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Evidence for postglacial signatures in gravity gradients: A clue in lower mantle viscosity

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ABSTRACT

The Earth's surface was depressed under the weight of ice during the last glaciations. Glacial Isostatic Adjustment (GIA) induces the slow recession of the trough that is left after deglaciation and is responsible for a contemporary uplift rate of more than 1 cm/yr around Hudson Bay. The present-day residual depression, an indicator of still-ongoing GIA, is difficult to identify in the observed topography, which is predominantly sensitive to crustal heterogeneities. According to the most widespread GIA models, which feature a viscosity of $2–3 \times 10^{21}$ Pa s on top of the lower mantle, the trough is approximately 100 m deep and cannot explain the observed gravity anomalies across North America. These large anomalies are therefore usually attributed to subcontinental density heterogeneities in the tectosphere or to slab downwelling in the deep mantle.

Here, we use observed gravity gradients (GG) to show that the uncompensated GIA trough is four times larger than expected and that it is the main source of the North American static gravity signal. We search for the contribution to these GGs from mantle mass anomalies, which are deduced from seismic tomography and are mechanically coupled to the global mantle flow. This contribution is found to be small over Laurentia, and at least 82% of the GGs are caused by GIA. Such a contribution from GIA in these GG observations implies a viscosity that is greater than 10^{22} Pa s in the lower mantle.

Our conclusions are a plea for GIA models with a highly viscous lower mantle, which confirm inferences from mantle dynamic models. Any change in GIA modelling has important paleoclimatological and environmental implications, encouraging scientists to re-evaluate the past ice history at a global scale. These implications, in turn, affect the contribution of bedrock uplift to the contemporaneous mass balance over Antarctica and Greenland and thus the present-day ice-melting rate as deduced from the GRACE space mission. Additionally, studies of the thermo-chemical structure of the lithosphere/crust under North America that exploit gravity or geodetic data should be corrected for a GIA model, which is not the case today.

1. Introduction

A few thousand years ago, the Laurentide ice sheet was covering most of Canada, inducing a large deflection of the ground over Laurentia (Peltier, 2004; Peltier et al., 2015; Argus and Peltier, 2010; Lambeck et al., 2014). Since then, Earth has been undergoing a Glacial Isostatic Adjustment (GIA) in response to ice mass retreats, particularly across North America. The Hudson Bay region, for instance, shows conspicuous vertical ground motions up to ∼15 mm/yr because of GIA viscoelastic deformations (e.g., Sella et al., 2007; Altamimi et al., 2011; Métivier et al., 2012). In addition, temporal gravity variations are evidenced by ground and space gravity measurements (e.g., Tamisiea et al., 2007; Sasgen et al., 2012).

Static geoid and Free-Air Gravity (FAG) anomalies that are observed over the Hudson Bay region, although remarkably correlated with the expected past location of the Laurentide ice sheet, are usually not assumed to be related to GIA. Most GIA models, including the most widely used ICE-5G/VM2 (Peltier, 2004), predict almost no static gravity anomaly. Thus, crustal structure

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analyses with gravity measurements over North America are currently not corrected for any GIA signals (e.g., Kaban et al., 2014). Since the 1980s, North American FAG anomalies are usually attributed to either sublithospheric cratonic roots (Peltier et al., 1992; Pari and Peltier, 2000) or deeper mantellic density anomalies (Forte et al., 2010). Seismic tomography models detect anomalously high seismic velocities below the North American crust down to 250 km depth (e.g., Ritsema et al., 2011; French and Romanowicz, 2014), which are interpreted as signs of a cratonic "tectosphere" – the shallow upper mantle below old continents (Jordan, 1978; Forte et al., 1995) – and a high velocity anomaly at larger depth, which is possibly caused by remnants of the subducted Farallon slab. Such velocity anomalies may be associated with density anomalies and therefore create gravity anomalies (e.g., Richards and Hager, 1984). However, the link between seismic velocities and density variations, which depends on the local temperature and chemistry, is poorly understood, particularly in the tectosphere (e.g., Forte et al., 1995; Pari and Peltier, 2000; Forte et al., 2010). Doin et al. (1996) studied geoid anomalies around the world and concluded that no anomaly was associated with cratons except over Laurentia. This suggests that the Laurentian gravity anomaly could result, at least partially, of incomplete GIA as proposed by Simons and Hager (1997). Distinguishing between GIA and lithosphere signatures in the Fennoscandian static gravity field seems difficult (Root et al., 2015).

Because of the periods of analyses, the majority of GIA studies on static gravity fields investigated very-low-resolution gravity signals and did not use modern data from space gravity missions. Here, we investigate the Gravity Gradients (GG) of the Earth, i.e., the 3×3 gradiometric tensor $\boldsymbol{T}$, which is composed of all the space derivatives of the gravity vector components. This symmetric tensor had been measured from space in 2009–2013 by the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite on a ∼250-km mean altitude orbit (Johanessen et al., 2003). Because of the filtering effect of space derivatives, these GGs are particularly sensitive to the shorter wavelengths of the Earth's density distribution. However, a study of the GOCE's GGs at the satellite altitude has evidenced long wavelength anomalies, which are mostly caused by the mantle dynamics (Panet et al., 2014; Greff-Lefftz et al., 2016). In addition, long wavelength anomalies can be seen over the Hudson Bay region, correlating with the past location of the Laurentide ice sheet. Here, we investigate these long wavelength GG anomalies. We show that GG anomalies are undoubtedly caused by GIA processes while the geoid or FAG anomalies over North America can be explained by either lithosphere/mantle dynamics or GIA.

In section 2, we present the data and viscosity profiles that were investigated in this study. In section 3, we construct and investigate a large set of lithosphere, mantle dynamics and GIA models, and we explore their possible contributions to GG anomalies. In section 4, we combine all the models together and present our final solution. We also show results from a Bayesian inversion of the mantle viscosity from the GIA contribution to GGs. Finally, section 5 is devoted to discussion and conclusions.

2. Data

2.1. Gravity gradient observations

Not all GOCE gradiometric components are measured with the same precision. In particular, the non-diagonal components of the tensor are known to be far less precise than the diagonal components (Rummel et al., 2011). Here, we want to investigate the full set of gradiometric tensor components, so our GG observations have been inferred from space derivatives of EGM2008's (Pavlis et al., 2008) spherical harmonic coefficients up to a degree of 180 and propagated at 250-km altitude instead of using direct GOCE observations. We use the approach of Métris et al. (1999) to calculate the second-order derivatives of the gravitational potential. Comparisons with GOCE observations on the diagonal components confirm that the obtained signals are identical at the wavelengths of our study. Even if we do not explicitly use GOCE data, we chose anyway to propagate our GG observations at the GOCE's mean altitude. We use this approach because GG observations are highly dominated by short wavelengths at the surface, making these data difficult to exploit for GIA investigations. The 250-km altitude happens to be a good compromise in terms of wavelength and signal magnitude. Indeed, upward propagation naturally filters the shorter wavelengths, but the signal still contains abundant information at GIA wavelengths at this altitude.

2.2. Viscosity profiles

One of the main difficulties in GIA and mantle dynamics modelling is that the viscosity profile in the Earth's mantle is still subject to debates (e.g., Steffen and Wu, 2011). Recently, Lambeck et al. (2014) used a large database of sea-level records and showed that two types of viscosity profiles could be considered acceptable for GIA calculations. The first profile exhibits a "low" viscosity in the lower mantle, while the other shows a "high" viscosity, facilitating a possible reconciliation between GIA and mantle dynamics studies. Given these results, we investigate different types of viscosity profiles (see Fig. 1). Some of these profiles come from GIA studies (or geodynamical investigations that include GIA observations) (Simons and Hager, 1997; Mitrovica and Forte, 2004; Peltier, 2004; Argus and Peltier, 2010; Lambeck et al., 2014), while others come from mantle dynamics studies with no GIA information (Ricard et al., 1993; Cadek and Fleitout, 2003; Steinberger and Calderwood, 2006; Yoshida and Nakakuki, 2009). The general difference between these two types of profiles is the jump in viscosity between the upper and lower mantle. Indeed, the most widely used "GIA-type" profiles show a small viscosity jump, while "mantle-dynamic-type" profiles feature a jump that is larger than 30. The MF profile actually exhibits a large jump because of its low viscosity zone at the bottom of the upper mantle, but this zone is very small and the jump remains very small if we consider the mean upper mantle viscosity. Table 1 shows the jump between the mean upper mantle viscosity and the mean viscosity in the first 600 km of the lower mantle. Among GIA-type profiles, the AN and SH profiles are notable exceptions, which exhibit characteristics that are closer to mantle-dynamic-type profiles, although their lower mantle viscosities are slightly smaller. The SH profile was proposed by Simons and Hager (1997), who first showed that geoid static anomalies may contain a GIA signature. However, this work was challenged (e.g., Pari and Peltier, 2000) and was not followed by new developments. On the other hand, Lambeck et al. (2014) proposed the "high" viscosity profile AN. This profile is associated with the ANU ice history model, which is still under construction. We investigate all these viscosity profiles, but the results in the following sections are illustrated with three viscosity profiles for the sake of brevity: V2, which is symptomatic of GIA studies; RA, which is a classical profile for global mantle dynamics; and MF, which is a classical profile that was inferred from a combination of GIA and geodynamical data.

3. Exploring each potential contribution to GGs across North America

We investigate a large panel of possible contributions to North America's GG anomalies. Among those contributions, we distinguish among four types of models: the GIA, the isostatically compensated lithosphere, subcontinental keels (in the tectosphere),