# CONSTRAINING RHEOLOGY OF THE ASTHENOSPHERE BASED ON POSTSEISMIC GPS AND GEOID OBSERVATIONS

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## Summary

Postseismic deformation after the Sumatra-Andaman earthquake of 2004 recorded by GPS at the Andaman Islands shows a behavior which cannot be interpreted by means of viscoelastic relaxation of a Maxwell-type asthenosphere and has thus been interpreted as being dominated by aseismic afterslip. Using biviscous Burgers rheology and an adequate coseismic slip model though, it is possible to reproduce timing and amplitudes of the observations without the need of significant afterslip. The inferred thickness of the purely elastic upper layer is 40 km, which coincides with the maximum depth of slip in the coseismic model. Below, the Maxwellian viscosity contributing to the long-term behavior has a typical value of 1e19 Pa·s, whereas the Kelvin-Voigt viscosity responsible for the transient response is ten times smaller. The rheological model obtained by analysis of this near field GPS data is used to compute the postseismic signature of the geoid change and compares well to observations by the GRACE satellites. The alternative model using Maxwell rheology and time dependent afterslip is not compatible with GRACE observations.

## Introduction

The relation between deformation and forces in the Earth is described by rheology, which therefore comprises a fundament of geodynamics. Recent geodynamic studies employ a number of methods to constrain rock rheology (see review by Bürgmann and Dresen, 2008) including monitoring of deformation using high precision GPS measurements. However, interpretation of postseismic GPS time series in terms of rheology often remains ambiguous. As was shown by Paul et al. (2007), the temporal characteristics of postseismic GPS data from the Andaman Islands cannot be interpreted by means of viscoelastic relaxation if assuming Maxwell rheology. Thus they concluded that the largest contribution to the observations stems from exponentially time dependent afterslip at the subduction interface down dip of the coseismic slip. Another interpretation was given by Pollitz et al. (2006, 2008), who analyzed postseismic GPS data from far-field stations in Singapore and Thailand and proposed to apply biviscous Burgers rheology for the asthenosphere. In this study we consider both afterslip and Burgers rheology models for the Sumatra earthquake of 2004 and discuss the possibility to distinguish between these models using geoid data.

## Methods and Data

We use postseismic GPS time series from the Andaman Islands published by Paul et al. (2007) and an improved coseismic slip model of the Mw=9.3 Sumatra-Andaman earthquake of 2004 by Hoechner et al. (2008, 2010). Modeling of the postseismic GPS response is performed for a layered viscoelastic half space using code PSGRN/PSCMP by Wang et al. (2006) applying various rheologies. Maxwell rheology can be represented by a spring in series with a dashpot, while Burgers rheology comprises an additional Kelvin-Voigt element (spring in parallel with a dashpot) in series with the Maxwell element. The Burgers body is the simplest rheological model accounting for elastic, transient and steady state deformation (Ranalli, 1995, p. 222). As was shown by Pollitz et al. (2006), Burgers rheology is better suited than Maxwell rheology for explaining postseismic time series of GPS stations several hundred kilometers away from the rupture. We perform a similar analysis for near field data. We vary the thickness of the purely elastic lithosphere, apply several Maxwell and Burgers rheologies for the asthenosphere, and use standard Maxwell rheology below the asthenosphere. Alternatively, we use a standard Maxwell rheology for the whole mantle and invert an exponentially time dependent afterslip model which is also in accordance with observed GPS time series (see Hoechner et al., 2010 for more details).

## Results

Using a typical Maxwell rheology with a viscosity of 1e19 Pa·s for the asthenosphere leads to modeled displacements being much too small. Using a viscosity of 2e18 Pa·s brings the amplitudes of the model 1.5 years after the earthquake to the right value, but the modeled relaxation time is much too large, and the model clearly overshoots the data. Applying Burgers rheology with a viscosity of 1e19 Pa·s for the Maxwell and 1e18 Pa·s for the Kelvin element removes the inconsistency, as is shown exemplarily for the vertical component at station CARI in figure 1 (magenta line).

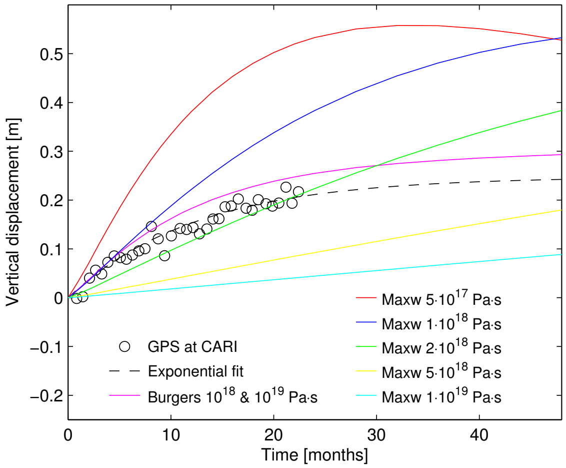

Figure 1: GPS time series of postseismic uplift at station CARI (down sampled for better visibility) and prediction of various rheological models for the asthenosphere.

The alternative explanation for the postseismic time series employing time-dependent postseismic slip (afterslip), mostly down-dip of the coseismic slip, removes the need for a transient rheology. We investigate this explanation using Maxwell rheology also for the asthenosphere with a typical viscosity of 1e19 Pa·s and thus being responsible only for the long term behavior, and invert for afterslip to obtain the postseismic signal after 18 months. Following Paul et al. (2007), we consider postseismic slip with an exponential decay shape function using a relaxation time of 12.5 months corresponding to the analysis of the GPS data. The amount of thus estimated postseismic slip is about 10% of coseismic slip. Conformance of the time series, shown in figure 2, has roughly the same quality as that from the Burgers asthenosphere model. Thus, based on this GPS data alone, a discrimination of the main contributor to postseismic displacement is not possible.

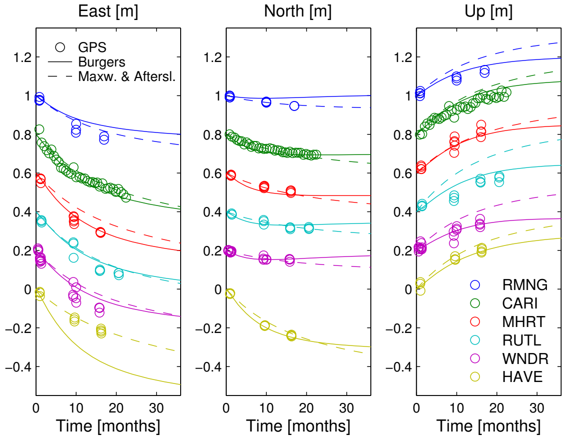

Figure2: Postseismic GPS time series at the Andaman Islands for Burgers asthenosphere (solid lines) as well as Maxwell rheology together with time dependent afterslip (dashed lines).

Since both the Burgers- as well as the Maxwell model with afterslip are in agreement with postseismic GPS displacements, we need an additional independent observation to distinguish between the two explanations. Therefore we calculate postseismic geoid change for the two and compare to observations by the GRACE satellites (Han et al., 2006; Einarsson et al., 2010). Computation of the geoid is done with PSGRN/PSCMP (Wang et al., 2006) and an additional tool (POTCON by R. Wang), to extrapolate the geopotential changes from the solid Earth surface (i.e. the ocean bottom) to the geoid and then filter them with a Gaussian of 250 km smoothing radius. In case of the afterslip, we have to extrapolate the model obtained for the Andaman Islands to the region of the Sumatra 2004 and Nias 2005 earthquakes assuming afterslip amounting to 10% of the coseismic slip down-dip of the fault. It is clear that the Maxwell model (including afterslip) yields too small magnitudes of geoid change, as can bee seen in figure 3. We thus confirm the finding of Han et al. (2008), that a biviscous Burgers rheology for the asthenosphere is more adequate for modeling the postseismic geoid response to the Sumatra earthquake.

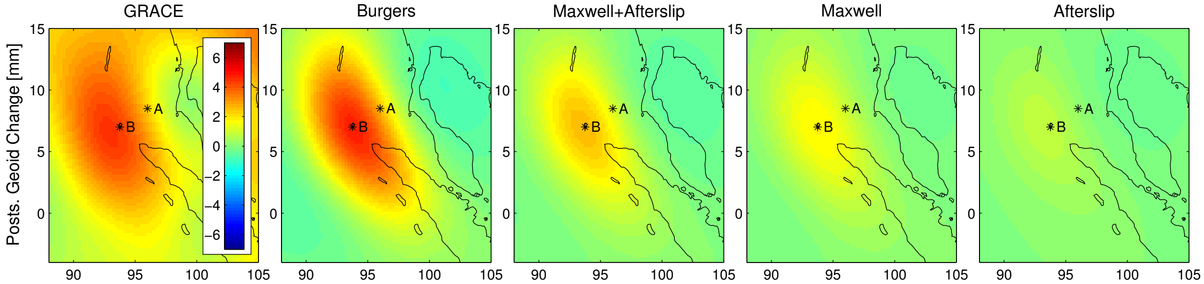

Figure 3: Postseismic geoid change after 4 years as observed by the GRACE satellites, as well as modeled by Burgers rheology asthenosphere, Maxwellian and afterslip models. Smoothing with a Gaussian of 250 km radius is applied to the models.

We conclude that satellite observations of geoid change after large earthquakes appear to be very useful to discriminate between rheological models. In the case of the Sumatra-Andaman earthquake of 2004, geoid data clearly favor a transient type of rheology in the upper mantle and do not confirm substantial aseismic afterslip.

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