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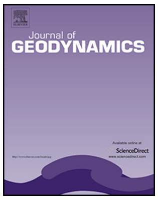

Technical note

The influence of viscosity structure in the lithosphere on predictions from models of glacial isostatic adjustment

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ABSTRACT

The thickness of the lithosphere inferred in most glacial isostatic adjustment (GIA) modelling studies tends to be significantly thinner than when found through seismic or thermal modelling studies. In those GIA studies, the lithosphere tends to be modelled as a plate of uniform and very high viscosity. We develop and test Earth models that include depth-dependent viscosity in the lithosphere to consider the implications for inferring lithospheric thickness from observed relative sea-level (RSL) changes. We find that when comparing predictions of RSL between the traditional plate lithosphere models and those with viscous structure, the latter produce RSL predictions that most closely resemble those from traditional models that are 10 s of km thinner. The greatest sensitivity to this change in the Earth model is most evident in regions loaded by relatively small ice sheets such as the British Isles. We also find that the effective elastic thickness of the lithosphere models with viscous structure is time-dependent, with thinning by tens of kilometres over a timescale of ∼10 kyr.

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1. Introduction

The lithosphere's response to stresses associated with various processes on a range of time scales helps shape the form of the Earth around us. The rheological structure of the lithosphere is not well determined in many regions but is essential to understand dynamical processes such as seismic and post-seismic deformation, flexure and isostatic adjustment due to surface loads (such as ice sheets and volcanos), sedimentary basin formation, and inter and intra plate deformation (e.g., Watts et al., 2013; Turcotte and Schubert, 2002). The particular property of the lithosphere that we are concerned with in this study is its thickness.

The thickness of the lithosphere has been estimated through a number of methods, including inversions of gravity and seismic observations (Audet and Mareschal, 2004) and through thermal (Tesauro et al., 2009) and geodynamic modelling – which includes glacial isostatic adjustment (GIA) modelling (Lambeck et al., 1998). The values obtained through these different methods vary widely for a given region as the thicknesses inferred relate to different properties. For example, a recent study inferred lithospheric thicknesses in Europe through seismic constraints on mantle temperatures (Tesauro et al., 2009) and by choosing the 1200 °C isotherm as defining the lithosphere-asthenosphere boundary. In the British Isles region, their inferred depth to this isotherm ranged from less than 100 km off the northwest coast of Scotland to almost 200 km in the North Sea, with an average value around 150 km. In contrast, GIA studies have inferred lithosphere thickness values of 60–90 km (Lambeck et al., 1996; Peltier et al., 2002; Bradley et al., 2009; Kuchar et al., 2012). As another example, a thermal study of the Canadian Shield (Levy et al., 2010) used surface heat flux measurements to infer the thickness of the lithosphere, and they found it varied from 200 km to 300 km. In contrast, GIA studies of the region typically adopt Earth models with lithosphere components around 120 km thick (e.g., Davis and Mitrovica, 1996; Sella et al., 2007). Finally, the effective elastic thickness (EET) of the Canadian Shield lithosphere was estimated to be 30 km to 130 km from Bouguer gravity anomaly data (Audet and Mareschal, 2004). A more detailed summary of lithosphere definitions and thickness estimates is given by Martinec and Wolf (2005), in the context of the Fennoscandian lithosphere.

The differences noted above are a reflection of the fact that the lithosphere thicknesses inferred relate to different properties or timescales. For example, the consistently low thicknesses estimated via GIA modelling are related to how the lithosphere tends to be defined in these models, which is as a region of very high and constant viscosity (often of order 10^{30} Pa s or higher), such that the lithosphere acts essentially as an elastic layer over typical GIA timescales (1–10 kyr). In this way, the inferences made via GIA

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studies are more compatible with the EET estimates from gravity data. We note, however, that the latter tends to result in even lower thickness estimates due to the longer timescales involved when considering this approach (and consequently more time for extensive stress relaxation through ductile failure; e.g., Ranalli, 1995).

The primary goal of this study is to consider how GIA model output is affected when the lithosphere is defined with viscous structure in order to gauge how inferences of lithospheric thickness, based on the typical elastic layer approach, might be affected. More specifically, we consider whether incorporating viscous structure in the lithosphere can result in estimates of this parameter that are more in line with those made using other methods, such as the thermal modelling approach outlined above. For convenience, we refer to the high viscosity lithospheres typical in GIA studies as “elastic lithospheres,” with the understanding that they are generally not modelled as being elastic, but rather as having Maxwell rheologies with very high viscosities. In this study we let the strength profile of the lithosphere be determined by temperature and composition, as described by the Dorn equation (see next section).

Previous GIA modelling studies have included lithosphere components with more structure by investigating the influence of a low viscosity region within an otherwise high viscosity lithosphere (DiDonato et al., 2000; Kendall et al., 2003; Klemann and Wolf, 1999), which resulted in a thinning of the lithosphere's EET to approximately the thickness of the lithosphere above the low viscosity zone. This differs from our own approach, which does not limit the ductile behaviour in the lithosphere to a small zone within it. Our approach is more closely aligned with that of Klemann and Wolf (1998) who estimated continuous changes in viscosity with depth associated with temperature-activated creep processes. Some recent studies have considered sub-crustal viscosity structure in the lithosphere within the context of non-linear, power-law deformation (van der Wal et al., 2013).

Additionally, it is known that the EET of the lithosphere depends on factors like the size and age of the load inducing the deformations (Watts et al., 2013), and so by incorporating more realistic viscous structure into the lithosphere we are effectively making the strength of the lithosphere time and load-size dependent. This may be an important consideration in GIA studies, where the time scales can range from thousands to tens of thousands of years and the load size from (typically) hundreds to thousands of kilometres.

2. Methodology

2.1. GIA model

In general, a GIA model has three key components: an ice history, provided in this study by ICE5G (Peltier, 2004; version 1.2); an Earth model to calculate solid Earth deformation and perturbation to the geopotential in response to the ice-ocean loading; and a sea level model that solves the sea level equation to determine how sea level changes in response to the ice loading and Earth deformation. We discuss the Earth model component in detail below. The sea level model we apply solves the generalised sea level equation (Kendall et al., 2005; Mitrovica and Milne, 2003), and therefore includes a treatment of time varying shorelines and sea level change in regions of ablating marine based ice. The influence of GIA-induced perturbations to the Earth's rotation vector on sea level is also included (Milne and Mitrovica, 1998; Mitrovica et al., 2005).

Table 1
Parameters adopted in defining the lithosphere viscosity profiles shown in Fig. 1.

Parameter	Upper crust	Lower crust
$\dot{\varepsilon}$ (s^{-1})	10^{-15}	10^{-15}
A_D ($Pa^{-n}\,s^{-1}$)	6.03×10^{-24}	8.83×10^{-22}
n	2.72	4.2
E_D (J mol^{-1})	134×10^3	445×10^3

All the Earth models in this study are spherically symmetric Maxwell bodies with an elastic and density structure given by PREM (Dziewonski and Anderson, 1981). The sub-lithosphere viscous structure is defined in two regions: the upper mantle (base of lithosphere to 660 km seismic discontinuity) and the lower mantle (660 km to the core-mantle boundary); we adopt values for these respective regions of 5×10^{20} Pa s and 10^{22} Pa s. As described above, the lithosphere is commonly defined as a shell of uniform and very high viscosity – several orders of magnitude higher than that of the upper mantle. We improve upon these simplistic lithosphere models by considering variations in lithosphere strength due to changes in composition and temperature. Specifically, we assume a quartzite composition to the Mohorovicic discontinuity (“Moho”) at 24.4 km depth, and a mafic granulite composition for the mantle component, with parameters given in Tesauro et al., 2009; see Table 1. We adopt a power law flow model for the lithosphere as defined by the Dorn equation,

$$\dot{\varepsilon} = A_D \sigma^n e^{-E_D/RT} \qquad (1)$$

where $\dot{\varepsilon}$ is the strain rate and is set to $10^{-15}\,s^{-1}$, E_D is the activation enthalpy, R is the gas constant, T is temperature, and A_D and n are experimentally determined parameters that depend on the type of rock, pressure and other environmental parameters that we will neglect in this preliminary analysis. Eq. (1) can be inverted to produce an expression for stress, σ (Table 1).

It is important to note an inconsistency in our approach: the Earth component of the GIA model we are applying assumes a Maxwell rheology, which has a linear stress–strain relationship, but we are defining the viscosity-depth structure in the lithosphere derived from a non-linear relationship (Eq. (1)). In a non-linear rheology the viscosity is stress dependent, with regions of higher stress being characterised by lower (effective) viscosities. In a Maxwell model, the viscosity values are constant and stress independent. We obtain the initial viscosity profile assuming a non-linear stress–strain relationship, but it is treated in our model linearly. We chose to follow this approach for two reasons: (1) there is growing evidence that non-linear (as opposed to linear) deformation is dominant in the lithosphere (e.g., Bürgmann and Dresen, 2008) and so application of Eq. (1), as opposed to a linear relation ($n = 1$), leads to a more accurate estimate of the viscosity structure; (2) while the application of a non-linear Earth model within our GIA model would be consistent with the application of Eq. (1), this adds a second advance compared to most previous GIA modelling studies and so interpretation of the results would be less straightforward. Our aim in this study is not to investigate the effects of non-linear versus linear rheology on postglacial rebound (e.g., Wu and Wang, 2008), rather, we adopt the Dorn equation to compute a viscosity profile for the lithosphere that should more closely resemble reality than does the traditional elastic layer model adopted in most previous GIA studies.

The lithosphere viscosity profile is modelled as two ductile zones separated by a discontinuity at the Moho. The Dorn Eq. (1) requires a temperature profile, for which we assume radiogenic heat production within the lithosphere. The analytic expression for temperature that we adopt within the lithosphere is (e.g., Turcotte and Schubert, 2002),

$$T(Z) = \frac{A_0 h^2}{K}\left(1 - e^{-Z/h}\right) + \left(T_0' - \frac{A_0 h}{K}\right) Z + T_0, \qquad (2)$$

where A_0 is the radiogenic heat production rate at the surface, h is a scaling parameter set to 11 km, K is the conductivity, set to a constant 3 W/mK, T_0' is the surface temperature gradient, and T_0

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