Interplay between the Scandes and the Trans-Scandinavian Igneous Belt: integrated thermo-rheological and potential field modelling of the Central Scandes profile

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Pascal, C., Ebbing, J. & Skilbrei, J.R. : Interplay between the Scandes and the Trans-Scandinavian Igneous Belt: integrated thermo-rheological and potential field modelling of the Central Scandes profile. *Norwegian Journal of Geology,* vol. 87, pp. 3-12,.Trondheim 2007. ISSN 029-196X.

Analysis of the gravity anomalies associated with the Scandinavian mountain range (i.e. the Scandes) suggests that the compensating loads are located at relatively shallow depths in the crust and/or in the mantle lithosphere. Potential crustal loads leading to positive buoyancy are the light Trans-Scandianvian Igneous Belt (TIB) granitoids that meet the Scandes in their central segment. In order to understand the mechanisms that led to the uplift of the Scandes, it is therefore of prime importance to determine the thickness and depth extent of such bodies and their role in maintaining the observed surface topography. The present paper focuses on the Central Scandes profile (CSP) running from west to east from Trondheim, in mid-Norway, to Östersund, in mid-Sweden, and crossing both the Central Scandes and an underlying TIB granitoid. Firstly, by means of potential field modelling, we show that different crustal geometries and, in particular, very different thicknesses for the TIB granitoid can equally fit the available geophysical data. Then, we apply thermo-rheological modelling to get additional constraints on the crustal geometry along the CSP. We concentrate on two "end-member" crustal models and, using newly acquired heat generation data, proceed to model their respective thermal regimes. Model A involving a 20 km thick TIB granitoid results in both very high surface heat flow (80 to 90 mW/m^2) and Moho temperatures (~750 ºC) and unreasonably low strength for the lithosphere. Reasonable heat flow values (60 to 70 mW/m^2), Moho temperatures (~600 ºC) and lithosphere strength are found in Model B where the TIB granitoid is reduced to a thickness of 12 kms. We therefore suggest that the contribution of the TIB granitoid to the isostatic state of the Central Scandes is less important than previously proposed.

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Introduction

Combined seismic and gravity studies show that the isostatic support to the topography of the Scandes must be located inside the crust and/or the mantle lithosphere (Balling 1980; Olesen et al. 2002; Ebbing & Olesen 2005). The old Precambrian crust of the Fennoscandian Shield is highly heterogeneous and the intrusion of huge volumes of granitoids along the Trans-Scandinavian Igneous Belt (TIB) ~1.8 to 1.65 Gyr ago (e.g. Gaál & Gorbatchev 1987) is expected to have significantly decreased the bulk density of the crust along a broad band (i.e. up to 200 kms wide at the surface) stretching from southern Sweden to northern Norway. The TIB meets the Scandes in its central part, about 100 kms east of Trondheim. The central Scandes are here characterised by lower topography than the northern and southern parts of the Scandes and appear to be a divide between two mountain ranges with contrasting denudation ages (Hendricks & Andriessen 2002) and distinct geomorphological and geophysical characteristics (Ebbing & Olesen 2005). The moderate elevation and the modest extent of the central Scandes might be a response to loads located at shallow depths in the crust. These, in turn, appear to be associated with relatively low-density TIB plutons that crop out in basement windows below the Caledonian nappes. Seismic experiments along the Central Scandes profile (CSP) (Schmidt 2000; Juhojuntti et al. 2001) failed to determine the depth extent of the TIB granitoids. Modelling of the gravity and magnetic field gives insights into the crustal structure, but various solutions could still fit the observed data (Skilbrei et al. 2002). Here we present the results of integrated potential field and thermo-rheological modelling. The latter modelling is used to explore the physical validity of crustal geometries deduced from potential field models, in terms of surface heat flow, Moho temperatures and lithosphere strength. In the first section of this paper, we summarise the results previously obtained from potential field studies along the CSP (Skilbrei et al. 2002). We then propose an alternative model for the profile based on isostatic gravity modelling of the Scandes (Ebbing, this volume). Finally, we propose to test the two potential field models against thermal and rheological models.

The Central Scandes profile: a previous potential field study

A detailed 2 1/2 D magnetic and density model along the CSP has been presented by Skilbrei et al. (2002). Here we briefly summarise the modelling procedure and its main

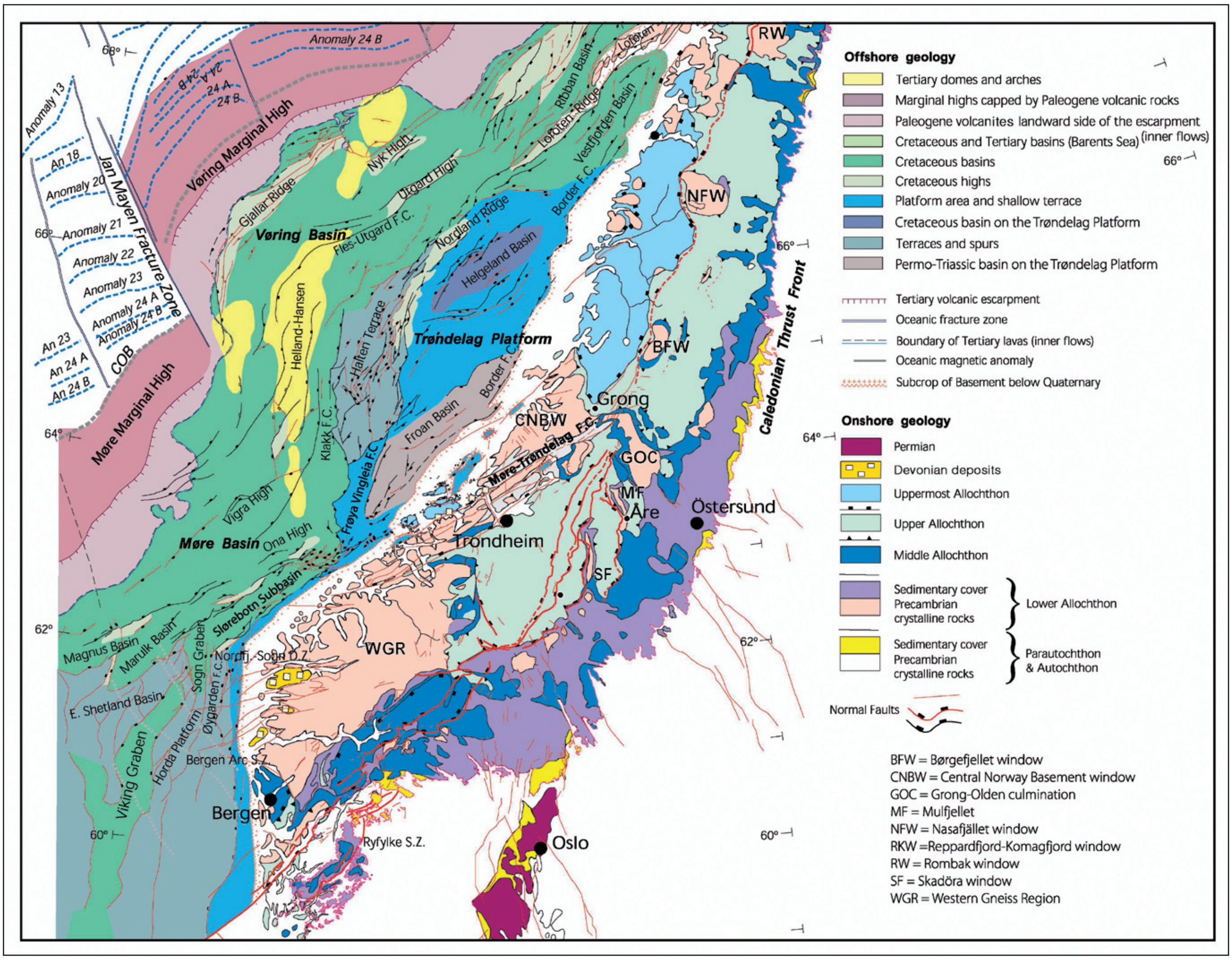

Fig. 1: Simplified geological map of western Scandinavia (after Mosar et al. 2002).

outcomes. Model calculations were performed using 2 1/2 D bodies and the commercial software package GMSYS-2D. The model is located in the central part of the Scandes and runs W-E from Trondheim in Norway to a point north of Östersund in Sweden (Figs. 1 and 2). The depth to the Moho was adapted from interpretations of seismic data (Guggisberg et al. 1991; Juhojuntti et al. 2001). The geometry of the modelled Moho is consistent with the seismic data, but its depth is not as well defined, since uncertainties in the velocity model can lead to variations by 2 to 5 kms (Schmidt 2000 and see discussion in Skilbrei et al. 2002). For the base of the lithosphere the model by Calcagnile (1982), showing a regular decrease from the Norwegian coast (120 km) towards the Bothnian Sea (160 km), was used. Modern data suggest a lithosphere-asthenosphere boundary at deeper levels in the eastern part of the profile (e.g. Balling 1995; Bruneton et al. 2004; Sandoval et al. 2004; Shomali et al. 2006). Nevertheless, this boundary affects only the long wavelengths gravity signal along the profile.

The most prominent Bouguer gravity anomaly along the profile is a low in the central part ($-80*10^{-5}$ m/s^2) correlating with a magnetic high (+450 nT). These anomalies have an extension of 200-250 km. Additionally, a variety of minor, short-wavelength anomalies can be observed along the profile, which can be correlated with surface geology (Wolf 1979; Dyrelius 1985; Skilbrei & Sindre 1991). Therefore, the geometry of the upper crustal structures was modelled by comparing the Bouguer gravity and magnetic fields with geological maps. The location and strike extents of the upper layers were taken from the geological maps and seismic data (Wolf 1979; Elming 1988; Juhojuntti et al. 2001; Koistinen et al. 2001). The densities and magnetic properties of the near-surface structures are based on rock samples analysed with respect to density and magnetic susceptibility (Table 1). Based on these constraints and relevant data, Model A was constructed (Skilbrei et al. 2002; Fig. 3).

The most prominent features of the model are the TIB granitoids. The main part of the negative Bouguer gravity and positive magnetic high is modelled as granitoid units within the TIB. The granitoid has a relatively low density (2690 kg/m3) and high mag-

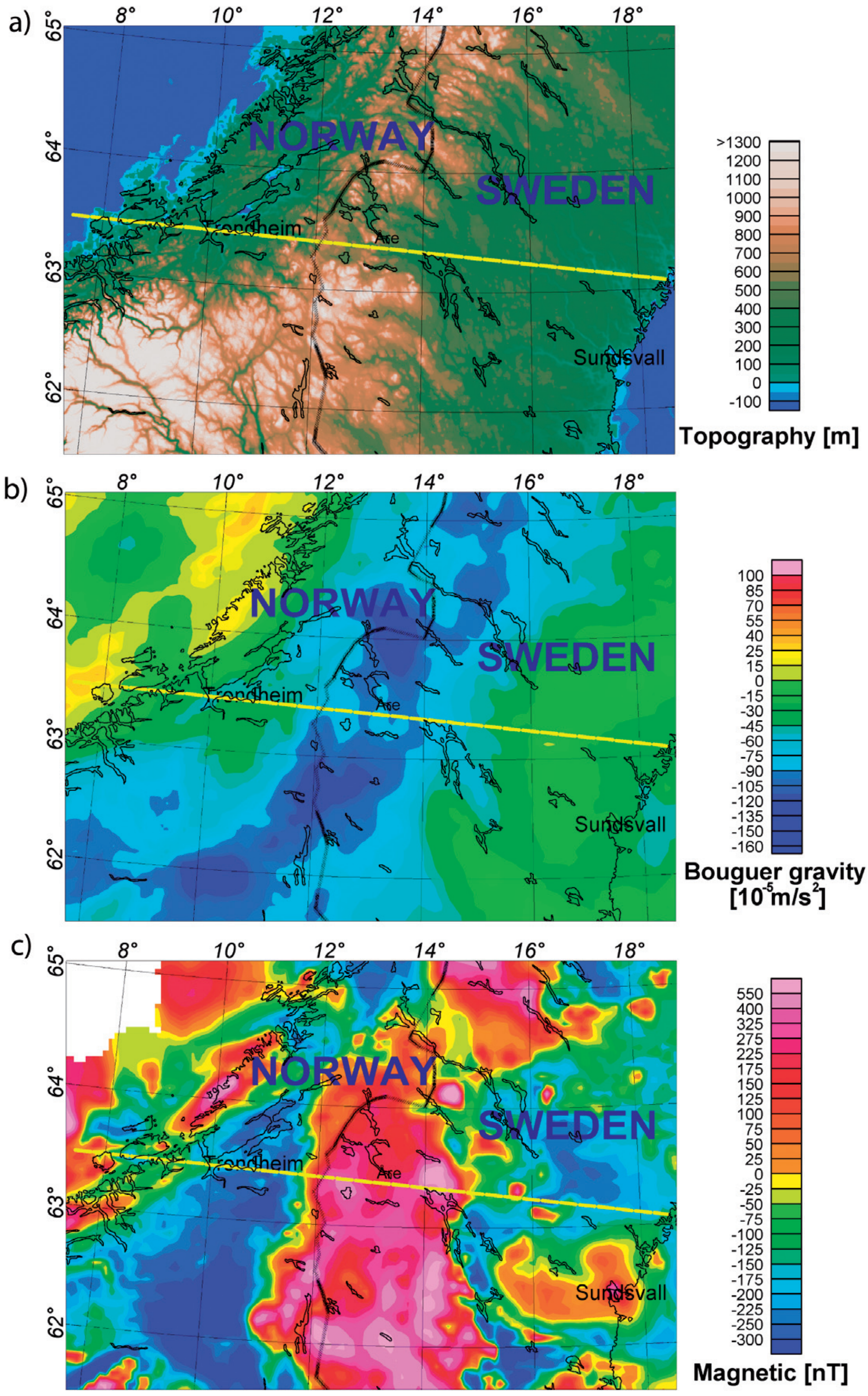

Fig. 2: (a) Topography/bathymetry of the Central Scandes and adjacent areas (after Dehls et al. 2000). (b) Bouguer anomaly map of the Central Scandes. The gravity data are based on the compilations by Skilbrei et al. (2000) and Korhonen et al. (2002a). The complete Bouguer reduction of the gravity data was computed using a rock density of 2670 kg/m³. (c) Aeromagnetic anomaly map of the Central Scandes. The magnetic anomaly map is based on the compilation by Olesen et al. (1997) and Korhonen et al. (2002b). The yellow line shows the location of the modelled profile.

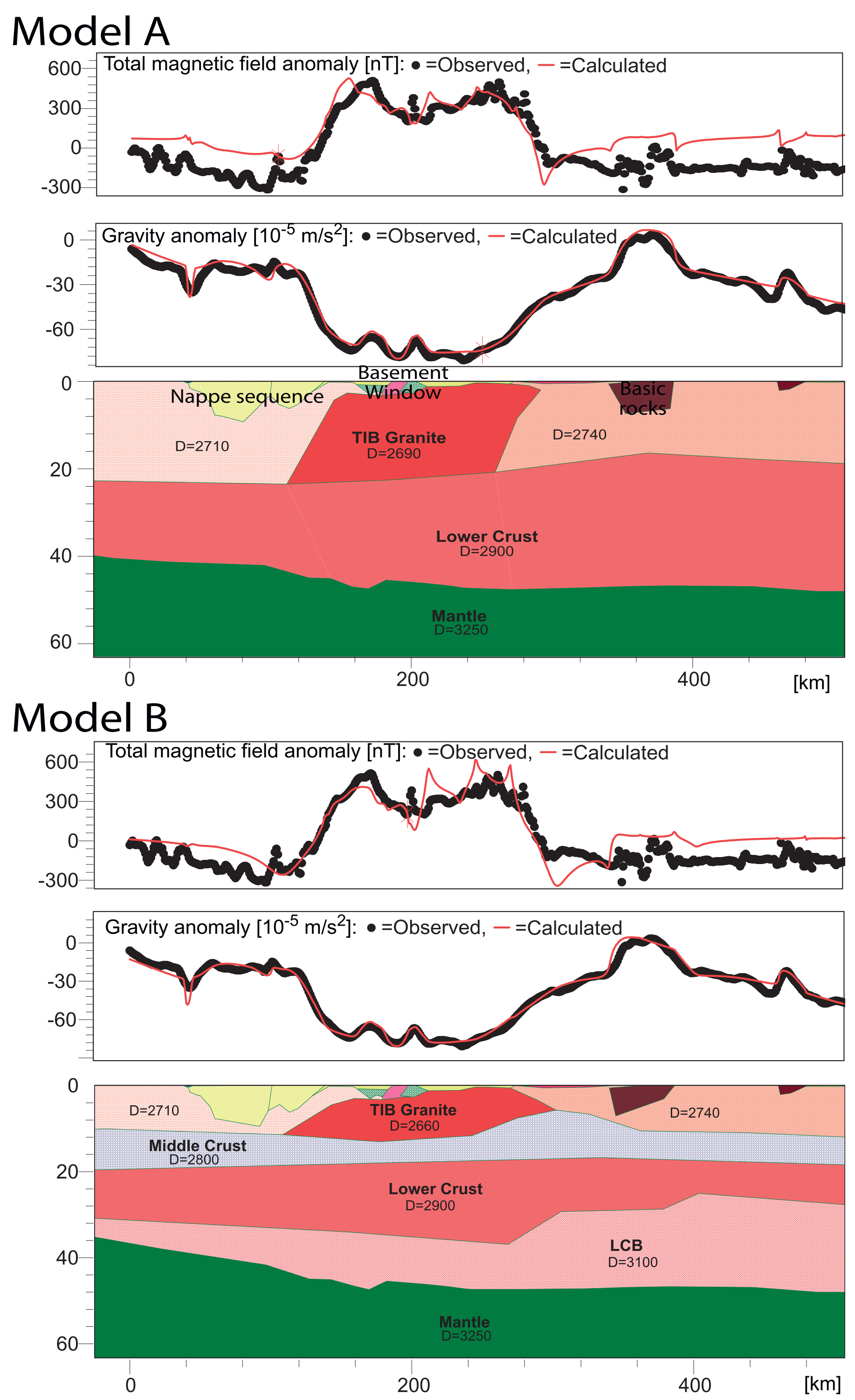

Fig. 3: Two alternative models of the density and magnetic structure for the Central Scandes – Model A: Density structure after Skilbrei et al. (2002). Model B: Density structure with a high-density lower crust. In both model calculations, the asthenosphere-mantle boundary is included at a depth of 120 (west) to 160 km (east) (not shown). Used near-surface densities and magnetic parameters are shown in Table 1. Location of the profile is shown in Fig. 2.

netic susceptibilities (SI 0.065) and extends to over 20 kms depth, similar to the interpretation by Dyrelius (1985). The lower crust is modelled with constant density and no internal variations. In addition to the upper crustal geometry and the TIB, only variations of the Moho surface along the profile influence the Bouguer anomaly pattern. Model A suggests that isostatic balancing of the topographic masses is a combination of Airy and Pratt types.

An alternative potential field model for the Central Scandes profile

As the internal part of the crust is not well constrained by seismic studies (Schmidt 2000; Juhojuntti et al. 2001), we test an alternative crustal structure based on the observation of high-velocity, high-density lower crust below parts of the Fennoscandian shield (e.g. Korsman et al. 1999) and isostatic considerations (Ebbing this volume).

Table 1: Used densities and magnetic susceptibilities for near-surface rocks.

Geological unit	Density [kg/m^3]	Magnetic susceptibility [SI]
Caledonian Nappe Sequence		
– metasedimentary rocks	2760	0.003
– metavolcanic	2840	0.01
Seve-Køli	2850	0.001
Basement Window	2650	0.01
(Tømmerås-Grong-Olden)		
TIB granitoid	2690/2660	0.065
Jotnian sediments	2610	0.001
Rapakivi granite	2640	0.0245

Table 2: Parameters used for the thermal modelling

Geological unit	Conductivity (W/m/K)	Heat Generation (µW/m^3)
Caledonian Nappes	2.5	1.2*
TIB granitoid	_	3*
Basic rocks	_	0.5
Upper and middle crust	_	1.7*
Lower crust (including LCB)	_	0.1
Mantle lithosphere	3.5	0

*Deduced from geochemical analyses (Olesen et al. 2005), other values are inferred.

Though the geometry of the near-surface structures, the Moho and the base lithosphere for Model B are identical to those of Model A (Fig. 3), we have introduced a high-density lower crust (3100 kg/m^3) to balance isostatically the section (for details see (Ebbing this volume)). The high-density lower crust has a thickness of up to 20 kms at the eastern end of the profile, but is only 12 kms thick below the TIB granite. The presence of high-density lower crust is consistent with the interpretation of a wide-angle seismic velocity model that shows high velocities (~6.8-7.2 km/s) at the base of the crust (Schmidt 2000). However, due to the uneven distribution of the seismic profiles, the areas where high velocities are observed in the lowermost crust do not match perfectly the areas where high densities are inferred from the isostatic study (Ebbing this volume).

As a consequence of the modified deep crustal geometry and density distribution, the TIB granitoid is now modelled with a thickness of only 12 kms and a density of 2660 kg/m^3. The latter value is similar to that used by Olesen et al. (2002) for the TIB granitoids of Northern Norway. The obtained thickness leaves the section isostatically balanced and is in agreement with the magnetic anomaly (Fig. 3). The adjustment to the magnetic anomaly is achieved for the TIB with parameter values similar to the ones used for Model A. However, since the magnetic anomaly is most sensitive to near-surface structures, minor structural modifications had to be applied to model the magnetic anomaly with the new crustal configuration. Both Models A and B are in agreement with available seismic, magnetic and gravity data. To further evaluate the two models, we apply thermo-rheological modelling.

Insights from thermo-rheological modelling

Thermal models

We used the commercial finite element package Ansys for the thermal modelling. The models are 2D steady-state conductive thermal models. We used 6-noded triangular elements, our models contain ~10 000 to ~20 000 elements allowing for both accurate and fast computations. Boundary conditions are set up as constant temperatures at the surface (i.e. 0°C) and constant heat flow at the base of the models. Basal heat flow is set equal to 25 mW/m^2. The selected basal heat flow remains in the range of values typically inferred for the western part of the Fennoscandian shield (Balling 1995; Artemieva & Mooney 2001). Previous thermal modelling suggests that basal heat flow increases from ~20 mW/m^2 in the eastern part of the profile to ~30 mW/m^2 in the western part (Balling 1995). A reduction of basal heat flow down to ~12 mW/m^2 below Finland (i.e. east the CSP) is indicated from mantle studies (Kukkonen & Peltonen 1999; Kukkonen et al. 2003). Since our main focus in the central part of the profile, where available data support the basal heat flow value selected in this study (Balling 1995), we preferred not to complicate the model by introducing lateral variations of the latter parameter. Model geometries are imported from potential field models A and B and heat productions are related to the different basement units in agreement with values deduced from geochemical analyses (Olesen et al. 2005 and Table 2). Because our current knowledge about surface heat flow values along the CSP is relatively poor, we kept the models simple. Consequently, we kept constant conductivities and radioactive heat generations for each crustal unit (Table 2). We will discuss the implications of our choice on the results in the following section.

Computed geotherms and heat flow values for both models A and B are presented in Figure 4. In the case of Model A, we note that the modelled thick granite results in a significant increase of the temperature in the lower crust below it. Moho temperatures below the granite are predicted to reach up to ~750°C, exceeding by 100°C Moho temperatures of the surrounding areas and close to melting temperatures associated with most crustal materials. Modelled surface heat flow values above the granite reach high values between 80 and 90 mW/m^2. To our knowledge, similar high values were measured at only two locations above two batholiths in southern Sweden (Eriksson & Malmqvist 1979).

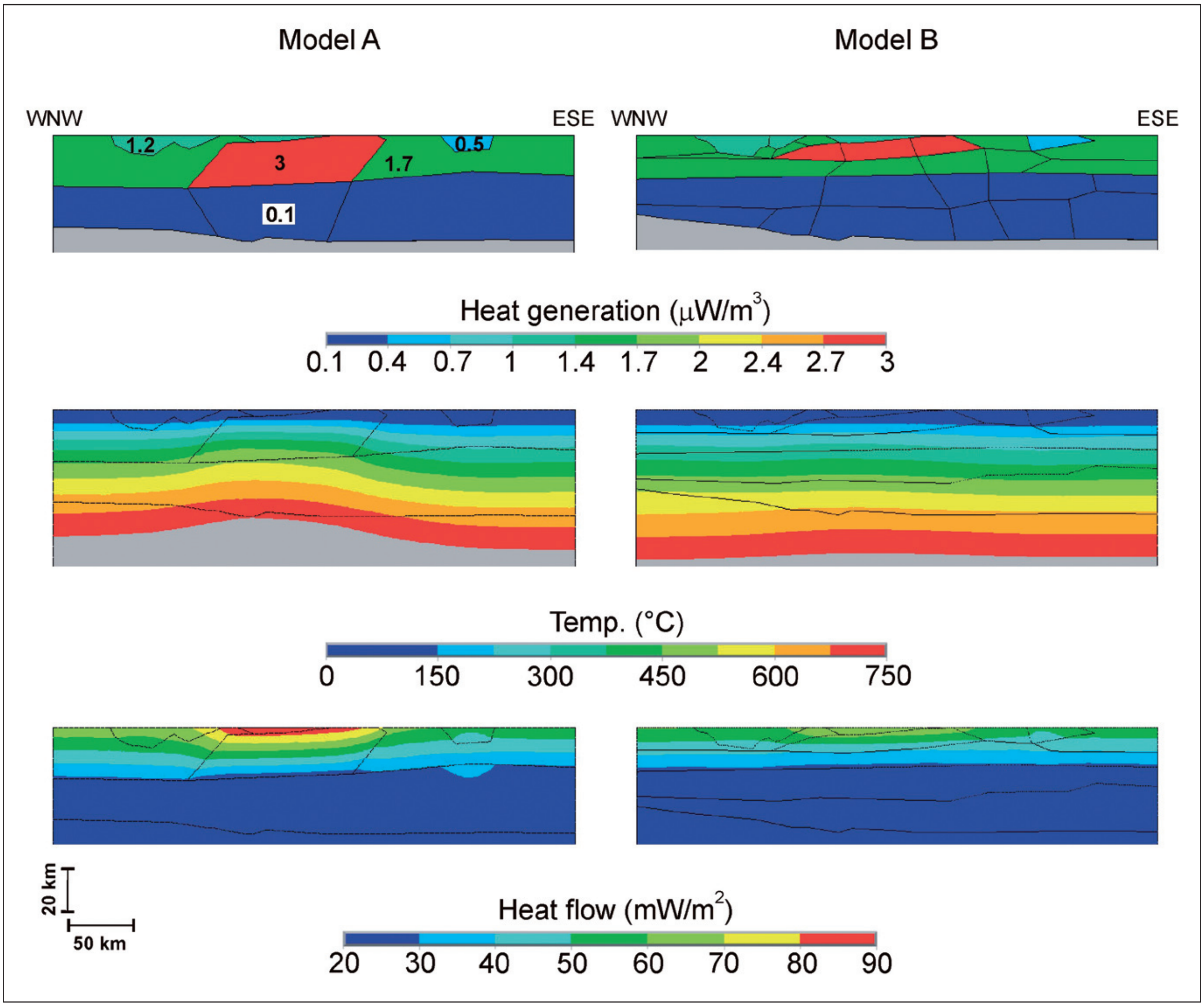

Fig. 4: Input heat generation values and computed temperature and heat flow values for the Central Scandes profile Models A (left) and B (right). Used heat generations for each crustal unit are indicated on Model A. Used conductivities are given in Table 2. Boundary conditions are T=0°C at the top and a basal heat flow of 25 mW/m² (VE:x2).

Computed isotherms for Model B (Fig. 3) show a much more moderate rise below the modelled granite that is thinner than in model A. Moho temperatures remain close to 600°C along the profile, in good agreement with previous thermal models (e.g. Artemieva 2003), and decrease by 100°C west of the Caledonian nappes. Interestingly, predicted surface heat flow values are in the range between 50-70 mW/m², reaching their maximum above the high heat-producing TIB pluton. These computed surface heat flow values appear to be in better agreement with commonly measured values in Proterozoic shields (Artemieva & Mooney 2001). Additionally, two heat flow values from shallow drill holes (i.e. ~300m) are available at the western end of the CSP (Hänel et al. 1979 and references therein). These resulted in values of 48 and 50 mW/m² which are most probably affected by the paleoclimate and lower than expected equilibrium values by about 10 mW/m² (Balling 1995). Two heat flow measurements exist at the eastern edge of the TIB body. These measurements result in corrected heat flow values by 70 mW/m² (Balling 1995) in good agreement with values modelled here.

Implications for the thermal and rheological structure of the lithosphere

From our thermal models it is possible to calculate the depth to the thermal base of the lithosphere taken as the 1300 °C isotherm. Depths to base lithosphere predicted by the two models do not differ significantly. Model A predicts a base lithosphere plunging from 130 km depth in the west to 136 km in the east, whereas Model B predicts deeper but less variable depths in the order of 140 km. The only conclusion that can be drawn from the present modelling is that there is reasonable agreement in between the modelled values and values obtained from surface wave

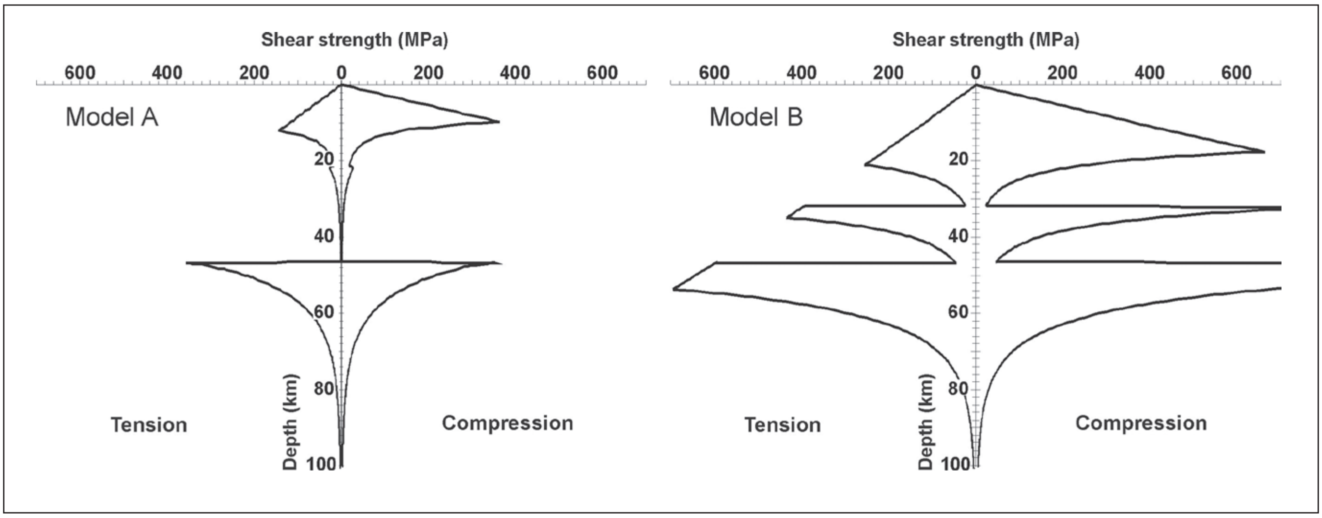

Fig. 5: Lithosphere strength envelopes calculated on the basis of thermal Models A and B at the location of the TIB body. "Tension" and "Compression" refer to lithosphere strength for applied normal and thrust faulting regimes respectively. Used rheological parameters are given in Table 3.

studies (140 to 150 km, Calcagnile 1982) and thermal modelling (~150 km, Artemieva 2003). However, much care has to be taken when discussing these previous determinations, because (1) there is no systematic correlation between seismic and thermal lithosphere and (2) the two studies were conducted on a very regional scale providing a crude resolution along the CSP.

The thermal state of the lithosphere exerts a strong control on its integrated strength (e.g. Ranalli 1995). We tentatively determined the strength envelopes for the central parts (i.e. at the location of the TIB granitoid) of Models A and B (Fig. 5). The parameters used for the construction of the envelopes are listed in Table 3. The strength envelopes give a first-order idea of the relative strength of the lithosphere. We should, however, keep in mind that the strength of the lithosphere can be drastically reduced by the pre-existence of weak fault zones (e.g. Pascal & Gabrielsen 2001; Bos & Spiers 2002) or water-saturated rocks (e.g. Ranalli 1995). At the location of the TIB batholith, Model A results in a very weak lithosphere with a brittle-ductile transition at ~10 km depth in the crust and a large viscous channel above the Moho. For Model B, the brittle-ductile transition is predicted to occur at ~20 km depth and the lower crust viscous channel is much less developed.

The Fennoscandian lithosphere is at present subject to relatively high tectonic stresses (Stephansson 1989; Olesen et al. 2004; Pascal et al. 2005). Therefore, the extremely weak lithosphere predicted by Model A is expected to show signs of high strain-rates. For a shallow brittle-ductile transition, as predicted in Model A, two thirds of the crust should creep but the upper brittle layer is expected to respond mechanically to the crustal flow taking place below it in the ductile layer. Therefore, a consequence of Model A is that a large number of low- to moderate-magnitude earthquakes are reasonably expected due to the high stresses that dominate the Scandinavian lithosphere at the present day. In contrast, the region of interest here (i.e. the region underlain by the TIB granitoid) is void of earthquakes (Dehls et al. 2000). It is, furthermore, interesting to note that frequent low- to moderate-magnitude earthquakes are indeed observed at the location of the large Bohus-Iddefjord granite in southern Sweden, where heat flow values similar to the ones predicted in Model A have been measured (Eriksson & Malmqvist 1989). These independent observations argue against extremely high heat flow at the location of the studied TIB body and, implicitly, against the presence of a very thick TIB granitoid below the Central Scandes.

Table 3: Rheological parameters used for lithosphere strength computations. A strain rate of 10^{-15} was applied to construct the strength envelopes. Creep parameters after Carter & Tsenn (1987)

Brittle deformation	Friction	Pore pressure ratio	
	0.6	0.35	
	Strain-rate coef.	Stress exponent	Activation energy
Power-law creep	(Pa^{-n}/s)		(kJ/mol)
TIB: dry granite	$3.16\ 10^{-26}$	3.3	187
Lower and middle crust:			
felsic granulite	$2.01\ 10^{-21}$	3.1	243
LCB: mafic granulite	$8.83\ 10^{-22}$	4.2	445
Lithospheric mantle:			
dry dunite	$7.94\ 10^{-18}$	3.6	535

Discussion

About homogeneous heat production through depth

The thermal modelling and, particularly, the rheological modelling suggest that an extremely (i.e. ~20 km) thick

TIB batholith below the Central Scandes is not likely. Our conclusion is mainly based on the impact of the thickness of the batholith on surface heat flow, Moho temperatures and lithosphere strength, assuming a homogeneous heat production inside the body. The latter hypothesis has been questioned since the 60s, and an exponential decay of radioactive heat production with depth is very often adopted (Lachenbruch 1968, 1970). This theoretical law seems to be at odds with actual measurements made on cores from the Kola (Kremenetsky et al. 1989) and the KTB (Pribnow & Winter 1997) superdeep drill holes. However, the exponential law was originally proposed for plutons only (Roy et al. 1968) and the superdeep boreholes were drilled in totally different geological environments. At first view, the study of exposed deep sections of batholiths seems to give some support to the exponential law (Lachenbruch 1968). In detail, recent work on the Sierra Nevada Batholith in California (Brady et al. 2006) suggests, however, a much more complex depth distribution for heat production than previously anticipated. It apparently decreases with depth but also increases significantly for some depth intervals. This is also in agreement with the study of the Vredefort Dome Structure by Nicolaysen et al. (1981).

Instead of modelling complex distributions for heat-producing elements in the studied TIB body, we preferred to keep the thermal models as simple as possible and concentrate on variations in the geometry of the crustal units. This choice was also motivated by the paucity of thermal data from the area under investigation here. Obviously, our results are strongly dependent, among other parameters, on the vertical distribution of heat-producing elements but, in the absence of more constraints, a systematic sensitivity analysis would not help us to discriminate in between a large collection of modelled alternatives. At the best, we may assume that the actual crustal structure lies in between our two "end-member" models but certainly closer to the structure of Model B.

Crustal structure and topography of the Central Scandes

The two alternative models for the Central Scandes show clearly that the interplay between the TIB and the Scandes influences the gravity and magnetic field as well as the isostatic state of the lithosphere. The TIB shows a prominent signal in the magnetic anomalies and is also reflected by lows in the Bouguer gravity field. However, estimates of the depth extension of the TIB are dependent on the deep crustal configuration. Wide-angle seismic results show that the deep crust is heterogeneous (Juhojuntti et al. 2001; Schmidt 2000), and indications of a high-velocity crust exist (Korsman et al. 1999). However, velocities in the deep crust have a relatively high uncertainty range (Schmidt 2000). This is an effect of the resolution of the available seismic data and the low reflectivity of the lower crust (Juhojuntti et al. 2001).

Our study shows, nevertheless, that the TIB coincides with the main topography and Bouguer gravity lows in the Central Scandes. While the magnetic signal can be associated directly with the TIB granitoids, the Bouguer gravity low is caused by a superposition of the TIB and the deep crustal geometry. The axis of highest elevation of the Scandes is associated with a Bouguer gravity low but no crustal root (Ebbing & Olesen 2005, (Ebbing this volume)). Therefore, the Bouguer gravity low can be interpreted to be largely related to the low-density granitoids of the TIB. The low-density rocks of the TIB have to be considered specially in order to explain the gravity field of the Scandes. The distribution near the surface causes a strong signal in the gravity field, even with a relatively small density contrast with respect to the surrounding rocks. However, the effect on the isostatic balance of the Scandes is less pronounced compared to the influence of deep-seated bodies.

Conclusions and recommendations

From the potential field modelling both presented models are possible for the Central Scandes. However, isostatic considerations and especially the thermal and rheological modelling make Model B more preferable. One of the keys to unveil the structure along the CSP is to do more focussed seismic studies. The results of a new receiver function study along the profile will be available in the near future, and combined processing with wide-angle data will hopefully allow for more insights into the deep structure along the transect. These, in turn, will provide a better background for modelling the upper crustal structures of the Central Scandes.

Acknowledgements: This study was conducted in the framework of the KONTIKI project financed by Statoil, we thank Øyvind Steen for his support. C. Pascal is grateful to Sierd Cloetingh and the Vrije Universiteit of Amsterdam for permission to use Ansys. We thank Richard W. England, Chris Juhlin and Odleiv Olesen for discussions and assistance. We are indebted to Drs. Niels Balling and Ilmo Kukkonen for their thoughtful and constructive reviews that helped to improve significantly the present Ms.

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