Isostatic density modelling explains the missing root of the Scandes

Jörg Ebbing

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The study presents a 3D lithospheric density model of the Scandinavian mountain chain (Scandes) and adjacent areas of the Fennoscandian shield. The high topography of the Scandes correlates with a Bouguer gravity low, indicating isostatic compensation. Seismic results, however, do not image a crustal root below the Scandes. Taking into account the geometry of the base lithosphere, isostatic balance can be achieved by introducing a high-density lower crust below the Fennoscandian shield with a thickness up to 25 km. This structure tapers out below the Scandes. A second feature necessary to explain the gravity field and to balance isostatically the model is the Trans-Scandinavian Igneous Belt (TIB). The TIB is partly adjacent to and partly coincident with the Scandes. The resulting isostatic balanced model explains the gravity field of the Fennoscandian shield except for two areas: the northern and southern Scandes, which coincide with Cenozoic uplift centres. Thus, a low-density domain may be found at shallow depth below the Moho.

Jörg Ebbing, Geological Survey of Norway (NGU), 7491 Trondheim, Norway. E-mail: Joerg.Ebbing@ngu.no

Introduction

The Scandinavian mountain range (Scandes) in Norway and Sweden is located onshore the passive margin system of the NE Atlantic. The present shape and height of the Scandes is a product of multiple tectonic events connected both to the North Atlantic Ocean and to the Fennoscandian shield as part of the East European Craton. The three most important tectonic events, when dealing with the long wavelength features of the topography are: Caledonian orogeny, Neogene uplift and post-glacial rebound.

The Caledonian orogeny and the post-orogenic collapse have formed the paleo-shape of the Scandes and the passive margin system (e.g. Andersen 1998). The interpretation of aeromagnetic data suggests a correlation of onshore detachment zones with the margin geometry offshore Mid-Norway (e.g. Olesen et al. 2002, Skilbrei et al. 2002, Ebbing et al. 2006). These detachment zones might also have controlled mass transfer from different segments of the Scandes mountain chain to the margin during the post-orogenic collapse phase. The second major process shaping the Scandes is Neogene uplift. Rohrman and van der Beek (1996), Riis (1996), and Lidmar-Bergström et al. (2000) proposed a Neogene uplift of more than 1000 m in southern Norway from apatite fission track data, extrapolation of the offshore Late Tertiary stratigraphy and modelling of geomorphology. Riis (1996) and Hendriks and Andriessen (2002) have also proposed a Neogene bedrock uplift of more than 1000 m in the Lofoten–Vesterålen area, and 600 m on the mainland to the east. For the mechanism of the Neogene uplift a variety of processes has been proposed, but none is as yet generally accepted (e.g. Gabrielsen et al. 2005 and references therein).

The third process shaping the Scandes and influencing lithospheric rheology is the post-glacial rebound of Fennoscandia (e.g. Niskanen 1939, Balling 1980). This rebound is still causing significant uplift in the central Fennoscandian shield, but also for the Scandes (1-4 mm/yr; Milne et al. 2001, 2004). Fjeldskaar et al. (2000) were able to identify a present-day tectonic uplift component within the post-glacial rebound pattern, which coincides with the thermochronologic defined areas of Neogene uplift (Redfield et al. 2005).

Analysis of the gravity field and seismic data provide a mean of studying structural differences within the Scandes. A clear image of the lithosphere below the Scandes and adjacent regions would give a mean of evaluating the proposed mechanism of exhumation of the mountain range and of distinguishing between different phases of mountain shaping.

Gravity and topography

The Scandes have an elevation of up to 2470 m and extend in a north-south direction over more than 1400 km (Fig. 1a). The northern and southern parts of the Scandes are most pronounced, while the central part is narrower and

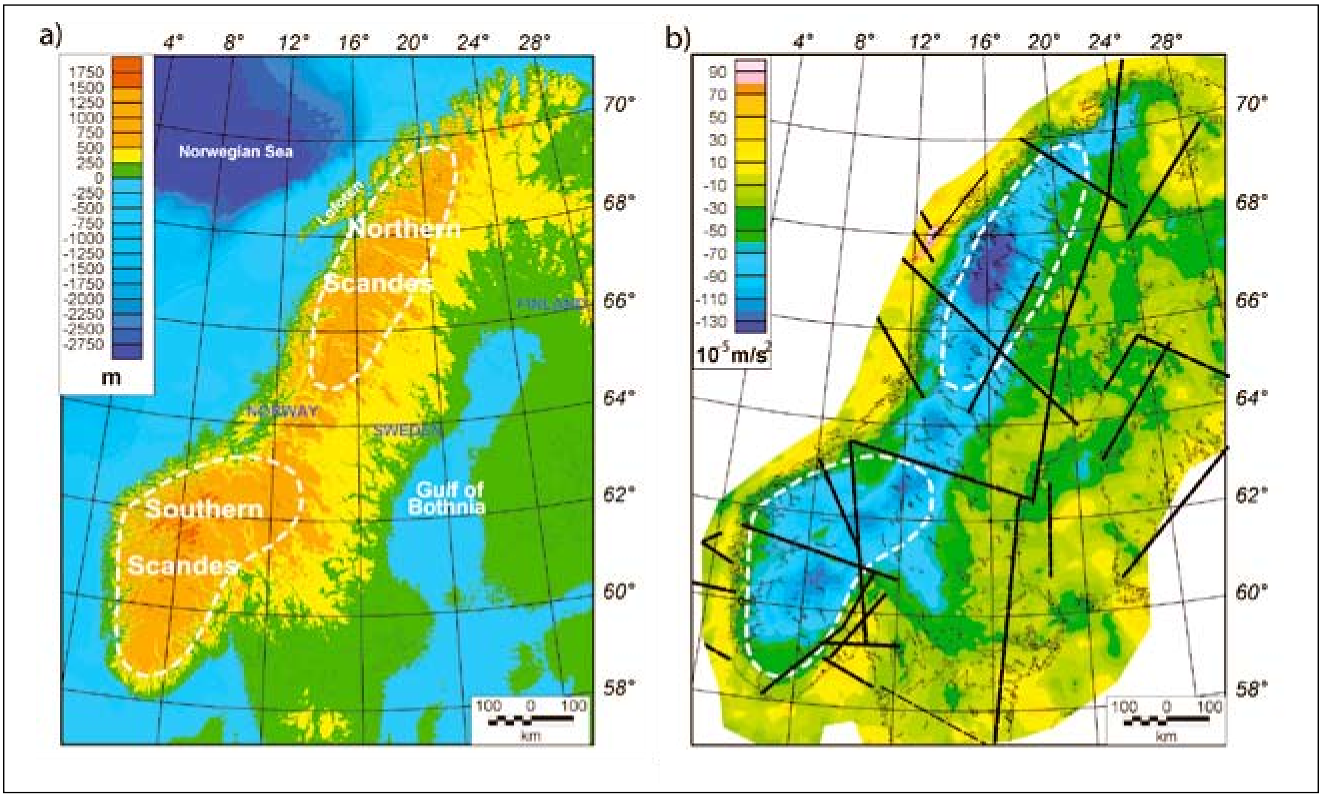

Fig.1. (a) Topography/bathymetry of Fennoscandia (after Dehls et al. 2000). Dotted lines depict the northern and southern Scandes and correspond roughly to 500 m above sea level. (b) Bouguer anomaly compiled by Skilbrei et al. (2000) and Korhonen et al. (2002a). Black lines indicate regional seismic lines in the study area (after Kinck et al.1993, Korsman et al. 1999). The Bouguer anomaly shows a gravity low correlating with the topography of the Scandes. In the southern Scandes local features can be identified in the Bouguer anomaly and in the northern Scandes the maximum axis of the gravity low is slightly shifted with respect to the topography.

less pronounced. The Bouguer anomaly shows a gravity low correlating with the topography of the Scandes. In the southern Scandes local features can be identified in the Bouguer anomaly and in the northern Scandes the maximum axis of the gravity low is slightly shifted with respect to the topography (Fig. 1). A detailed discussion of the correlation between topography and gravity signal can be found in Balling (1980, 1984), Olesen et al. (2002) and Ebbing & Olesen (2005). In these studies the correlation is especially discussed when applying the concept of Airy-Heiskanen isostasy. For collisional orogens, such as the Alps or the Himalayas (e.g. Watts 2001 and references therein) often a clear connection between topography and Bouguer gravity is observed, which led to the development of the concept of Airy-Heiskanen isostasy.

In this concept the mass excess of the topography is balanced by replacing mantle material with relatively low density material in the form of a crustal root. For the Scandes, when applying the concept of Airy-Heiskanen isostasy and the observed correlation between topography and Bouguer gravity anomaly the presence of a crustal root is indicated (Balling 1980, Ebbing & Olesen 2005). Figure 2 shows the Airy isostatic root and the isostatic gravity residuals. The Airy isostatic calculations are done using the parameters: topographic density of 2670 kg/m^3, water density of 1030 kg/m^3, a density contrast of 350 kg/m^3 between crust and mantle and a normal crustal thickness of 30 km. The value of 30 km for the normal crustal thickness is in agreement with seismic results for the Norwegian coast (e.g. Kinck et al. 1993; Schmidt, 2000). The topography was averaged on a grid with cell size 10x10 km^2 without low-pass pre-filtering. The resulting Airy isostatic root has a depth up to 45 km below the Scandes and increases towards the west and east. Generally speaking, this Airy isostatic root leads to a high-degree of compensation, but the Airy isostatic gravity residual shows large local deviations and shows clear differences for the southern and northern Scandes (Fig. 2b). In the southern Scandes the Airy isostatic gravity residual shows an irregular shaped anomaly. Most of the local residual anomalies can be correlated with surface geology and explained by deviations of the actual rock density to the constant topographic density used (2670 kg/m^3). An interesting feature is that the mean level of the isostatic gravity residual anomaly is negative, and one may speculate that an additional long wavelength component from the mantle exists. Isostatic investigation with varying flexural rigidity indicated that this offset is a feature which is enhanced with increasing flexural rigidity (Ebbing & Olesen 2005). The isostatic situation in the northern Scandes is more complicated. Here, the isostatic gravity residual anomalies are very high and a circular shaped isostatic residual low persists. Olesen et al. (2002)

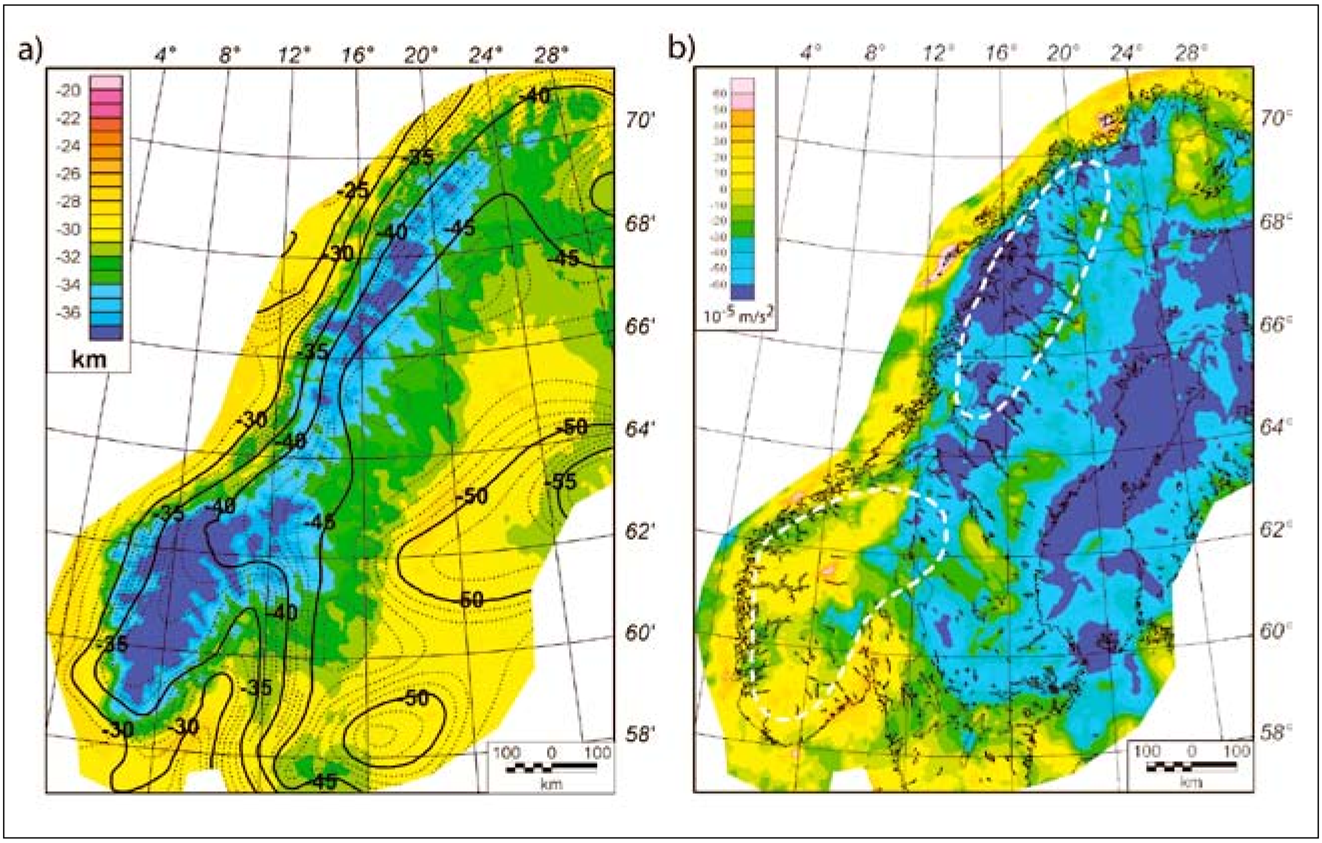

Fig.2. (a) Depth to Moho map. The coloured map shows the Airy isostatic depth to Moho and the seismic Moho after Kinck et al. (1993) with contour lines on top. (b) Airy isostatic gravity residual. The gravity effect of the isostatic Moho map (a) was subtracted from the Bouguer anomaly map (Fig. 1b) to calculate the isostatic residual map.

and Ebbing & Olesen (2005) show that this residual must be related to shallow crustal structures, e.g. the granitoids of the Trans-Scandinavian Igneous Belt (TIB). These observations are considered in the construction of the regional 3D lithosphere model.

Seismic database of the Scandes

The presence of a large root below the Scandes must also be observed by seismic studies. For the Scandes mountain range a variety of reflection and refraction seismic profiles (see Fig. 1b) have been carried out in the past (e.g. Kanestrøm & Haugland 1971, Hirschleber et al. 1975, Cassell et al. 1983, Schmidt 2000) and interpretations combining seismic and gravity data, have enabled compilations of the Moho geometry to be made (Kinck et al. 1993, Korsman et al. 1999, Olesen et al. 2002, Mjelde et al. 2005). These compilations indicate that the Scandes, despite their topographic expression, have no pronounced crustal root. However, the shallow Moho below the Oslo Rift creates an "apparent" root below the southern Scandes (Fig. 2a). While the resolution of the seismic results hardly allows crustal internal structures to be interpreted, the geometry of the Moho is consistent with recent seismic studies (e.g. Ottemöller and Midzi 2003, Schmidt 2000, Svenningsen et al. in press). However, the absolute depth to the Moho is less well constrained (Schmidt 2000). Comparison between the seismically derived Moho map and the isostatic Moho shows differences in the shape and depth of the Moho (Fig. 2a). Therefore, it is clear that the Scandes lack a crustal root, though the topography has to be isostatically compensated. For this compensation three obvious candidates are: (1) the base of the lithosphere, (2) density structures within the crust, or (3) flexural forces within the elastic lithosphere.

Base of lithosphere

In addition to the Moho image, a model of the lithosphere-asthenosphere boundary below the Fennoscandian shield is available (Calcagnile 1982). The model shows a deepening of the lithospheric base from 110 km below the southern Scandes to 170 km below the Bothnian Sea without revealing local patterns below the Scandes. The results for the base of the lithosphere from Calcagnile (1982) are consistent with a more recent study of the thermal lithospheric thickness by Artemieva & Mooney (2001) and Artemieva et al. (in press), but for asthenospheric structures no detailed model is yet available. The geometry of the lithospheric thickness has to be

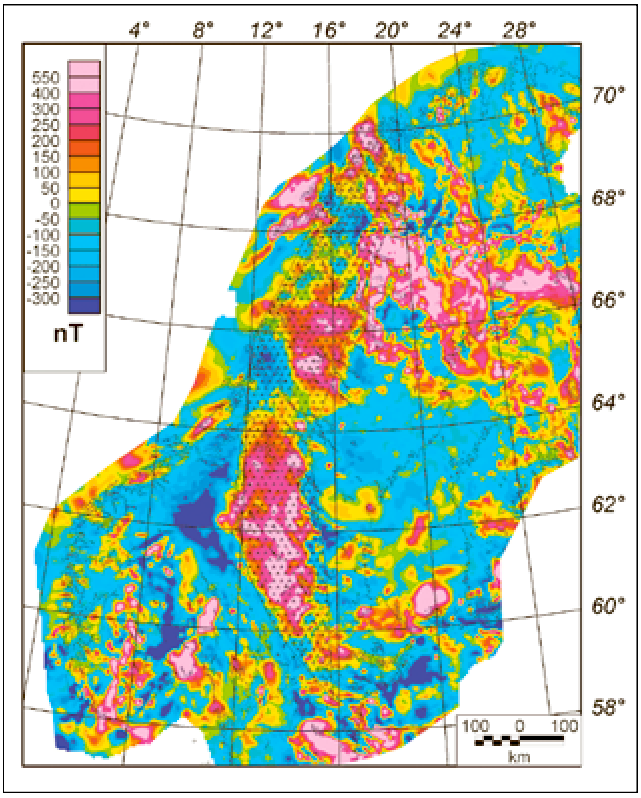

Fig.3. Magnetic anomaly map and outline of TIB. The magnetic anomaly map is based on the compilation by Korhonen et al. (2002b). The dotted area shows the area of reduced upper crustal densities (2640 kg/m^3) in the density model related to the granitoid Trans-Scandinavian Igneous belt (TIB). The outline of the area was drawn according to geological mapping and the aeromagnetic signature of the high-magnetic rocks.

taken into account to calculate the effect on the gravity by the density distribution at the lithosphere-asthenosphere boundary. However, the geometry of this boundary has, due to its long wavelength, a large influence on the geoid undulations, but is less visible in the gravity signal. The geometry of the lithosphere-asthenosphere boundary was previously applied to model the gravity field along a 2D lithospheric profile running from the Norwegian shelf to the central Fennoscandian shield within the Central Caledonides (Bielik et al. 1996). However, the geometry of this boundary does not isostatically balance the lithosphere of the Scandes (Ebbing & Olesen 2005).

Density structures within the crust

Clearly, any crustal density structures will influence the isostatic system. The TIB can be observed at the surface from southern Sweden up to the northern Scandes and is also evident on magnetic anomaly maps (Fig. 3). The granitoid rocks of the TIB have low densities (~2640 kg/m^3; Skilbrei et al. 2002) and high heat production, which is also reflected in the heat-flow of Fennoscandia (e.g. Balling 1995, Slagstad 2005). From forward modelling in the northern Scandes and central Scandes it is known that these granitoids can have a depth extension of ≥15 km (Olesen et al. 2002, Skilbrei et al. 2002, Pascal et al. this volume). Such high volumes of relatively low-density material certainly have an effect on the gravity field and influence the isostatic system.

Indications of a high-velocity lower crust (P-velocities > 7 km/s) below the central Fennoscandian shield can be found from seismic observations (Henkel et al. 1990, Korsman et al. 1999, Perez-Gussinye et al. 2004). The seismic results provide support for a minor density contrast (200 kg/m3) between crust and mantle and for additional loading in the crust surrounding the Scandes. The insufficient distribution of seismic lines does not allow clear definition of this structure. Especially westwards, its extension below the Scandes is obscure, but seismic studies indicate a thickness of up to 20 km below the Bothnian Sea (Korsmann et al. 1999). Mapping the high-density lower crust is certainly important for calculating lithospheric loading.

Flexural forces within the elastic lithosphere

To what extent the lithosphere responds to loading is further controlled by its flexural rigidity. The flexural rigidity characterizes the apparent strength of the lithosphere, which acts against the forces induced by loading. Studies of the flexural rigidity for the Scandes and the Fennoscandian shield (e.g. Fjeldskaar 1997, Poudjom Djomani et al. 1999, Rohrmann et al. 2002, Perez-Gussinye et al. 2004, Ebbing & Olesen 2005) all indicate that the Scandes have a lower flexural rigidity than the centre of the Fennoscandian shield. Poudjom Djomani et al. (1999) and Rohrmann et al. (2002) conclude that the Scandes have low flexural rigidities of the order of 1.5-7.5x10^{22} to 1x10^{23} Nm in the north and <1x10^{21} in the south. However, these studies use a purely isostatic approach to estimate the flexural rigidity of the Fennoscandian lithosphere without considering the component of isostatic balancing by the lithosphere-asthenosphere boundary. This is especially important for Fennoscandia due to the response to post-glacial rebound (Steffen & Kaufmann 2005), when considering the base of the lithosphere, Ebbing & Olesen (2005) calculated a maximum flexural rigidity of 10^{23} Nm in the southern Scandes with decreasing values to the north. Ebbing & Olesen (2005) discuss their results in detail with previous studies and show that the lithosphere below the Scandes is rather elastic and that the isostatic state is more influenced by the crustal density distribution.

3D isostatically balanced density model

The 3D forward modelling was carried out with the software package GMSYS-3D. The 3D model is defined by a number of surface grids (cell size: 10 x 10 km^2) with a density distribution assigned to each layer. The gravity effect of the model is then calculated in the wave number domain with the Parker algorithm (1972) for each of the layers and added together (Popowski et al. 2005).

The model relates to a reference lithosphere (Table 1), which allows modelling the absolute value of the gravity field and not only the shape of the anomaly. The load imposed by the Scandes must be isostatically supported at depth by substantial volumes of low-density material within the crust or the mantle, or at the crust/mantle or lithosphere/asthenosphere interfaces. Thus, these interfaces are important boundaries with regard to isostatic processes. The density contrast at the Moho is 350 kg/m^3. This is in agreement with densities converted from seismic velocities from regional studies (Kanestrøm and Haugland 1971, Schmidt 2000), which indicate a density contrast between 300 and 400 kg/m^3 between crust and mantle The density of the asthenospheric mantle can only be regarded as a relative density contrast (30 kg/m^3) and is chosen to reflect the small density contrast at the base of the lithosphere in agreement with global reference models (e.g. PREM: Dziewonski & Anderson 1981).

The 3D lithospheric model features a three-layered crust as described above, a crustal base according to the Moho model by Kinck et al. (1993) and the lithospheric base after Calcagnile (1982). The simple model already provides a good correlation between the modelled and observed gravity at the Norwegian coastline, but increasingly large negative discrepancies occur towards the central Fennoscandian shield. Consequently, high-density material in the lithosphere has to be added and the most likely source is the high-density lower crust (LCB) as observed in seismic studies.

The thickness and distribution of the LCB is calculated by estimating the required loading to balance isostatically the lithosphere. First the mass surplus and deficit are estimated by:

$$\rho_{Topo}D_{Topo} + \sum_{i=1}^{3}\rho_{ci}D_{ci} + \rho_{mantle}D_{mantle} + \rho_{asth}D_{asth} - \sum_{i=1}^{5}\rho_{refi}D_{refi} = \Delta Load / g \quad (1)$$

with density ρ and height D for topography, crust, lithospheric and asthenospheric mantle and reference model as described above. g is the normal gravity field and $\Delta Load$ indicates the mass surplus and deficit. The calculation shows that high-density material is missing especially below the central Fennoscandian shield. The missing masses can be explained by introducing a high-density Lower Crustal Body (LCB) with density 3100 kg/m^3. This body has a higher density (+200 kg/m^3) compared to normal lower crust. Adding this component ($\rho_{LCB}D_{LCB}$) leads to $\Delta Load$ being zero and Eq. (1) for the isostatic balance can be reformulated to:

$$\rho_{Topo}D_{Topo} + \sum_{i=1}^{3}\rho_{ci}D_{ci} + \rho_{LCB}D_{LCB} + \rho_{mantle}D_{mantle} + \rho_{asth}D_{asth} = \sum_{i=1}^{5}\rho_{refi}D_{refi} \quad (2)$$

In this way the equation is balanced only for the missing masses as the mass surplus cannot be related to the LCB. To balance the mass surplus low-density structures are needed. This approach results in a LCB with a thickness up to 25 km in the central Fennoscandian shield, which is in agreement with estimates from seismic studies (Korsman et al., 1999).

The next step is to calculate the gravity effect of the lithospheric model. The isostatic lithosphere structure is used to calculate the gravity effect. A lowpass-filtered gravity anomaly with a cut-off wavelength of 100 km is used for the isostatic gravity modelling. This cut-off wavelength suppresses short-wavelength features (e.g. local sources within the upper crust) that are not a subject of the present study as the main focus is given to large-scale regional structures. The resulting gravity effect of the isostatic model (not shown here) features a north-south trending band of negative residual from the northern Scandes southwards to the east of the Oslo Rift, coinciding with the distribution of the TIB. Therefore, a low-density body is introduced into the upper crust (2640 kg/m^3). The lateral extent of the TIB structure is as defined in Fig. 3 and has a thickness of 12 km. This simplified model is in agreement with local models for the TIB (Olesen et al. 2002, Pascal et al. this volume). While the influence of the TIB granitoids on the gravity field is strong due to their location at the surface, the influence on the loading is less prominent due to a rather small density contrast to the surrounding upper crust (-30 kg/m^3). However, the thickness of the LCB is now recalculated using Eqs. (1)

Table 1. Parameters for the isostatic and density modelling

Structure	Depth [km]	Thickness Indices [km]		Density Indices [km]	
Reference model					
Upper crust	0-12	D_{ref1}	12	ρ_{ref1}	2670
Middle crust	12-20	D_{Cref2}	8	ρ_{ref2}	2800
Lower crust	20-35	D_{ref3}	15	ρ_{ref3}	2900
Lith. mantle	35-120	D_{mantle}	85	ρ_{ref4}	3250
Asthenospheric mantle	>120	D_{asth}		ρ_{ref5}	3220
Geological model					
Topography		D_{Topo}		ρ_{Topo}	2670
Upper crust	0-12	D_{C1}		ρ_{C1}	2670
Middle crust	12-20	D_{C2}		ρ_{C2}	2800
Lower crust	20-LCB	D_{C3}		ρ_{C3}	2900
High-density lower crust (LCB)	LCB-Moho	D_{LCB}		ρ_{LCB}	3100
Lith. mantle	Moho-Asth.	D_{mantle}		ρ_{mantle}	3250
Asthenospheric mantle	>Asth.	D_{asth}		ρ_{ref5}	3220

Table 1. Parameters for the isostatic and density modelling. The reference model is based on global reference models (e.g. PREM: Dziewonski and Anderson, 1981) and is in agreement with regional studies from Fennoscandia (e.g. Calganile 1982).

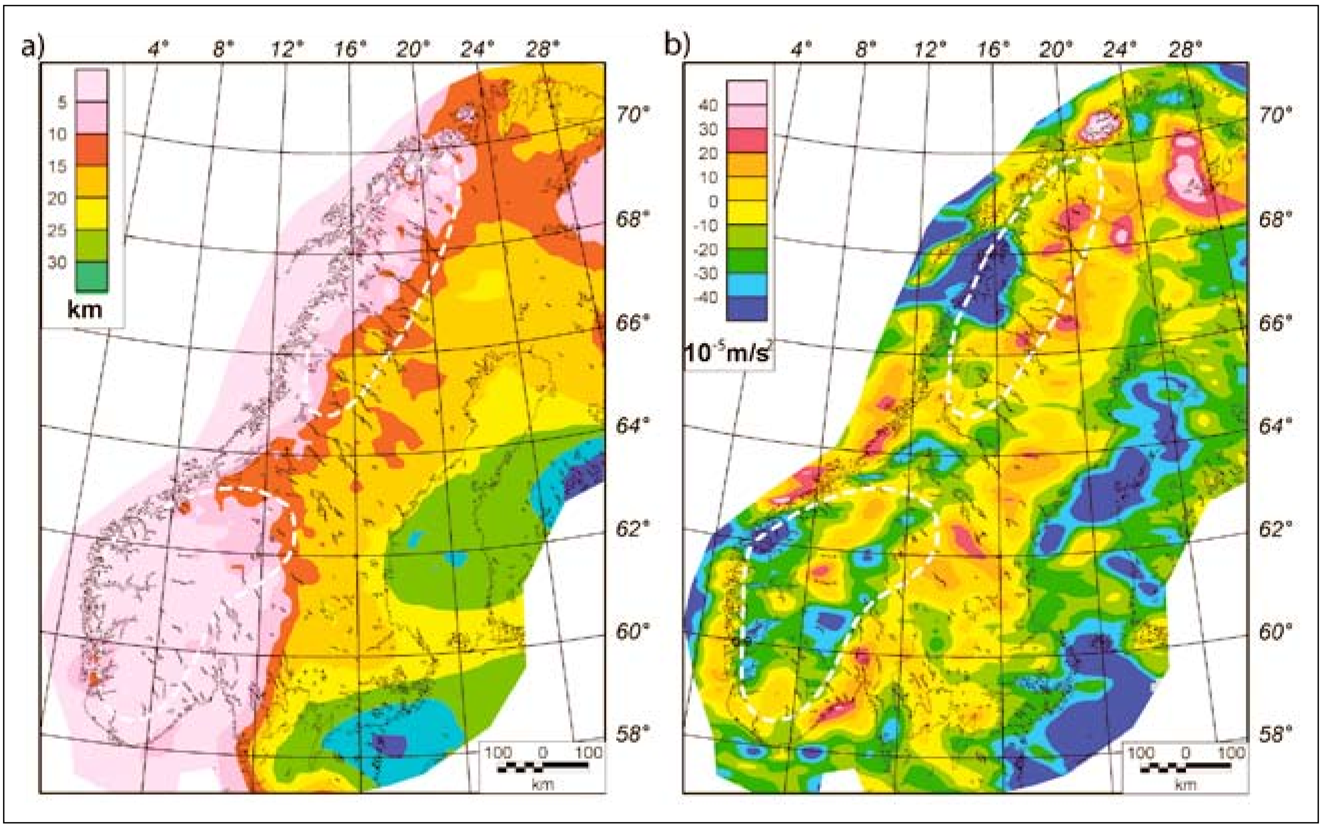

Fig.4. (a) Thickness of high-density lower crust (LCB). The thickness of the LCB was estimated by isostatically balancing the lithosphere of the Fennoscandian shield. (b) Residual gravity anomaly of isostatic 3D lithosphere model. The residual is the difference between the lithospheric 3D model and the Bouguer anomaly. Note the large negative residuals below the northern and southern Scandes, coinciding with the centres of Neogene uplift.

and (2) and the gravity effect of the lithospheric model. The calculated residual between the observed and the calculated gravity field now satisfies for the regional structures (Fig. 4a and b). However, two regional minima are clearly visible in the residual gravity field, i.e. the Neogene uplift centres in the southern and northern Scandes.

Discussion and conclusions

The 3D lithospheric density model shows that the Scandes are not compensated for by a simple crustal root in the sense of Airy-Heiskanen isostasy, but rather in the sense of a combination of Airy and Pratt isostasy. That is to say a root exists below the Scandes, if one maps the top of the high-density lower crust. This high-density lower crust compensats for the deep Moho in the central Fennoscandian Shield and tapers out below the Scandes (Fig. 4a). The TIB represents a second structure overprinting the root of the Scandes, while the base of the lithosphere constitutes an additional long-wavelength component. Introduction of low-density granites into the upper crust explains to a large extent the gravity low and these granitoids can be observed at the surface and correlated with magnetic anomalies (Skilbrei et al. 2002, Pascal et al. this volume).

The presence of the high-density lower crust below the Fennoscandian shield raises the question about its origin. Also on the outer mid-Norwegian margin similar high-density/velocity bodies can be observed at the base of the crust (e.g. Eldholm & Grue 1994, Ebbing et al. 2006). While their origin is still disputed, their distribution shows an apparent correlation with detachments observed onshore (e.g. Ebbing et al. 2006), which might point to the orogenic collapse of the Scandes as a main factor controlling the distribution of high-density lower crust. This conclusion still remains speculative.

The two regions that are not explained by the present 3D model are the areas of recent, tectonic uplift and the negative residual points to low-density material in the crust or the mantle. There is no or only minor evidence from seismic experiments for low-density structures in the middle and lower crust (e.g. Kinck et al. 1993). Therefore, the presence of low-density material in the mantle seems more likely. However, the area of Neogene uplift in the northern Scandes as defined by thermochronological data (Hendriks & Andriessen 2002) also correlates closely with the Bouguer (and isostatic) gravity low and the extension of the TIB granitoids. Fission tracks are unstable at high temperatures (e.g. Hendriks & Andriessen 2002) and therefore, a possible contamination of the thermochronological data might be caused by high heat production from the TIB granitoids, as calculated for the Central Caledonides (Pascal et al. this volume). If the thermochronological data are affected by the heat produced in the TIB, support for a Neogene uplift phase of the northern Scandes would be significantly reduced.

Subsurface loading, both in the crust and upper mantle, has to be estimated further to refine the results. The information about depth to Moho is, however, ambiguous, due to the quality and resolution of the seismic experiments. (Kinck et al. 1993, Korsman et al. 1999, Ottemöller & Midzi 2003). A careful review of seismic and seismological investigations shows that new, detailed studies of the deep crust and upper mantle are needed to provide such information (Ebbing & Olesen 2005). If low-density structures in the upper mantle exist, these are the most likely candidates to have triggered the Neogene uplift of the northern and southern Scandes. This would imply that models of dynamic topography or related processes in the upper mantle (e.g. Rohrman and van der Beek 1996, Nielsen et al. 2002, Marquart & Schmeling 2004) are more valid than recent models combining thermochronological data and comparison with flexural modelling (e.g. Redfield et al. 2005) suggest.

Towards the central Fennoscandian shield a general shift can be observed between the gravity field of the presented lithospheric model and the reference model. This can be related to a low-velocity/low-density zone in the asthenosphere related to the glacial rebound of Fennoscandia (e.g. Balling 1980, Lambeck et al. 1998). Further improvement of the presented 3D lithosphere model requires therefore more detailed tomographic study of the lithospheric mantle below the Scandes. From theoretical calculations there is also some evidence for an increase in mantle densities from the Norwegian coast towards the central Fennoscandian shield (Pascal 2006). However, incorporation of such a density distribution goes beyond the purpose of the present study and the present database.

The presented model explains the isostatic loading of the lithosphere assuming a combination of Pratt and Airy isostatic equilibrium and two elements have therefore to be considered in future studies. First, the Fennoscandian shield is currently being uplifted and both gravity data and the topography have to be corrected for this. The uplift ratios for the Scandes are less pronounced, but certainly have to be considered. Second, the flexural rigidity is changing across the Fennoscandian Shield and within the Scandes mountain belt the flexural rigidity values are generally small but vary from north to south (e.g. Ebbing & Olesen 2005). The general geometry of the crust and especially of the Moho is important for exact calculation of the isostatic response. The current seismic database allows only exact calculations to be performed across single transects (e.g. Svenningsen et al. in press) and not for the entire Scandes. The aim of the current study is not to consider all possible elements, but to provide a general 3D model which explains the gravity field and the isostatic state in a very general way, thus providing a basis for further investigations. The presented approach already casts doubts about some of the models for the Neogene uplift of the Scandes. For the Scandes, as part of the NE Atlantic passive margin system, resolving the loading and isostatic response within the crust and mantle are an important elements for unveiling its tectonic history.

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References

Andersen, T.B.,1998: Extensional tectonics in the Caledonides of southern Norway, an overview. *Tectonophysics 285*, 333–351.

Artemieva, I.M. & Mooney, W.D. 2001: Thermal thickness and evolution of Precambrian lithosphere: A global study. *Journal of Geophysical Research 106*, 16387-16414.

Artemieva I.M., Thybo H. & Kaban M.K., 2006 Deep Europe today: Geophysical synthesis of the upper mantle structure and lithospheric processes over 3.5 Billion years. *In* Gee D. & Stephenson R. (eds.): *European Lithosphere Dynamics.* Geol. Soc. London Memoirs, 35, 11-41.

Balling, N. 1980: The land uplift in Fennoscandia, gravity field anomalies and isostasy. *In* Mörner, N.-A. (ed.): *Earth Rheology, Isostasy and Eustasy,*. Jon Wiley & Sons, New York, 297-321.

Balling, N. 1984: Gravity and isostasy in the Baltic Shield. *In* Galson, D.A. & Mueller, S. (eds.): *First EGT Workshop: The Northern Segment.* European Science Foundation, 53-68.

Balling, N. 1995: Heat flow and thermal structure of the lithosphere across the Baltic Shield and northern Tornquist Zone. T*ectonophysics 244*, 13-50.

Bielik, M., Dyrelius, D. & Lillie, R.J. 1996: Caledonian lithosphere - gravity structure and comparison with Carpathian lithosphere. *Contributions of the Geophysical Institute of the Slovak Academy of Sciences 26*, 72-84.

Calcagnile, G. 1982: The lithosphere-asthenosphere system in Fennoscandia. *Tectonophysics 90*, 19-35.

Cassell, B.R., Mykkeltveit, S., Kanestrøm, R. & Husebye, E.S. 1983: A North Sea southern Norway seismic crustal profile. *Geophyscal Journal Of the Royal Astronomical Society 72*, 733-753.

Dehls, J.F., Olesen, O., Bungum, H., Hicks, E., Lindholm, C.D. & Riis, F. 2000: *Neotectonic map, Norway and adjacent areas 1:3 mill.* Norges geologiske undersøkelse, Trondheim, Norway.

Dziewonski, A.M. & Anderson, D.L. 1981: Preliminary reference earth model. *Physics of the Earth and Planetary Interiors 25*, 297-356.

Ebbing, J. & Olesen, O. 2005: The Northern and Southern Scandes - Structural differences revealed by an analysis of gravity anomalies, the geoid and regional isostasy. *Tectonophysics 411*, 73–87.

Ebbing, J., Lundin, E., Olesen, O. & Hansen, E.K. 2006: The mid-Norwegian margin: A discussion of crustal lineaments, mafic intrusions, and remnants of the Caledonian root by 3D density modelling and structural interpretation. *Journal of the Geological Society, London 163,* 47-60.

Eldholm, O. & Grue, K. 1994: North Atlantic volcanic margins: Dimensions and production rates. *Journal of Geophysical research 99,* 2955-2968.

Fjeldskaar, W. 1997: Flexural rigidity of Fennoscandia inferred from the postglacial uplift. *Tectonics 16,* 596-608.

Fjeldskaar, W., Lindholm, C., Dehls, J.F. & Fjeldskaar, I. 2000: Postglacial uplift, neotectonics and seismicity in Fennocscandia. *Quarternary Science Reviews 19,* 1413-1422.

Gabrielsen, R.H., Braathen, A., Olesen, O., Faleide, J.I., Kyrkjebø, R., &

Redfield, T.F. 2005: Vertical movements in south-western Fennoscandia: a discussion of regions and processes from the present to the Devonian. *In* Wandås, B.T.G., Eide, E.A., Gradstein, F. & Nystuen, J.P. (eds): *Onshore-Offshore relationships on the North Atlantic Margin.* Norwegian Petroleum Society (NPF), Special Publication 12, Elsevier, Amsterdam. 1-28.

Hendriks, B.W.H. & Andriessen, P.A.M. 2002: Pattern and timing of the post-Caledonian denudation of northern Scandinavia constrained by apatite fission track thermochronology. *In* Doré, A.G., Cartwright, J., Stoker, M. S., Turner, J. P., White, N. (eds.): *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration.* Geological Society of London, Special Publication, 196, 117-137.

Henkel, H., Lee, M.K. & Lund, C.-E.1990: An integrated geophysical interpretationof the 200 km FENNOLORA section of the Baltic Shield. *In* Freeman, R., Giese, P., Mueller, St. (eds.): *The European Geotraverse: Integrated Studies.* European Science Foundation, Strasbourg, 1-48.

Hirschleber, H.B., Lund, C., Meissner, R., Vogel, A. & Weinrebe, W. 1975: Seismic investigations along the Blue Road traverse. *Journal of Geophysics 41,* 135-148.

Kanestrøm, R. & Haugland, K. 1971: Crustal structure in Southeastern Norway from Seismic Refraction measurements. Scientific Report No. 5, Seismological Observatory, University of Bergen, Norway, 72 pp.

Kinck, J.J., Husebye, E.S. & Larsson, F.R. 1993: The Moho depth distribution in Fennoscandia and the regional tectonic evolution from Archean to Permian times. *Precambrian Research 64,* 23-51.

Korhonen, J.,V., Aaro, S., All, T., Elo, S., Haller, L.Å., Kääriäinen, J., Kulinich, A., Skilbrei, J.R., Solheim, D., Säävuori, H., Vaher, R., Zhdanova, L. & Koistinen, T. 2002a: *Bouguer anomaly map of the Fennoscandian shield 1: 2 000 000.* Geological Surveys of Finland, Norway and Sweden and Ministry of Natural Resources of Russian Federation.

Korhonen, J.,V., Aaro, S., All, T., Nevanlinna, H., Skilbrei, J.R., Säävuori, H., Vaher, R., Zhadanova, L. & Koistinen, T. 2002b: *Magnetic anomaly map of the Fennoscandian shield 1: 2 000 000.* Geological Surveys of Finland, Norway and Sweden and Ministry of Natural Resources of Russian Federation.

Korsman, K., Korja, T., Pajunen, M., Virransalo, P. & GGT/SVEKA Working Group 1999: The GGT/SVEKA Transect: Structure and evolution of the continental crust in the Paleoproterozoic Svecofennian Orogen in Finland. *International Geology Review 41*, 287-333.

Lambeck, K., Smither, C. & Johnston, P. 1998: Sea-level change, glacial rebound and mantle viscosity for northern Europe. *Geophysical Journal International 134*, 102-144.

Lidmar-Bergstrom, K., Ollier, C.D. & Sulebak, J.R. 2000: Landforms and uplift history of Southern Norway. *Global and Planetary Change 24*, 211-231.

Marquart, G. & Schmeling, H. 2004: A dynamic model for the Iceland Plume and the North Atlantic based on tomography and gravity data. *Geophysical Journal International 159*, 40–52

Milne, G.A., Davis, J.L., Mitrovica, J.X., Scherneck, H.-G., Johansson, J.M., Vermeer, M. & Koivula, H. 2001: Space-geodetic constraints on glacial isostatic adjustment in Fennoscandia. *Science 291,* 2381-2385.

Milne, G.A., Mitrovica, J.X., Scherneck, H.-G., Davis, J.L., Johansson, J.M., Koivula, H. & Vermeer, M. 2004: Continuous GPS measurements of postglacial adjustment in Fennoscandia - 2. Modeling results. *Journal of Geophysical Research 109*, B02412, doi:10.1029/2003JB002619.

Mjelde, R., Raum, T., Breivik. A., Shimamura, H., Murai, Y., Takanami, T. & Faleide, J.I. 2005: Crustal structure of the Vøring margin, NE Atlantic: a review of geological implications based on recent OBS-data. *In* Doré, A.G. & Vining, B.A. (eds.): *Petroleum Geology: North-West Europe and Global Perspectives. Proceedings of the 6th Petroleum Geology Conference.* Geological Society Special Publication, The Geological Society, London, 803-813.

Nielsen, S.B., Paulsen, G.E., Hansen, D.L., Gemmer, L., Clausen, O.R., Jacobsen, B.H., Balling, N., Huuse, M. & Gallgher, K. 2002: Paleocene initiation of Cenozoic uplift in Norway. *In* Doré, A.G., Cartwright, J., Stoker, M. S., Turner, J. P., White, N. (eds.): *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration.* Geological Society of London, Special Publication 196, 45-65.

Niskanen, E. 1939: On the upheavel of land in Fennoscandia. *Ann. Acad. Sci. Fenn.,* Ser. A, 53, 1-30.

Olesen, O., Lundin, E., Nordgulen, Ø., Osmundsen, P.T., Skilbrei, J.R., Smethurst, M.A., Solli, A., Bugge, T. & Fichler, C. 2002: Bridging the gap between the onshore and offshore geology in Nordland, northern Norway. *Norwegian Journal of Geology 82,* 243-262.

Ottemöller, L. & Midzi, V. 2003: The crustal structure of Norway from inversion of teleseismic receiver functions. *Journal of Seismology 7,* 35-48.

Pascal, C. 2006:. On the role of heat flow, lithosphere thickness and lithosphere density on gravitational potential stresses. *Tectonophysics 425,* 83-99.

Pascal, C., Ebbing, J. & Skilbrei, J.R. 2007: Interplay between the Scandes and the Transcandinavian Igneous Belt: integrated thermal and potential field modelling of the Central Scandes Profile. *Norwegian Journal of Geology,* this volume, 3-12.

Parker, R.L. 1972: The rapid calculation of potential anomalies. *Geophysical Journal of the Royal Astronomical Society 31,* 447-455.

Perez-Gussinye, M., Lowry, A.R., Watts, A.B. & Velicogna, I. 2004: On the recovery of effective elastic thickness using spectral methods: Examples from synthetic data and from the Fennoscandian shield. *Journal of Geophysical Research 109,* B10409, doi: 10.1029/2003JB002788.

Poudjom Djomani, Y.H., Fairhead J.D. & Griffin, W.L. 1999: The flexural rigidity of Fennoscandia: reflection of the tectonothermal age of the lithospheric mantle. *Earth and Planetary Science Letters 174,* 139-154.

Popowski, T., Connard, G. & French. R. 2005: GMSYS-3D User Guide. Northwest Geophysical Associates, Inc., Corvallis, Oregon, 32p.

Redfield, T. F., Osmundsen, P. T. & Hendriks, B. W. H. 2005: The role of fault reactivation and growth in the uplift of western Fennoscandia. *Journal of the Geological Society, London 162,* 1013-1030.

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.

Rohrman, M. & van der Beek, P. 1996: Cenozoic postrift domal uplift of North Atlantic margins: An asthenospheric diapirism model. *Geology 24,* 901-904.

Rohrmann, M., van der Beek, P., van der Hilst, R.B. & Reemst, P., 2002: Timing and mechanism of North Atlantic Cenozoic uplift: evidence for mantle upwelling, In: Doré, A.G., Cartwright, J., Stoker, M. S., Turner, J. P., White, N. (eds.) *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration.* Geological Society of London, Special Publication 196, 27-43.

Schmidt, J. 2000: Deep seismic studies in the western part of the Baltic shield. Uppsala Dissertations from the Faculty of Science and Technology, No. 24.

Skilbrei, J.R., Kihle, O., Olesen, O., Gellein, J., Sindre, A., Solheim, D. & Nyland, B., 2000: Gravity anomaly map Norway and adjacent ocean areas, scale 1:3 Million, Geological Survey of Norway, Trondheim.

Skilbrei, J.R., Olesen, O., Osmundsen, P.T., Kihle, O., Aaro, S. & Fjellanger, E.: 2002: A study of basement structures and onshore-offshore correlations in Central Norway. *Norwegian Journal of Geology 82*, 263-279.

Slagstad, T. 2005: Heat flow. *In* Olesen, O. et al. (eds.): *KONTIKI Annual Report 2004, Continental Crust and Heat Generation in 3D,* 21-24. NGU Report 2005.008.

Steffen, H. & Kaufmann, G. 2005: Glacial isostatic adjustment of Scandinavia and northwestern Europe and the radial viscosity structure of the Earth's mantle. *Geophysical Journal International 163,* 801-812.

Svenningsen, L., Balling, N., Jacobsen, B.H., Kind, R., Wylegalla, W. & Schweitzer J. in press: Crustal thickness beneath the highlands of southern Norway from teleseismic receiver functions. *Geophysical Journal International.*

Watts, A.B. 2001: Isostasy and flexure of the lithosphere. Cambridge University Press, Cambridge. 458 pp.