Earth and Planetary Science Letters 446 (2016) 1–9

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Isostatic and dynamic support of high topography on a North Atlantic passive margin

Vivi K. Pedersen [a,*], Ritske S. Huismans [a], Robert Moucha [b]

[a] Department of Earth Science, University of Bergen, Allegaten 41, N-5007 Bergen, Norway
[b] Department of Earth Sciences, Syracuse University, Syracuse, NY 13210, United States

ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form 18 April 2016
Accepted 19 April 2016
Available online 28 April 2016
Editor: A. Yin

Keywords:
isostasy
dynamic topography
passive margin topography
Scandinavia

ABSTRACT

Substantial controversy surrounds the origin of high topography along passive continental margins. Here we focus on the well-documented elevated passive margin in southwestern Scandinavia, and quantify the relative contributions of crustal isostasy and dynamic topography in controlling the present topography. We find that majority of the topography is compensated by the crustal structure, suggesting a topographic age that is in accord with the 400 Myr old Caledonian orogenesis. In addition, we propose that dynamic uplift of ~300 m has rejuvenated existing topography locally in the coastal region over the last 10 Myr. Such uplift, combined with a general sea level fall, can help explain a variety of observations that have traditionally been interpreted in favor of a peneplain uplift model. We conclude that high topography along the Scandinavian margin cannot represent remnants of a peneplain uplifted within the last 20 Myr. The topography must have been high since the Caledonian orogeny.

1. Introduction

A surprisingly significant part of global high topography is associated with rifted passive continental margins such as along the North Atlantic margins in Scandinavia and Greenland, the south Atlantic Brazilian and African margins, the east Australian margin, the Red Sea, and western India. A number of mechanisms have been suggested for such high topography to exist far beyond the most recent period of active rifting, including flexural isostasy related to i) lithosphere necking (Braun and Beaumont, 1989), ii) mechanical unloading during extension (Weissel and Karner, 1989), and iii) differential denudation (Gilchrist and Summerfield, 1990). Other mechanisms include underplating and intrusions in the lower crust (McKenzie, 1984), anticlinal, lithospheric folds caused by compression (Japsen et al., 2012), and the notion that topography may have survived orogenic collapse and rifting to leave again remnants from earlier orogenesis (Nielsen et al., 2009). However, a comprehensive understanding of why these margins are elevated today and whether they share a common origin remains enigmatic. Herein we focus on the well-documented southwestern Scandinavian margin in the North Atlantic as an archetype of an elevated passive continental margin.

The topography in western Scandinavia shows distinct high-elevation low-relief regions that have traditionally been interpreted as remnants of a Mesozoic peneplain uplifted in the Cenozoic (Fig. 1, Hypothesis 1, time frame T2–T3; e.g. Lidmar-Bergström et al., 2000). This interpretation has been supported by offshore studies identifying increased sedimentation in the Cenozoic, overburial of coast-proximal tilted sedimentary strata, and an angular unconformity at the base of the Quaternary (e.g. Japsen, 1988; Riis, 1996; Stuevold and Eldholm, 1996). However, it has also been recently suggested that prolonged climate-dependent erosion and isostatic uplift of old remnant topography from the Caledonian orogeny that survived Mesozoic and early Cenozoic rifting may equally well explain these key observations (Fig. 1, Hypothesis 2, T1–T3; Goledowski et al., 2012; Nielsen et al., 2009; Steer et al., 2012).

These diametrically opposing end-member hypotheses imply distinctly different crustal structure and degree of crustal compensation of present-day topography (Fig. 1). Peneplain formation requires complete erosion of existing topography to the degree where any crustal root has been obliterated. The peneplain in Hypothesis 1 should therefore be associated with a non-buoyant crust (Fig. 1, T2). This should also be the case for an uplifted peneplain (Fig. 1, T3). For the inherited remnant topography in Hypothesis 2, a thickened buoyant crust is expected to compensate all present-day topography (Fig. 1, T2–T3). We emphasize in this context, that a thin crust may compensate positive topography, if low-density material acts as a crustal root (mass deficit). Conversely, a thick

* Corresponding author.
E-mail address: vivi.pedersen@geo.uib.no (V.K. Pedersen).

http://dx.doi.org/10.1016/j.epsl.2016.04.019

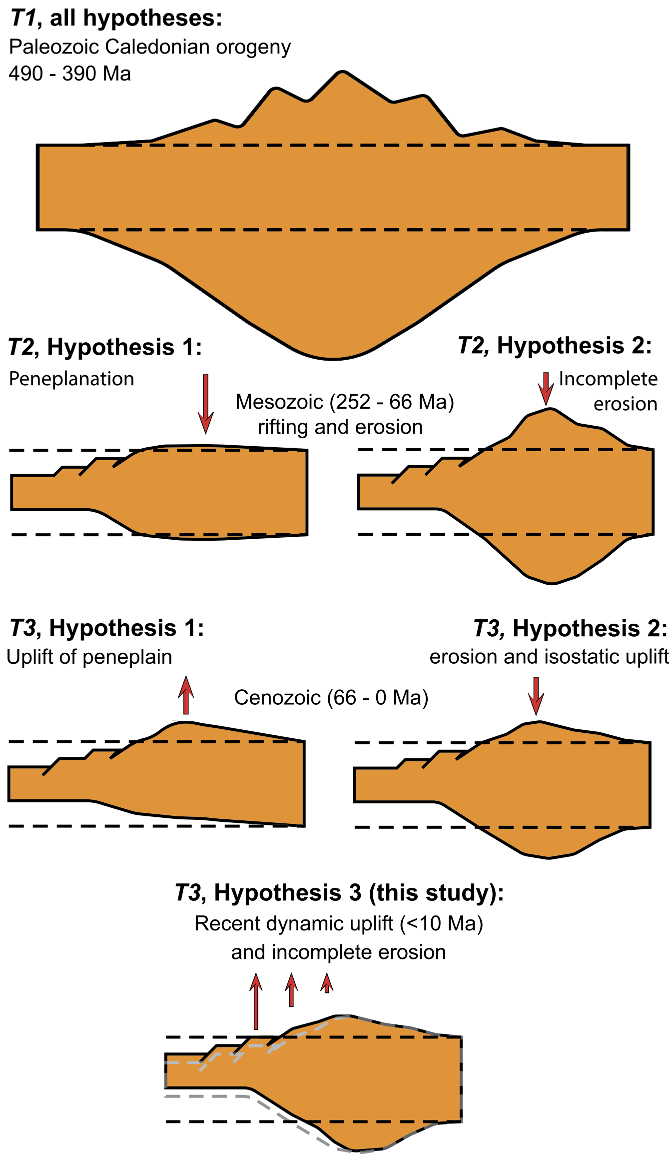

Fig. 1. Schematic models for post-Caledonian geodynamic evolution in western Scandinavia. Existing hypotheses (Hypothesis 1 and Hypothesis 2) for the geodynamic evolution of western Scandinavia since the Caledonian orogeny illustrated by crust and topography structure at three snapshots in time (T1, T2, T3), and the hypothesis proposed in this study (Hypothesis 3). Dashed black lines represent a reference crustal thickness with zero compensated topography. Arrows indicate changes in surface elevation. Note figure is not to scale.

crust cannot necessarily compensate significant positive topography, if the buoyancy-effect of the crustal root is reduced by high-density material (mass excess).

The high topography along the Scandinavian margin roughly coincides with a significant negative (∼−85 mGal) Bouguer gravity anomaly (Fig. 2; Balling, 1980; Pavlis et al., 2012) and suggests that a mass deficit exists at depth. The relatively short wavelength of the gravity anomaly (∼250 km) compared to crust- and lithosphere-thickness indicates that this mass deficit is located at shallow crustal depths and may compensate part or all of the present-day topography. However, the degree of compensation by the crustal structure is still debated, in part because an offset exists between the maximum topography and the thickest crust, and because of possible contributions from the lithospheric mantle and/or the asthenosphere (Ebbing and Olesen, 2005; Ebbing, 2007; Ebbing et al., 2012; England and Ebbing, 2012; Maupin et al., 2013; Stratford et al., 2009).

Here we quantify the degree of isostatic topographic compensation using refraction seismic data (Stratford et al., 2009) to constrain a hybrid approach considering crustal thickness (Airy isostasy), crustal density (Pratt isostasy), and the flexural strength of the lithosphere. We combine these quantitative estimates with predictions of recent dynamic uplift in order to test whether a combination of elements from previous end-member hypotheses may best explain the current high topography along this margin (Fig. 1, Hypothesis 3).

2. Methods

2.1. Local isostatic compensation of topography

We compute the degree of local isostatic compensation of present-day topography by the crustal structure with a three-dimensional density structure based on recently published seismic data from southern Norway (Stratford et al., 2009). These new seismic observations permit us to define a general velocity–depth relationship for this region by assuming a linear increase in velocity between four tie-points down through the crust (Fig. 3B). We convert this velocity model to density using a standard procedure described in Brocher (2005).

We calculate the amount of topography that can be compensated locally by the crust by balancing the load of each crustal column against a reference crustal column down to a common compensation depth where no lateral variation in density is assumed. That is,

$$\rho_{topo} h_{isostasy} g + \int_0^{moho} \rho_{crust}(z) g \, dz = \int_0^{Cref} \rho_{Cref}(z) g \, dz + \rho_m \Delta r g$$

where on the left-hand-side, the load of any local crustal column is given by the sum of the topographic load and the load of the crust. We assume a constant topographic load density ρ_{topo} of 2670 kg/m^3, corresponding to observed P-wave velocities at sea level. The crustal load is found by integrating the depth-dependent density profile $\rho_{crust}(z)$ from sea level down to the local *Moho* depth. On the right-hand-side, the reference column is defined as the load of a reference crust with thickness *Cref* and depth-dependent density profile, $\rho_{Cref}(z)$, plus a load from the mantle corresponding to any excess crust at the specific location ($\Delta r = moho - Cref$). The mantle lithosphere density ρ_m is assumed constant (3300 kg/m^3). With this load balance we can determine the local isostatically compensated topography $h_{isostasy}$:

$$h_{isostasy} = \frac{\int_0^{Cref} \rho_{Cref}(z) dz + \rho_m \Delta r - \int_0^{moho} \rho_{crust}(z) dz}{\rho_{topo}}.$$

For regions where the estimated isostatically compensated topography is less than zero, we substitute $h_{isostasy}$ with a corrected water depth d. The correction is done using the local depth-averaged crustal density, ρ_{avc}, iterating in order to consider the effect of the water depth, d, on the averaged crustal density itself, and the change in Moho thickness due to the water load.

$$d = \Delta a \frac{(\rho_m - \rho_{avc})}{(\rho_{avc} - \rho_w)}$$

where Δa is the thickness of the crustal deficit ($\Delta a = -\Delta r$) and ρ_w is the density of water.

The topography that can be locally compensated by a given crustal structure will depend on the choice of a reference crustal column that is assumed to give rise to zero topography. This is, however, inherently difficult to determine, because part of the topography may be due to buoyancy effects from within the mantle