | 40 | **17** |
| 600 | 30 | 50 | **23** |
| 600 | 30 | 60 | **28** |

***Table 4.1***: *Volume mismatch estimates for PSL values of 200 m and 600 m, with varying porosity of both offshore sedimentation volume and shelf wedge volume.*

# 5. Discussion

The present-day topography of western Norway display a landscape that have been modified by glacial erosion (Steer et al., 2012). This erosion deepened the already existing valleys and formed the fjords. In addition to these spectacular fjords, there is also high-altitude low-relief surfaces, which are not so easy to explain (Steer et al., 2012, Egholm et al., 2017). From the two end-member hypotheses (hypotheses 1 and 2), it is suggested that the present topography have either been developed from Cenozoic tectonic uplift of a Mesozoic peneplain, or that it is remnants of the Caldeonian orogeny, that have been modified by glacial and periglacial erosion.

The focus of this thesis has been to match the offshore sedimentation volume from the last 4 Ma, deposited along the Norwegian margin and in the northern North Sea, with the erosional volume that could be expected from fjords, valleys and from erosion of older sediments on the shelf. The discussion will focus on the uncertainty values that are needed for this balance to be complete. In addition, I will discuss the most realistic values for radius, used in the geophysical relief method, PSL values and porosity values for offshore sedimentation volume and the shelf wedge volume.

## 5.2 Onshore Fjord Erosion and Offshore Sediment Matrix Volume

Steer et al. (2012) suggested a test to distinguish between the two end-member hypotheses presented in section 1.3 (hypothesis 1 and 2), which lies is their ability to quantitatively match the onshore erosional volume with offshore sedimentation. Thus, by quantifying the volume of fjord and valley erosion in western Norway and comparing this with sediments deposited offshore in Scandinavia during late Pliocene and Quaternary, it is possible to assess whether erosion has also taken place elsewhere during this period (Steer et al., 2012).

The total offshore sediment volume, used in this thesis, is from the past 4 Ma and is $221.9 \times 10^3$ $km^3$ (Gołędowski et al., 2012). In converting this to an erosional volume equivalent (offshore sediment matrix volume), the porosity was assumed to be 20 - 30% (Steer et al., 2012), which gives an erosional volume between $155.33 \times 10^3$ $km^3$ and $177.52 \times 10^3$ $km^3$. This correspond well with the values used by Steer et al., (2012), where a total offshore sediment volume from the last 2.8 Ma, was assumed to be $225 \pm 20 \times 10^3$ $km^3$, and converted into an erosional volume equivalent of $180 \pm 16 \times 10^3$ km$^3$, with an assumed porosity of 20 % (Dowdeswell et al., 2010). In the volume mismatch test, this sediment matrix volume represents the offshore volume that is compared with the onshore erosional potential, consisting of shelf matrix erosion (see section 5.3), and onshore fjord and valley erosion, which is discussed in the next paragraph.

Fjord and valley erosion, is estimated with a similar geophysical relief approach as is used in Steer et al. (2012), and thus gives similar estimates. By varying the radius of the sliding window between 1 - 10 km, we get a fjord and valley erosion volume from $33 \times 10^3$ km$^3$ to $165 \times 10^3$ km$^3$. The fjord and valley erosion volume calculated with a sliding window of 2 km is estimated to be about $66 \times 10^3$ km$^3$, which corresponds to only about 44 - 50 % of the total offshore volume. For fjord and valley erosion to match the total offshore sediment volume, a sliding window of 8 - 9 km would be required. However, based on observations in Steer et al. (2012), a radius larger than 2 km would be an overestimation. These results confirm that there must have been significant erosion from somewhere else than just the fjords and valleys, contributing to the offshore sediment deposition between 4 - 0 Ma.

## 5.2 Reconstruction of Topography and Bathymetry

The concept used to reconstruct the topography and bathymetry is explained by equation 3.1. This equation shows the different components that are needed to successfully reconstruct paleo topography and bathymetry from 4 Ma ago. After this reconstruction, a shelf wedge is added on the inner shelf and along the coastline, which contributes to the volume mismatch test as a part of the onshore erosional potential. This shelf wedge contribution is discussed in the next section.

Estimates of fjord and valley erosion and the offshore sediment volume deposits are discussed in the previous section. In the reconstruction of topography and bathymetry, the flexural isostatic response due to i) fjord and valley erosion and ii) offshore sediment deposition is also considered. The resulting reconstructed topography and bathymetry is shown in figure 4.6, and the total surface changes are displayed in figures 4.7 and 4.8. Negative surface changes are found in the patches onshore outside of fjords and valleys, and along the coast, which indicate that some areas were several hundred meters lower than at present.

Figure 4.8, indicate an uplift of about 100 - 300 m of high-altitude low-relief surfaces, such as Hardangervidda, which correspond with the dynamic uplift values in Pedersen et al. (2016), where it is found that there might have been around 300 - 400 m of dynamic uplift in southern Norway. The observations also correspond well with the results from Gołędowski et al. (2013), where they reconstruct the topography based on a fluvial landscape algorithm, and consideres the isostatic respons of the transfer of rock masses. Gołędowski et al. (2013) compare the reconstructed topography and present-day topography, where the results demonstrate areas that are hundreds of meter lower than the present-day topography. According to Gołędowski et al. (2013), this indicate that isostatic rebound exceeded the erosion during the whole Cenozoic in these areas. The results from Gołędowski et al. (2013) therefore confirm that the trend observed in this thesis for the last 4 Myr is consistent for the whole Cenozoic.

## 5.3 Shelf Wedge Volume

The shelf wedge volume represents the erosion of older sediments at the coast and inner shelf, which according to Hall et al. (2013) may be the sediment volume that can solve the mismatch between onshore fjord and valley erosion and offshore deposition found by Steer et al. (2012). Hall et al. (2013) have estimated that about 70 000 $km^3$ of material has been removed from the inner shelf. Hall et al., (2013) define this shelf volume by setting an average inner shelf of 100 km and the removal of 0,5 km of rock. This give an estimated volume of 42 000 $km^3$ from southern Norway and 30 000 $km^3$ from middle Norway (Hall et al., 2013). These estimates are based on sediment geometry, vitrinite reflection data of Jurassic shales (Nielsen et al., 2009) and compaction studies of Late Cretaceous chalk (Japsen, 1998), that indicate a removal of 0 - 1 km of overburden, where most of the erosion occurred during the last 3 Ma (Riis, 1996).

In this thesis, the shelf wedge volume is estimated with a new method, where the sediments are re-placed in a wedge from the Miocene-Pliocene boundary up to a PSL (figure 3.3). These sediments may be as old as Jurassic shales, and Late Cretaceous chalk (Hall et al., 2013), which indicate that the shelf wedge sediments, that have now been eroded, could have had a largely variable porosity. It does not seem like Hall et al. (2013) have considered the porosity of the inner shelf sediments, which would change the result of their sediment volume considerably. This thesis finds a shelf wedge volume that varies from $47.655 \times 10^3$ $km^3$ using a PSL at 200 m to 105.39 $\times$ $10^3$ $km^3$ with a PSL of 800 m, if the sediments wedge is not corrected for porosity. This correspond well with the results from Hall et al. (2013). However, when taking account for varying porosity of 20 - 60 %, the shelf matrix erosion changes considerably.

In the study by Halland et al. (2014), porosities for some of the old sediment units are found to vary between 19 - 34 %, which give an indication for a reliable porosity. I therefore conclude that a porosity of 20 % would give a somewhat realistic results. As mentioned in section 3.1, I assume that the relative sea level has been at least 200 m above present-day sea level (Miller et al., 2005), which give shelf matrix erosion between 19 $\times$ $10^3$ $km^3$ and 38 $\times$ $10^3$ $km^3$. By including the dynamic topography (Pedersen et al., 2016), the relative sea level could have been much higher. I have tested with a maximum PSL of 800 m, which give a shelf matrix erosion between 42 $\times$ $10^3$ $km^3$ and 84 $\times$ $10^3$ $km^3$, with porosity corrections of 60 % and 20 %, respectively (figure 4.10).

## 5.4 Volume mismatch

The main focus of this thesis is to explore which scenarios result in a balance in the volume equation defined in section 3.3 (eq. 3.2) and thereby resolves the mismatch that has previously been put forward by Steer el. (2012). Therefore, I find the onshore erosional potential of south-western Scandinavia, which is a combination of onshore fjord and valley erosion of older sediments in coast-near regions and on the inner shelf (shelf wedge volume). This onshore erosional potential varies with different values of i) radius used in the geophysical relief method, ii) the maximum relative sea level in the period where the older shelf sediments were deposited (PSL), and iii) porosity of offshore sedimentation volume and the older shelf wedge sediments. By testing reasonable ranges for these parameters, I can explore what values that result in the balance in the volume equation (eq. 3.2). However, these values may not be the most realistic values, meaning it may be an overestimation. The term “onshore erosion outside fjords and valleys” have not been constrained here, this will be discussed in relation to the parameters that is assumed to be the most realistic values.

Fjord and onshore valley erosion estimated with radius of 2 km, represent about 44 - 50 % of offshore sediment matrix volume. The shelf wedge volume estimated in this thesis, with a PSL of 200 m and no correction for porosity, represent 26 - 30 % of the offshore sediment matrix volume. This gives a volume mismatch of 18 - 29 %, which could represent onshore erosion outside fjords and valleys. By correcting for porosity of 20 - 60 % for the shelf wedge volume, the mismatch increases, as is shown in figure 4.10 and table 4.1. This give a volume mismatch of 25 - 45 % for a PSL of 200 m.

Estimates of fjord and valley erosion, calculated in the study by Steer et al. (2012), corresponds to 35 - 55 % of the total volume of offshore sediment, which coincide with the estimates of this thesis (44 - 50 %). The small difference, can be explained by the parameters used. Steer et al. (2012) base the estimates on a radius of 1 - 2 km, and a constant porosity correction (of total offshore sediment) of 20 %, while my estimates are based on a constant radius of 2 km, and a porosity correction of 20 - 30 %. However, Steer et al. (2012) do the volume mismatch test with just onshore fjord and valley erosion, which is only one of the components in the onshore erosional potential that is considered in my thesis.

Hall et al. (2013) consider both fjord and valley erosion, and shelf wedge volume in the onshore erosional potential. However, the method used for defining the shelf wedge and volume is very different from the approach taken in this thesis. According to Hall et al. (2013), the inner shelf sediment would resolve the mismatch, which indicate that there has been no extra onshore erosion outside the fjords. This do not correspond with my results, which indicate that there is no realistic scenario which would fulfil the mismatch test.

In table 4.1, the volume mismatch is presented for the most realistic PSLs, which is a relative sea level of 200 - 600 m above present-day sea level. This is based on eustatic, global sea level changes (Miller et al., 2005) and dynamic topography (Pedersen et al., 2016). The porosities for the old sediments in the shelf wedge, are tested with corrections of 20 - 60 %. However, a porosity of 20 % is a realistic assumption, based on observations of some of the sediment units (Halland et al., 2014). With these values, my results indicate an estimated volume mismatch between a minimum of 7 % and maximum 34 % (table 4.1), which means that there has been some additional onshore erosion outside fjords.

## 5.5 Inclination

Gołędowski et al. (2013) have reconstructed a pre-Cenozoic fluvial landscape without elevated low-relief surfaces. From this reconstruction, the present-day inclination of the Base Cenozoic surface vary between 0° - 8°, while the inclination after reconstruction are between 0° - 3°. The approach used in this thesis, give a similar result, although not to the same extent, since the reconstructed shelf in this thesis is calculate for 4 Ma, while Gołędowski et al. (2013) use the whole Cenozoic. The reconstructed shelf in this thesis have inclinations between 0.2° and 0.3°, when calculated with a PSL of 200 m, and about 0.3° - 0.4° when calculated with a PSL of 800 m. These inclination values are much lower than the observed inclinations in Gołędowski et al. (2013), even in the scenario where the sediments are balanced. This suggests that way too much sediment would be added if the true inclinations of the sediment layers were extrapolated onto the topography, as suggested by Riis (1996).

This landscape reconstruction by Gołędowski et al. (2013), implies that the present tilt of the offshore strata was partly caused by isostatic adjustment, which were unrelated to other forms of tectonism. The present-day inclination of Base Cenozoic, in some areas, are relatively high. This, according to Gołędowski et al., (2013), indicate that the remaining tilt that is present at the reconstructed offshore bathymetry, are caused by continued thermal subsidence and compaction of pre-Cenozoic sediments.

# 6. Conclusion

Throughout this thesis, I have attempted to compare the Pliocene-Pleistocene offshore sediment volume found in the northern North Sea and along the Norwegian margin, with onshore erosional potential. The onshore erosional volume includes fjord and valley erosion and erosion of older sediments of the inner shelf and cost-near regions. Similar volume mismatch studies have been done previously by Steer et al. (2012) and by Hall et al. (2013). However, these former studies either neglected the erosion contribution from older sediments eroded on the shelf (shelf wedge) and in coast-near regions altogether (Steer et al., 2012), or estimated this contribution with a very simplistic approach (Hall et al., 2013). In this thesis, I have tested a more precise approach in quantifying the potential contribution from erosion of a shelf wedge, thereby answering the question, whether there has been some onshore erosion outside fjords and valleys during the last 4 Ma.

Estimates of fjord and valley erosion volume are calculated with a varying sliding window radius of 1 - 10 km. A sliding window radius of 8 - 9 km would be required for the fjord and valley erosion volume to match the offshore sediment matrix volume. However, I found that a radius of 2 km best reflect the fjord and valley erosion, as a larger radius would fill in more than just the fjords and valleys (Steer et al., 2012).

Estimates of the shelf wedge volume, which is the difference between reconstructed topography and the reconstructed shelf, varies greatly due to the uncertainty of PSL values and the porosity of the older sediments in the shelf wedge. For the balance between offshore sedimentation and onshore erosional potential, with porosity corrections for the shelf wedge, to be complete, a PSL above 800 m is required, in addition to 30 % correction of porosity for the offshore sediment volume. Realistic values of PSL could be between 200 - 600 m (Miller et al., 2005, Pedersen et al., 2016), while a porosity of 20 % is a realistic assumption for the older sediment in the shelf wedge (Halland et al., 2014). The total relative sea level change, is found to be 320 m above present-day sea level, when assumed PSL of 200 m, and 740 m above present-day sea level, when assumed PSL of 600 m.

Taking all this into consideration, there seem to be no realistic scenarios which would fulfil the mismatch test. By quantifying the contribution from shelf wedge erosion to the onshore-offshore volume balance, my thesis work gives support to the idea that some erosion has taken place outside of fjords and valleys (Egholm et al., 2017, Andersen et al., 2018). However, the amount of erosion is roughly about a third of the amount previously suggested by Steer et al. (2012). This indicates that about 33 - 50 meters of erosion may have taken place at the high-altitude low-relief regions during the last 4 Ma. These results are not consistent with the classical model (hypothesis 1), which suggest that the high-altitude low-relief surfaces are remnants of a Mesozoic peneplain. However, the results are consistent with both the ICE-hypothesis (hypothesis 2), which suggest glacial and periglacial erosion of the high-altitude low-relief surfaces, and the combination of the previous end-member hypotheses (hypothesis 3). The result indicates that there must have been a PSL value above 200 m to even get close to an onshore-offshore volume balance. This suggest that there has been some dynamic uplift along the coast, which correspond well with hypothesis 3.

# 7. References


ANDERSEN, J., EGHOLM, D., KNUDSEN, M., LINGE, H., JANSEN, J., PEDERSEN, V., NIELSEN, S. B., TIKHOMIROV, D., OLSEN, J., FABEL, D. & XU, S. 2018. Widespread erosion on high plateaus during recent glaciations in Scandinavia. *Nat Commun,* 9**,** 830-830.

ANDERSEN, T. B., JAMTVEIT, B., DEWEY, J. F. & SWENSSON, E. 1991. Subduction and eduction of continental crust: major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the south Norwegian Caledonides. *Terra Nova,* 3**,** 303-310.

ANDERSEN, T. B., TORSVIK, T. H., EIDE, E. A., OSMUNDSEN, P. T. & FALEIDE, J. I. 1999. Permian and Mesozoic extensional faulting within the Caledonides of central south Norway. *J. Geol. Soc.,* 156**,** 1073-1080.

ANELL, I., THYBO, H. & STRATFORD, W. 2010. Relating Cenozoic North Sea sediments to topography in southern Norway: The interplay between tectonics and climate. *Earth and Planetary Science Letters,* 300**,** 19-32.

CHAMPAGNAC, J. D., MOLNAR, P., ANDERSON, R. S., SUE, C. & DELACOU, B. 2007. Quaternary erosion-induced isostatic rebound in the western Alps. *Geology,* 35**,** 195-198.

CLIFT, P. D., CARTER, A. & HURFORD, A. J. 1998. The erosional and uplift history of NE Atlantic passive margins: constraints on a passing plume. *Journal of the Geological Society,* 155**,** 787-800.

COCKS, L. R. M. & TORSVIK, T. H. 2002. Earth geography from 500 to 400 million years ago: a faunal and palaeomagnetic review.(Abstract). *Journal of the Geological Society,* 159**,** 631.

DOWDESWELL, J. A., OTTESEN, D. & RISE, L. 2010. Rates of sediment delivery from the Fennoscandian Ice Sheet through an ice age. *Geology,* 38**,** 3-6.

DUNLAP, W. J. & FOSSEN, H. 1998. Early Paleozoic orogenic collapse, tectonic stability, and late Paleozoic continental rifting revealed through thermochronology of K-feldspars, Southern Norway. *Tectonics,* 17**,** 604-620.

EGHOLM, D. L., JANSEN, J. D., BRÆDSTRUP, C. F., PEDERSEN, V. K., ANDERSEN, J. L., UGELVIG, S. V., LARSEN, N. K. & KNUDSEN, M. F. 2017. Formation of plateau landscapes on glaciated continental margins. *Nature Geoscience,* 10.

EGHOLM, D. L., NIELSEN, S. B., PEDERSEN, V. K. & LESEMANN, J.-E. 2009. Glacial effects limiting mountain height. *Nature,* 460**,** 884.

FOSSEN, H. 2008. *Geologi : stein, mineraler, fossiler og olje,* Bergen, Fagbokforlaget.

FOSSEN, H. & DUNLAP, W. J. 1999. On the age and tectonic significance of Permo-Triassic dikes in the Bergen-Sunnhordland region, southwestern Norway. *Norsk Geologisk Tidsskrift,* 79**,** 169-177.

FOWLER, C. M. R. 2005. *The solid earth : an introduction to global geophysics,* Cambridge, Cambridge University Press.

GOŁĘDOWSKI, B., EGHOLM, D. L., NIELSEN, S. B., CLAUSEN, O. R. & MCGREGOR, E. D. 2013. Cenozoic erosion and flexural isostasy of Scandinavia. *Journal of Geodynamics,* 70**,** 49-57.

GOŁĘDOWSKI, B., NIELSEN, S. B. & CLAUSEN, O. R. 2012. Patterns of Cenozoic sediment flux from western Scandinavia. *Basin Research,* 24**,** 377-400.

GROTZINGER, J. & ROYDEN, L. 1990. Elastic strength of the Slave craton at 1.9 Gyr and implications for the thermal evolution of the continents. *Nature,* 347**,** 64.

HALL, A. M., EBERT, K., KLEMAN, J., NESJE, A. & OTTESEN, D. 2013. Selective glacial erosion on the Norwegian passive margin.(Author abstract). *Geology,* 41**,** 1203.

HALLAND, E., BJØRNESTAD, A., MAGNUS, C., RIIS, F., MELING, I. M., GJELDVIK, I. T., TAPPEL, I. M., MUJEZINOVIC, J., BJØRHEIM, M. & RØD, R. S. 2014. Compiled CO 2 atlas for the Norwegian Continental Shelf. *Norwegian Petroleum Directorate*.

HUUSE, M., LYKKE-ANDERSEN, H. & MICHELSEN, O. 2001. Cenozoic evolution of the eastern Danish North Sea. *Marine Geology,* 177**,** 243-269.

HUUSE, M., LYKKE-ANDERSEN, H. & MICHELSEN, O. 2002. Reply to comment of P. Japsen et al. on "Cenozoic evolution of the eastern Danish North Sea".

JAPSEN, P. 1997. Regional Neogene exhumation of Britain and the western North Sea. *Journal of the Geological Society,* 154**,** 239-247.

JAPSEN, P. 1998. Regional velocity-depth anomalies, North Sea Chalk: a record of overpressure and Neogene uplift and erosion. *AAPG bulletin,* 82**,** 2031-2074.

JAPSEN, P. & CHALMERS, J. A. 2000. Neogene uplift and tectonics around the North Atlantic: overview. *Global and Planetary Change,* 24**,** 165-173.

MILLER, K., KOMINZ, M. A., BROWNING, J., WRIGHT, J. D., MOUNTAIN, G., KATZ, M. E., SUGARMAN, P., CRAMER, B. S., CHRISTIE-BLICK, N. & PEKAR, S. 2005. The phanerozoic record of global sea-level change. *Science.*

MOSAR, J. 2003. Scandinavia's North Atlantic passive margin. *Journal of Geophysical Research: Solid Earth,* 108**,** n/a-n/a.

MUSSETT, A. E. & KHAN, M. A. 2000. *Looking into the earth : an introduction to geological geophysics,* Cambridge, Cambridge University Press.

NESJE, A., DAHL, S. O., ANDA, E. & RYE, N. 1988. Block fields in southern Norway: Significance for the Late Weichselian ice sheet. *Norsk Geologisk Tidsskrift,* 68**,** 149-169.

NIELSEN, S. B. 2003. *A post mid-Cretaceous North Sea model*, Aarhus Universitet.

NIELSEN, S. B., GALLAGHER, K., LEIGHTON, C., BALLING, N., SVENNINGSEN, L., JACOBSEN, B. H., THOMSEN, E., NIELSEN, O. B., HEILMANN-CLAUSEN, C., EGHOLM, D. L., SUMMERFIELD, M. A., CLAUSEN, O. R., PIOTROWSKI, J. A., THORSEN, M. R., HUUSE, M., ABRAHAMSEN, N., KING, C. & LYKKE-ANDERSEN, H. 2009. The evolution of western Scandinavian topography: A review of Neogene uplift versus the ICE (isostasy–climate–erosion) hypothesis. *Journal of Geodynamics,* 47**,** 72-95.

NIELSEN, S. B., PAULSEN, G. E., HANSEN, D. L., GEMMER, L., CLAUSEN, O. R., JACOBSEN, B. H., BALLING, N., HUUSE, M. & GALLAGHER, K. 2002. Paleocene initiation of Cenozoic uplift in Norway. *Geological Society, London, Special Publications,* 196**,** 45-65.

NIELSEN, S. B., STEPHENSON, R. A., THOMSEN, E. & TECTONICS 2007. Dynamics of Mid-Palaeocene North Atlantic rifting linked with European intra-plate deformations. *Nature,* 450**,** 1071-1074.

OSKIN, M. & BURBANK, D. W. 2005. Alpine landscape evolution dominated by cirque retreat. *Geology,* 33**,** 933-936.

PEDERSEN, V. K., HUISMANS, R. S. & MOUCHA, R. 2016. Isostatic and dynamic support of high topography on a North Atlantic passive margin. *Earth and Planetary Science Letters,* 446**,** 1-9.

PÉREZ-GUSSINYÉ, M. & WATTS, A. B. 2005. The long-term strength of Europe and its implications for plate-forming processes. *Nature,* 436**,** 381.

REDFIELD, T. F. & OSMUNDSEN, P. T. 2013. The long-term topographic response of a continent adjacent to a hyperextended margin: A case study from Scandinavia. *Bulletin,* 125**,** 184-200.
RIIS, F. 1996. Quantification of Cenozoic vertical movements of Scandinavia by correlation of morphological surfaces with offshore data. *Global and Planetary Change,* 12**,** 331-357.
RUDBERG, S. 1994. Glacial cirques in Scandinavia.
SIGMOND, E. M. O. 1992. *Norge med havområder. Berggrunnskart; Norge;1:3 mill.* Norges geologiske undersøkelse.
SKOGSEID, J., PLANKE, S., FALEIDE, J. I., PEDERSEN, T., ELDHOLM, O. & NEVERDAL, F. 2000. NE Atlantic continental rifting and volcanic margin formation. *Geological Society, London, Special Publications,* 167**,** 295-326.
SMALL, E. E. & ANDERSON, R. S. 1998. Pleistocene relief production in Laramide mountain ranges, western United States. *Geology,* 26**,** 123-126.
SOPER, N. J., STRACHAN, R. A., HOLDSWORTH, R. E., GAYER, R. A. & GREILING, R. O. 1992. Sinistral transpression and the Silurian closure of Iapetus. *Journal of the Geological Society,* 149**,** 871-880.
STEER, P., HUISMANS, R., S. , VALLA, P., G. , GAC, S. & HERMAN, F. 2012. Bimodal Plio–Quaternary glacial erosion of fjords and low-relief surfaces in Scandinavia. *Nature Geoscience,* 5**,** 635.
STÜWE, K. 2007. *Geodynamics of the Lithosphere: An Introduction,* Berlin, Heidelberg, Springer Berlin Heidelberg: Berlin, Heidelberg.
WICKERT, A. D. 2015. Open-source modular solutions for flexural isostasy: gFlex v1.0. *Geoscientific Model Development Discussions,* 8**,** 4245-4292.