Lithosphere and upper mantle structure in Northwestern gravity data

Background

The tectonic history of the Arctic – North Atlantic passive plate margin is still under debate. In particular, the contributions of the lithosphere and the mantle to the uplift that resulted in the Norwegian mountains are not well constrained; inferences from seismic observations and gravity measurements disagree. With the March 2009 launch of the GOCE satellite, an image of the static gravity field will be observed with improved accuracy at wavelengths of 100-500 km. Therefore, the GOCE observations provide a unique opportunity to study the crustal and upper mantle structure.

Variations in the gravity field can be due to density anomalies in the crust or the mantle, changes in crustal thickness or isostatic imbalance due to loading by Late-Pleistocene ice sheets.

We aim to produce a consistent model of the gravity field from crustal thickness, density anomalies and GIA, which makes full use of the GOCE resolution. Decomposing the GOCE gravity field in this way will provide new information on the Earth’s structure at a passive continental plate margin. In particular it will shed light on the roles of the solid Earth and climate uplift of the Norwegian mountains.

Methodology

The research consists of two parts. The goal of the first part of the research is to construct a realistic 3D Earth model of the lithosphere and upper mantle below Fennoscandia. For this, we use seismological, geological and geophysical data and models. The Earth model can be forward modeled into a gravity potential field. This field will be validated with GOCE gravity observations.

To constrain the model with extra information, observations of the post-glacial rebound in the area are used. This is the goal of the second part of the research. Here we use the finite-element software ABACUS to model the Earth’s response of the melting of the Late-Pleistocene ice-sheets, which is called Glacial Isostatic Adjustment (GIA).

In an iterative loop, we try to improve current Earth models using seismological, geological and geophysical data. Combining seismic, gravity and GIA observations is a novel procedure and it is suspected to get new insights into the structure and rheology of the lithosphere and upper mantle.

The density model consists of several spherical layers, which are approximated by a binomial series expansion in the following way (Novak, et. al., 2005):

\[ f_{\text{binomial}} = \sum_{n=0}^{N} \binom{N}{n} r^n (1-r)^{N-n} \]

This can be written in a spherical harmonic (SH) series, with the coefficients \( F_{n,m} \) being calculated by a weighted least squares SH analysis. After summation of the coefficients of the layers, with the glacial deflection superimposed, the gravity potential can be calculated by performing a SH synthesis with the final coefficients:

\[ \nabla^2 g = \sum_{n,m} \frac{4\pi}{n!} F_{n,m} \frac{R^3}{r^{n+2}} L_n^m(r) \]

Where \( V_{n,m} \) is:

\[ V_{n,m} = \frac{1}{2n+1} \frac{1}{\rho} F_{n,m} \]

This method is capable of calculating a 3D density model with varying geometry and laterally varying density profiles. The method is capable of computing a global gravity potential field and its spatial derivatives, the gravity vector and the gravity gradient tensor. Especially the tensor is useful, because the GOCE satellite directly observes several components of the Earth’s gravity gradient tensor.

GIA gravity correction concept (current work)

The GIA gravity correction is calculated in the GIA modeling (van der Wal, et. al., 2009). This gravity correction uses a constant crustal thickness (T) and a constant crustal and mantle density (Method 1). When a realistic Earth model is used, we use a global spherical harmonics-based forward modeling method to compute the gravity effect (Method 2).

Method 2 is capable of using a more realistic Earth model and GOCE coverage of density anomalies in the crust or the mantle, changes in crustal thickness or isostatic imbalance due to loading by Late-Pleistocene ice sheets.

Latest Results

First results were obtained by using the latest GIA model constructed with the best fitted mantle viscosities to relative sea level observations. The GIA model provides the lithospheric deflection due to the Late-Pleistocene ice-sheets. The calculated gravity anomaly due to this deflection is seen in figure 4:

![Figure 4](image)

When a more realistic model of the lithosphere is used in the computations a reduction of 6 mGal is seen in the GIA gravity correction.

Publications

- (expected) GIA gravity correction in Fennoscandia: A lithosphere model with realistic structure and rheology, B.C.Root et. al., (2013)