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On the implementation of faults in finite-element glacial isostatic adjustment models

Rebekka Steffen [a,*], Patrick Wu [a], Holger Steffen [a,b], David W. Eaton [a]

[a] Department of Geoscience, University of Calgary, 2500 University Drive NW, Calgary, Alberta, Canada T2N 1N4
[b] Lantmäteriet, Lantmäterigatan 2c, 80182 Gävle, Sweden

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ABSTRACT

Stresses induced in the crust and mantle by continental-scale ice sheets during glaciation have triggered earthquakes along pre-existing faults, commencing near the end of the deglaciation. In order to get a better understanding of the relationship between glacial loading/unloading and fault movement due to the spatio-temporal evolution of stresses, a commonly used model for glacial isostatic adjustment (GIA) is extended by including a fault structure. Solving this problem is enabled by development of a workflow involving three cascaded finite-element simulations. Each step has identical lithospheric and mantle structure and properties, but evolving stress conditions along the fault.

The purpose of the first simulation is to compute the spatio-temporal evolution of rebound stress when the fault is tied together. An ice load with a parabolic profile and simple ice history is applied to represent glacial loading of the Laurentide Ice Sheet. The results of the first step describe the evolution of the stress and displacement induced by the rebound process. The second step in the procedure augments the results of the first, by computing the spatio-temporal evolution of total stress (i.e. rebound stress plus tectonic background stress and overburden pressure) and displacement with reaction forces that can hold the model in equilibrium. The background stress is estimated by assuming that the fault is in frictional equilibrium before glaciation. The third step simulates fault movement induced by the spatio-temporal evolution of total stress by evaluating fault stability in a subroutine. If the fault remains stable, no movement occurs; in case of fault instability, the fault displacement is computed.

We show an example of fault motion along a 45°-dipping fault at the ice-sheet centre for a two-dimensional model. Stable conditions along the fault are found during glaciation and the initial part of deglaciation. Before deglaciation ends, the fault starts to move, and fault offsets of up to 22 m are obtained. A fault scarp at the surface of 19.74 m is determined. The fault is stable in the following time steps with a high stress accumulation at the fault tip. Along the upper part of the fault, GIA stresses are released in one earthquake.

1. Introduction

In the Earth's crust, stress can be subdivided into tectonic background stress, overburden pressure, and pore-fluid pressure. The superposition of the first two and the variation of the third part are factors in controlling movement along faults (e.g. Twiss and Moores, 2007). Furthermore, stresses due to sedimentation and erosion contribute to the total stress field. In deglaciated regions, an additional stress must be considered: the rebound stress, which is related to rebounding of the crust and mantle after deglaciation (e.g. Wu and Hasegawa, 1996a; Wu, 1996).

During the growth of a continental ice sheet, the lithosphere under the ice load is deformed into the mantle and the removal of the ice load during deglaciation initiates a rebound process. The uplift is well known in formerly glaciated areas, e.g. North America and Scandinavia, and in currently deglaciating areas, e.g. Alaska, Antarctica, and Greenland. The whole process of subsiding and uplifting during the growth and melting of an ice load and all related phenomena is known as glacial isostatic adjustment (GIA).

During the process of glaciation, the surface of the lithosphere is depressed underneath the ice load and compressional flexural stresses are induced in the upper lithosphere, whereas the bottom of the lithosphere experiences tensional flexural stresses (e.g. Adams, 1989a; Wu and Hasegawa, 1996a). An additional vertical stress due to the ice load is present, which decreases to zero during deglaciation (e.g. Wu and Hasegawa, 1996a). During rebound, flexural stresses relax slowly. These stresses are able to change the original stress directions and regime (Wu, 1996).

In a thrusting background stress regime with the maximum principal stress in the horizontal direction and the minimum

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[*] Corresponding author. Tel.: +1 4034013537.
E-mail address: rsteffen@ucalgary.ca (R. Steffen).

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principal stress in the vertical direction, the stresses of flexure and vertical loading lead to stable conditions along a fault during loading (Johnston, 1987), and unstable conditions during deglaciation and afterwards (Wu and Hasegawa, 1996a, 1996b). This stress regime is dominant in formerly glaciated continental areas; however, in some areas normal or strike-slip regimes occur (e.g. Adams, 1989b; Slunga, 1991; Wu, 1996, 1997; Lund and Zoback, 1999; Heidbach et al., 2008; Lund et al., 2009; Mazotti and Townend, 2010; Steffen and Wu, 2011; Steffen et al., 2012).

In the presence of ice, the vertical load increases the minimum principal stress, but horizontal stress (maximum principal stress) is also increased due to flexure. After glacial maximum, the mass of the ice load decreases and the vertical stress induced by this load decreases to zero at the end of the deglaciation. But at this time point, the flexural stress in the horizontal direction still exceeds the initial state, leaving an additional stress in the crust that is able to reactivate a pre-existing fault structure (Wu and Hasegawa, 1996a).

Several faults with high fault scarps, which document the occurrence of large earthquakes during and after the end of deglaciation, have been identified in North America and Europe (e.g. Kujansuu, 1964; Lagerbäck, 1978; Olesen, 1988; Dyke et al., 1991). Field investigations indicate that post-glacial unloading and rebound led to the formation or re-activation of faults in continental shields (e.g. Lagerbäck, 1978; Adams, 1989a). Furthermore, formerly glaciated areas are generally characterized by moderate seismic activity today.

During the last 15 years, various numerical models have been developed to simulate the occurrence of earthquakes during the glacial period. Of these, two different types of models exist to investigate fault stability. The first type has been employed by Wu (1996, 1997), Wu and Hasegawa (1996a, 1996b), Johnston et al. (1998), Klemann and Wolf (1998), Lund (2005) and Lund et al. (2009) using either the finite-element methodology (FEM) or spectral method. These models are based on general GIA models including crust and mantle; they have no explicit fault structure, but instead considered virtual faults, which have no effect on the surrounding stress or displacement. This approach is normally used to analyze the isostatic adjustment process in a viscoelastic Earth, in which the lateral boundaries do not have any plate velocity applied. Stress changes and stability of pre-existing faults are evaluated at assumed fault locations (Wu and Hasegawa, 1996a). Since, fault surfaces are not included in these models, the estimation of the total stress is made after the modelling of GIA (see Section 2). Therefore, it is not possible to obtain fault slip values with these types of models without modifications.

The rebound stress obtained from these models is combined with the horizontal and vertical background stresses, which are taken into account in the computation of fault stability. Assuming a thrusting tectonic background stress regime, the area below an ice sheet tends to be stable during glaciation and deglaciation, but becomes unstable immediately after the end of deglaciation (Wu and Hasegawa, 1996a). Conversely, faults in a normal or strike-slip regime are stable after deglaciation, but may be unstable during glaciation (Wu and Hasegawa, 1996a). A comparison of the present day stress orientation in northeastern Canada inferred from focal mechanism data with predictions from this class of GIA models exhibits large differences indicating that these GIA models do not adequately capture stress changes due to local fault zones (see Steffen et al., 2012).

The second type of GIA induced faulting models was developed by Hetzel and Hampel (2005), Hampel and Hetzel (2006) and Hampel et al. (2009). These models include a real fault, but only consist of a lithospheric layer that has horizontal plate velocities prescribed at the lateral boundaries. However, the Earth's response to glaciation and deglaciation depends not only on the lithosphere but also on the underlying mantle. Therefore, the inclusion of a deeper mantle in the models is necessary to obtain correct displacement and stress values for the GIA process. Thus, although a fault is already included in these models, fault movement is partially driven by the horizontal plate velocities and rebound stress is not completely taken into account. The results by Hampel et al. (2009) show stable conditions along the fault during glaciation for a thrusting regime. During and after the end of deglaciation the fault starts to move.

In general, both type of models yield similar results. However, the former models do not include an explicit fault, while the latter models do not include the influence of the deeper mantle or rebound stress. Therefore, both models provide only an approximate representation of fault movement in formerly glaciated areas.

In this study, we will present a new two-dimensional (2D) model based on the ABAQUS FEM (Hibbitt et al., 2011), which combines the aforementioned model types by using a defined fault in a general GIA model. The purpose of this paper is to present a new approach, which allows the estimation of fault slip and activation time under realistic rebound conditions. As this is a preliminary investigation, it is not our goal to match modelled results to observed data; consequently detailed earth and ice models are not considered. Rather, our aim is to extend and adapt existing GIA models for fault slip estimation.

The theoretical background of fault stability and the application of FEM for GIA purposes is discussed in the following two sections. In the fourth section, the model setup is summarized. This is followed by results for a simple example that includes a fault.

2. Stress analysis

In order to evaluate the stability of a fault in a GIA model we need to model the spatio-temporal evolution of the stress. The state of stress in a region is described by the magnitude of vertical and horizontal stresses, and in an area affected by GIA, this consists of the overburden pressure, tectonic background stress, and a rebound component to be determined by the model.

2.1. Fault stability

In a stable crust, where no faults exist, rebound stresses are not large enough to fracture rocks and generate earthquakes (e.g. Quinlan, 1984). However, the crust is not always in a stable state, because it is interspersed with fractures and faults that constitute zones of weaknesses (e.g. Twiss and Moores, 2007). The stress conditions in weak but stable zones in a rock mass can be represented by using a Mohr diagram (Fig. 1).

The line of failure (black and red lines in Fig. 1) gives information about the stability and frictional behaviour of a fault or rock mass, and relates the shear stress τ to the normal stress σ_n. The difference in shear stress between line of failure and Mohr circle is used to estimate the stability of the crust or a fault, which is known as the Coulomb Failure Stress (*CFS*) (Harris, 1998). The *CFS* at a specific normal stress σ_n is defined as

$$\begin{aligned} CFS &= \tau - \tau', \\ &= \tau - (\mu(\sigma_n - P_f) + C), \\ &= \frac{\sigma_1 - \sigma_3}{2} \left| \sin 2\Theta \right| - \mu\left(\frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\Theta\right) + \mu P_f - C, \\ &= \frac{\sigma_1 - \sigma_3}{2} (\left| \sin 2\Theta \right| - \mu \cos 2\Theta) - \mu \frac{\sigma_1 + \sigma_3}{2} + \mu P_f - C. \end{aligned} \quad (1)$$

In Eq. (1), negative *CFS* values indicate stable conditions and a change to positive values refers to a change from stability to instability along the fault, creating a state where earthquakes may occur.