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Postglacial isostatic adjustment in a self-gravitating spherical earth with power-law rheology

Patrick Wu[a,*], Hansheng Wang[b]

[a] Department of Geology & Geophysics, University of Calgary, Earth Science Building, Room 276, Alberta, Canada T2N 1N4
[b] Institute of Geodesy and Geophysics, Chinese Academy of Sciences, Wuhan 430077, China

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ABSTRACT

Since microphysics cannot say definitively whether the rheology of the mantle is linear or non-linear, the aim of this paper is to constrain mantle rheology from observations related to the glacial isostatic adjustment (GIA) process—namely relative sea-levels (RSLs), land uplift rate from GPS and gravity-rate-of-change from GRACE. We consider three earth model types that can have power-law rheology ($n = 3$ or 4) in the upper mantle, the lower mantle or throughout the mantle. For each model type, a range of A parameter in the creep law will be explored and the predicted GIA responses will be compared to the observations to see which value of A has the potential to explain all the data simultaneously. The coupled Laplace finite-element (CLFE) method is used to calculate the response of a 3D spherical self-gravitating viscoelastic Earth to forcing by the ICE-4G ice history model with ocean loads in self-gravitating oceans. Results show that ice thickness in Laurentide needs to increase significantly or delayed by 2 ka, otherwise the predicted uplift rate, gravity rate-of-change and the amplitude of the RSL for sites inside the ice margin of Laurentide are too low to be able to explain the observations. However, the ice thickness elsewhere outside Laurentide needs to be slightly modified in order to explain the global RSL data outside Laurentide. If the ice model is modified in this way, then the results of this paper indicate that models with power-law rheology in the lower mantle (with $A \sim 10^{-35}$ Pa^{-3} s^{-1} for $n = 3$) have the highest potential to simultaneously explain all the observed RSL, uplift rate and gravity rate-of-change data than the other model types.

1. Introduction

Since the dynamics of Earth is strongly influenced by the rheology of the mantle (e.g., Yuen and Schubert, 1976), an important question is whether the flow law in the mantle is linear (Newtonian) or non-linear (power-law)? In general, if the stress level is low or the grain size small, deformation occurs mainly through diffusion creep and the flow law is linear. In contrast, at high stress level or large grain size, deformation proceeds mainly by dislocation creep and the flow law is non-linear but insensitive to grain size. This is because both linear diffusion creep and non-linear dislocation creep operate in the mantle, and the mechanism that gives the higher strain rate for the given temperature and pressure, becomes the dominant creep mechanism. High-temperature and high-pressure creep experiments on relevant rock material suggest that power-law rheology prevails in the shallow part of the upper mantle (e.g., Goetze and Kohlstedt, 1973; Ranalli, 1991; Karato and Wu, 1993) but linear diffusion creep dominates in the transition zone (Karato and Wu, 1993; Wang and Ji, 2000; Karato et al., 2001). However, Mainprice et al. (2005) argued that the transition zone may also be non-linear. The situation in the lower mantle is also controversial. Creep experiments from perovskite analogues (Karato and Li, 1992; Li et al., 1996) suggest that the lower mantle is linear, while creep experiments on (Mg,Fe)O, which probably has a lower creep strength than perovskite, is non-linear (Yamazaki and Karato, 2002). Recently Cordier et al. (2004) produced experimental evidence that silicate perovskite under lower-mantle conditions also deforms by dislocation creep. However, due to the large extrapolation in experimental conditions and the large uncertainty of the transition conditions between linear and non-linear creep mechanisms (e.g., Ranalli, 1995, 2001), the dominant mechanisms may be overridden by local conditions. The situation is further complicated by the role of water (e.g., Mei and Kohlstedt, 2000; Dixon et al., 2004) and post-perovskite in the lower mantle (Merkel et al., 2006; Carrez et al., 2007). Thus, microphysics cannot say definitively whether the rheology in the mantle is linear or non-linear.

Another approach is to infer mantle rheology from geophysical observations. Recently Van Hunen et al. (2005) found evidence for dislocation creep from geodynamic modeling of the Pacific upper mantle. Freed et al. (2006) also inferred power-law flow

* Corresponding author. Tel.: +1 403 220 7855; fax: +1 403 284 0074.
E-mail address: ppwu@ucalgary.ca (P. Wu).

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in the uppermost mantle using observations of postseismic displacements. Here we constrain mantle rheology from observations related to the isostatic adjustment of Earth in response to the glaciation and deglaciation of the ice sheets in the last Ice Age—namely relative sea-levels (RSLs), land uplift rate (e.g., from GPS) and gravity-rate-of-change from GRACE.

The effect of power-law with stress exponent n (see Eq. (1)) is well known. First of all, the effective viscosity is inversely proportional to the magnitude of the Mises stress (hereafter called 'stress level') raised to the $n-1$ power (see Eq. (3)). Thus for $n>1$, the larger the stress level, the lower the effective viscosity. For the glacial isostatic adjustment (GIA) process, the stress level varies both in space and time, thus the effective viscosity is heterogeneous both in the lateral and radial directions while the value of effective viscosity changes also in time. Since ambient tectonic stress can also contribute to the stress level, the effective viscosity of the mantle and its evolution in time may also depend on the amplitude of the ambient tectonic stress.

An important question is: can the observations of GIA tell whether the rheology of the mantle is linear or non-linear? Schmeling (1987) showed that, for a non-linear mantle, if the ambient tectonic stress level is higher than that induced by GIA, then mantle convection sees the rheology of the mantle as non-linear, while the GIA process sees a linear but anisotropic creep law! The latter implies that observations of GIA cannot tell if the rheology of the mantle is non-linear. This is verified by Gasperini et al. (1992) who modeled the land uplift at the center of rebound after the loading and removal of a parabolic ice cap on a flat-earth. However, in their formulation of the creep law, Gasperini et al. (1992) treated both tectonic stress and rebound stress as scalars and represent their interaction by the scalar sum of the two quantities. Taking into account the tensoral nature of the stresses in a 3D flat-earth model and realistic ICE-3G deglaciation history, Wu (2001) found that a non-linear uniform mantle can behave like a linear mantle and is able to fit the RSL data in and around Laurentide only if the ambient stress level is about 10 MPa and A is about $10^{-35}\ \mathrm{Pa}^{-3}\ \mathrm{s}^{-1}$. But if the ambient stress level and A parameter are much different from these values, then power-law rheology has a special signature for RSL sites just outside the ice margin, e.g., Boston (see discussion of the VSZ below)—so that one can tell from the RSL prediction whether mantle rheology is linear or non-linear (Wu, 1995).

Another important question is whether there is any interaction between the ambient tectonic stress and the stress induced by GIA. While the above works emphasize the importance of the ambient tectonic stress in the modeling of GIA in a power-law mantle, Karato (1998) argued that because the strain due to GIA is orders of magnitudes smaller than that due to tectonics and the time scales involved are vastly different, the distance that dislocations move during postglacial rebound does not significantly exceed the average distance of dislocations. Therefore dislocation density is unlikely to change appreciably during rebound. This implies that there is little interaction between ambient tectonic stress and GIA-induced stress. Earlier GIA modeling studies (see review in Wu, 1998) either assume that there is no interaction with ambient tectonic stress or equivalently that there is interaction, but the tectonic stress level is low. This paper will also take this approach and the case with stress interaction will be studied in a separate paper.

Whether there is interaction between rebound stress and tectonic stress, there is the problem of the "viscously stationary zone (VSZ)". Early studies, with flat-earths and simple ice models where the ice margin does not migrate inwards as the ice sheet collapses, found that power law rheologies have difficulties explaining the RSL observations for sites in the RSL-transition zone. The observational RSL data at the RSL-transition zone just outside the ice margin (e.g., Boston) are characterized by early land emergence from the sea followed by submergence during the last 6–8 ka (see data in Fig. 11) and this is traditionally explained by the inward migration and collapse of the peripheral bulge. However, power-law rheology does not support a migrating bulge, instead, it induces a VSZ just outside the ice margin which is characterized by little or no vertical motion after the end of deglaciation (Wu, 1998). Between the center of rebound and the VSZ, land emerges continuously, and outside the zone, land submerges continuously after the end of deglaciation, and the VSZ acts as a hinge line. This characteristic is due to the stress-induced low viscosity channel underneath the load and this laterally varying channel terminates just outside the ice margin (Wu, 1993). With the more realistic ICE3G model that includes the migration of the ice margin as the ice retreats, a VSZ also develops after 10 ka BP when the ice margin finished retreating and the bulge stops migrating (Wu, 1999). So, for sites near or within the VSZ, the predicted amplitude of land emergence or submergence is small during the last 6 ka, and is thus unable to explain the observed RSL data. One purpose of this paper is to investigate whether this problem still persists for a spherical, self-gravitating earth with consistent sea-levels.

Which part of the mantle is dominated by non-linear rheology? As the temperature, grain size and other creep parameters change throughout the mantle, it is reasonable to assume that the dominant creep mechanism varies as a function of depth. Based on experimentally determined creep data, RSL data and seismic anisotropy of the Earth, Karato and Wu (1993) proposed that the shallow part of the upper mantle (above 300 km depth) is likely to be non-linear and below that linear rheology dominates. Using a more realistic GIA model and more RSL data in and around Laurentide (the Hudson Bay area in North America), Wu (1999, 2002a) found that a model with a linear upper mantle and a non-linear lower mantle below 670 km depth is also consistent with the observed RSL data. In the above studies, the mantle is artificially divided into two different layers and they are assigned to be either linear or non-linear. However, there is no strong reason why that is so. Due to the state of stress, it is entirely possible that the transition between linear and non-linear rheology result in multi-layers and the transition can also occur laterally. This has led Gasperini et al. (1992, 2004), Giunchi and Spada (2000) and Dal Forno et al. (2005) to develop and study "composite rheology", which includes simultaneously the contribution from linear (diffusion) and non-linear (dislocation) creep to the total strain rate. But as pointed out earlier, the tensorial nature of the stresses are neglected in their formulation. Recently, we have developed a new formulation of composite rheology, that takes into account the tensorial nature of stresses (van der Wal et al., submitted). Preliminary results show that, depending on the value of the A parameter used, composite rheology can be approximated by either a linear or non-linear rheology. Thus in this paper, we will continue to divide the mantle artificially into an upper and lower mantle.

So far, most of the GIA models mentioned above are flat non-self-gravitating earth models and only the RSL data in Laurentide are used to constrain mantle rheology. Giunchi and Spada (2000) have used an axisymmetric spherical earth to study GIA with composite rheology and found that with non-Newtonian upper mantle, the time variations of the Earth's oblateness become insensitive to the viscosity of the lower mantle. However, their model neglects self-gravity in the solid earth, which is important for degree 2 harmonic deformations. Wu (2002b) included self-gravity in his spherical finite-element model and found that non-linear lower mantle rheology is compatible with the observed rate of change in Earth's oblateness (J_2-dot). However, the model of Wu (2002b) did not include a realistic ice model and self-gravity in the ocean is also neglected. Recently, Wu (2004) developed the coupled Laplace finite-element (CLFE) method, which can handle 3D spherical self-