Introduction

In most regions, the stress in a region is defined by the tectonic background stress and the lithostatic stress. The superposition of these two is one factor in controlling the movement along faults. In deglaciated regions, an additional stress is found: the rebound stress. This stress is related to the rebounding of the crust and mantle after deglaciation.

The process of rebounding, called glacial isostatic adjustment (GIA), is observed in northeastern Canada, where a GIA signal of up to 12 mm/a is found by GPS measurements (Wu et al., 2010). Several models have been developed to analyse the viscosity, rheology and structure of the mantle. Wu (1996, 1997) used these models to find the GIA stress behaviour during and after glaciation in northeastern Canada. The GIA stress is the superposition of rebound, tectonic background and lithostatic stress. It has rotated after the end of deglaciation until today, and is consistent with the tectonic background stress now. However, these models do not include faults, and are not able to represent local stress changes. A recent study by Steffen et al. (2012) showed that the local stress field due to the fault systems in the northeastern Hudson Bay is rotated by up to 90° to the regional stress direction of NE-SW of eastern Canada, which is mainly due to the ridge-push of the mid-Atlantic. Therefore, it is necessary to include faults into GIA models to identify local stress directions.

Fig. 1 shows the stress behaviour for a thrust regime due to glaciation and deglaciation, and their impacts on the Mohr circle. The Mohr circle is a way to represent different stress settings and their effects on fault stability. In a thrust regime, the maximum stress is the horizontal stress, and the vertical stress is the minimum. A point in the crust is therefore affected by $\sigma_1$ in the horizontal, and $\sigma_3$ in the vertical. The point is close to failure, which is indicated by a relative small distance between the Mohr circle and the line of failure. During the glaciation process, the horizontal stress is increased due to flexure in the lithosphere, and the vertical stress is increasing both due to flexure in the lithosphere and the vertical applied load of the ice sheet. Therefore, the Mohr circle is moving in the positive direction along the normal stress axis, and away from the line of failure, thus suppressing any fault movement. As soon as the ice is melting, the load is decreased, but the flexure in the lithosphere due to the glaciation remains. Decreasing of the load reduces the vertical stress only, leaving a high horizontal stress. Therefore, the radius of the Mohr circle is increasing and the midpoint of the circle is moving in the negative direction along the normal stress axis. The circle touches or crosses the line of failure, and the fault will start to move, releasing the stress in earthquakes.

The goal of this study is to show the aforementioned stress settings in a GIA model, including a lithosphere and mantle. This has to be done by advancing current GIA models by including a fault into these models.

Methodology

Several methods have been developed to model the process of GIA (see Steffen & Wu, 2011; for an overview). In this study, the finite-element method based on Wu (2004) is used. A flat two-dimensional earth model is developed, which consists of six layers (Fig. 2), but can be divided in three different parts. The first part is the lithosphere composed of a 20 km thick crustal layer, and a lithospheric mantle of 100 km. The lithosphere behaves elastic. The upper mantle builds up the second part, divided into two layers with thicknesses of 330 km and 220 km. In contrast to the lithosphere, the upper mantle is a visco-elastic layer. The lower mantle, the third part of the earth model, behaves also visco-elastic. The sides of the earth model are fixed in the horizontal direction. To account for gravity in the model, so-called Winkler foundations are used, which are applied along density contrasts. These foundations represent the buoyancy forces, holding the model in equilibrium. The earth models of this study include a fault surface without density contrast.

On top of the earth model, a parabolic ice model (Fig. 2) is applied which simulates the last glacial cycle in North America. The ice sheet has a maximum thickness of 3,500 m at glacial maximum, and a width of 3,000 km. Both parameters are similar to realistic ice sheets by Peltier (2004) and Lambeck et al. (1998). The volume of the ice sheet increases for 100,000 years, and decreases in the following 10,000 years.
Figure 1: Schematic sketch of fault stability before, during and after glaciation for a thrusting regime. The upper row shows the state of stress and Mohr circle before glaciation (BG), the middle row represents the stresses for maximum glaciation (DG: during glaciation), and the lower row indicates the stress behaviour at the end of deglaciation and during uplifting (AG: after glaciation). The horizontal stress is $\sigma_1$, the vertical stress is $\sigma_3$, $\sigma_n$ represents the normal stress and $\tau$ the shear stress.

Results
Several fault factors are tested in the models, e.g. friction coefficient, location, and fault angle. In the following, we will concentrate on the vertical displacement behaviour along the fault for a varying friction coefficient only. The fault is located at the centre of the ice sheet, which is expected to observe the highest fault offset due to GIA, as the maximum load was applied in that area. The fault has a dipping of 45°.

The stress used as input for the fault model is a GIA stress, therefore, consisting of tectonic background, lithostatic and rebound stress induced by the GIA process. The movement along the faults is only driven by the changes of horizontal compared to vertical stress. Additional extension or shortening of the model is not applied.

Fig. 3 shows the vertical displacement along the fault after the end of deglaciation for friction coefficient of 0.6. Results for other friction coefficients are summarized in Table 1. The area shown represents only a small part of the model. The length of the fault is 28.5 km up to a depth of 20 km. The displacement due to GIA is not shown, as it has values of up to 280 m in that area. A thrusting movement is observed for all four friction coefficients. The slip rate varies between 2.8 and 3.5 m, with the highest values for a friction of 0.2, and the lowest value for a friction of 0.8 (Table 1).

Table 1 compares the dependence of the friction coefficient on the fault offsets for different locations of the fault. The fault at 750 km is located in the middle between centre and border of ice sheet. 200 km to the east of the ice sheet border a third fault is implemented. The fourth fault is included in the forebulge area. Only one fault is activated at each time. The fault offset is decreasing from the centre of the ice sheet to the boundary area. In contrast, in the forebulge area a higher fault offset is found compared to the third fault area. The vertical GIA displacement is also higher for the area beneath the ice sheet and in the forebulge area compared to the position close to the boundary of the ice sheet, which is close to the axis of tilting. For a friction coefficient of 0.2 a smaller offset of up to 0.8 m is found. The highest fault offsets are observed for friction coefficients of 0.4 and 0.6. In general, a thrusting mechanism is found for all faults, related to the background stress, which is a thrust regime.
Figure 3: Vertical displacement behaviour for a fault located at the centre of the ice sheet for a friction coefficient of 0.6. The fault offset is indicated in Table 1.

Table 1: Fault offsets depending on friction coefficients and location of the fault.

<table>
<thead>
<tr>
<th>Location</th>
<th>Friction coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td>0 km</td>
<td>3.5 m</td>
</tr>
<tr>
<td>750 km</td>
<td>2.3 m</td>
</tr>
<tr>
<td>1700 km</td>
<td>1.2 m</td>
</tr>
<tr>
<td>2200 km</td>
<td>1.6 m</td>
</tr>
</tbody>
</table>

Discussion
The amount of fault offset for different locations is mostly depending on the flexure and deformation in that area. The fault at the ice sheet centre shows the highest displacement due to GIA and is depressed at most. Moving to the ice sheet boundary, the area is not much depressed anymore. Further away from the ice sheet, in the forebulge area, the opposite case is happening, as the crust is uplifted during glaciation and is now depressing since the ice is gone. Therefore, the flexural effects are higher than for locations close to the boundary of the ice sheet.

The thrusting mechanism found for all fault locations and friction coefficients agrees with observations of earthquake data in eastern Canada and Scandinavia (e.g. Steffen & Wu, 2011, Steffen et al., 2012). The amount of fault slip rate obtained from the models is similar to offsets in eastern Canada. The largest earthquake in northeastern Canada happened in Ungava Peninsula 1989 and an offset of up to 1.8 m was found (Adams et al., 1991). This fault is assumed to be post-glacial. The Ungava Peninsula is not at the centre of the former ice sheet. However, fault offsets in Scandinavia of up to 10 m are found, which are higher than the estimated offsets from this study. As the fault in our models is located in a homogeneous crust without density contrasts, the stress is not accumulated at the fault and is continuous along the boundary as well. For a fault that separates two different materials, stress will be different on both sides, leading to a larger movement along the fault. In nature, faults are mostly represented by two different materials on both sides.

Conclusion
In this study faults have been implemented into current GIA models to test the effect of different friction coefficients and location of the faults in relation to the ice sheet. As it was observed in a previous study that such GIA models show no agreement with observed stress directions, the implementation of a fault has been inevitable.

Preliminary results from new GIA models including a fault, suggest fault offsets of at least 2 m depending on the location of the fault related to the former ice sheet, and the friction coefficient. These offsets fit to observed ones in Ungava Peninsula in northeastern Canada. In future studies, several parameter will be tested to account for more realistic fault offsets found in Scandinavia and northeastern Canada, e.g. different time steps, realistic ice sheets, density contrast along the faults, fault angle, and mantle viscosity.

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References


