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Density and visco-elasticity of Natrosol 250 HH solutions: Determining their suitability for experimental tectonics

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ABSTRACT

Analogue models often require that materials with specific physical properties be engineered to satisfy scaling conditions. To achieve this goal we investigate the rheology of aqueous solutions of Natrosol 250 HH, a rheology modifier employed in various industries to thicken viscous solutions. We report the rheological properties as functions of the concentration and temperature and discuss the advantages and limitations of these materials in view of their use in analogue modelling experiments. The solutions are linear visco-elastic for low stresses (or strain-rates), becoming shear-thinning for larger stresses. For the typically slow analogue experiments of tectonics, the solutions can be considered linear visco-elastic with a Maxwell relaxation time much smaller than the characteristic observation time. This simplification is even more appropriate when the solutions are employed at temperatures higher than 20 °C, since the solutions then display a behaviour that is more viscous, less elastic at the same shear-rate, while the Newtonian viscosity reduces and the shear-rate limit between Newtonian and shear-thinning behaviours increases. The Newtonian viscosity is shown to increase non-linearly with concentration and decrease non-linearly with temperature. With concentrations between 0 and 3% and temperature between 20 and 40 °C, the viscosity varied between 10^{-1} and 4000 Pa s, while the density remained close to the density of water. Natrosol 250 HH thus offers the possibility to control the viscosity of a solution without significantly affecting the density, thereby facilitating the design and setup of analogue experiments.

1. Introduction

The concept of similar systems rests on the idea that multiple systems may share the same underpinning physics and therefore one can draw inferences from observations in any of the similar systems. The concept can be traced back to famous seventeenth century physicists Galileo and Newton and has since been frequently employed to investigate a variety of phenomena (Sterrett, 2009, and reference therein).

In Earth sciences, the concept of similar systems and the use of scaled models, have been employed for over a century to investigate geological processes (Koyi, 1997; Ranalli, 2001; Graveleau et al., 2012, and reference therein). Scaled models are used to test hypotheses on the driving mechanisms of tectonic processes derived from and constrained by a variety of geological and geophysical data. The scaled model passes through an evolution which simulates that of the original, but on a much more convenient scale (Buckingham, 1914; Hubbert, 1937; Ramberg, 1967). The process can thus be precisely monitored in time and space, thereby allowing its dynamics to be investigated.

The selection of appropriate analogue materials is a central consideration in the design of realistic physical models, and a number of studies have focused on quantifying the physical properties of various possible analogue materials (e.g. McClay, 1976; Dixon and Summers, 1986; Weijermars and Schmeling, 1986; Weijermars, 1986; Rossetti et al., 1999; Schellart, 2000, 2011; Di Giuseppe et al., 2009, 2012, 2015; Schöpfer and Zulauf, 2002; ten Grotenhuis et al., 2002; Lohrmann et al., 2003; Zulauf and Zulauf, 2004; Boutelier et al., 2008; Kavanagh et al., 2013; Duarte et al., 2014; Rudolf et al., 2015). This can be because the physical properties of the candidate analogue materials have not been precisely measured yet, or because the published physical characteristics are

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insufficient to carefully evaluate their suitability in analogue modelling experiments.

Here we investigate the rheological properties of aqueous solutions of Natrosol 250 HH, a cellulose polymer regularly employed in various industries as a rheology modifier (Aqualon, 1999; Ashland, 2011). Our aim is to produce a series of viscous fluids with specific physical characteristics (i.e. a range of different viscosities, but similar densities) to be used in analogue experiments. We detail the scaling of our thermo-mechanical experiments to illustrate the scaling constrains that led us to investigating the use of Natrosol solutions. To be usefull to a broad range of experimental setups, we detail the physical properties for a range of concentrations of Natrosol, temperatures, stresses or strain-rates and discuss the advantages and limitations of using Natrosol solution in analogue modelling experiments.

2. Constrains from previous modelling

The choice of an analogue material generally conditions the scaling of several model parameters while the remaining free parameters must be adjusted to satisfy the scaling laws. For example in previous thermo-mechanical laboratory experiments of plate tectonics performed by the authors (e.g. Boutelier et al., 2012, 2014), water was used to model the low-viscosity asthenosphere, which set the scale for densities (Fig. 1a). Then the length scale was chosen such that the models would be conveniently small to set-up in the laboratory. The scaling factors for pressure, stresses and forces were derived from the scaling of densities and lengths using dimensional relationships (Buckingham, 1914; Hubbert, 1937; Ramberg, 1967).

$$\frac{\sigma}{\rho g H} = Const \tag{1}$$

where σ is the stress (Fig. 1), ρ is the density, g is the gravitational acceleration and H is the length scale. The dimensionless ratio can be expressed in terms of parameters in the model (i.e., subscript m) and nature (i.e., n),

$$\frac{\sigma_m}{\rho_m g_m H_m} = \frac{\sigma_n}{\rho_n g_n H_n} \tag{2}$$

or using the scaling factors (superscript *, $\sigma^* = \sigma_n/\sigma_m$):

$$\sigma^* = \rho^* g^* H^* \tag{3}$$

In the previous thermo-mechanical laboratory experiments of plate tectonics performed by the authors (Boutelier et al., 2012, 2014), the layers of the lithosphere were modelled using various alloys of solid hydrocarbons (paraffin wax), mineral oils and fine powder, displaying macroscopic ductile elasto-plastic with strain softening rheological behavior, and therefore capable of forming narrow shear zones throughout the model lithosphere (Fig. 1b). Therefore the stress in Eq. (1) was the plastic yield stress. This parameter is strongly temperature-dependant and therefore imposing a temperature gradient through the model lithosphere results in a rheological stratification (Fig. 1c). The choice of the temperatures imposed at the surface and base of the model lithosphere controls this stratification, which can be scaled using the same scaling factor for stress (Boutelier and Oncken, 2011). The elasticity in the model lithosphere is also scaled using the same scaling relationship. The elastic stress in the model is proportional to strain via the Young elastic modulus or the elastic shear modulus. Therefore, the elastic modulus is scaled with stress, and is proportional to the hydrostatic pressure in the model plate (Boutelier and Oncken, 2011). We note that while here we derived a scaling of the rheological properties from the scaling of length and forces, it is also commun to scale the length and rheological properties to ensure proper scaling of forces (e.g. Davy and Cobbold, 1991).

This modelling scheme allowed scaling of isostatic response as well as the three-dimensional dynamical interactions of the solid lithospheric plates, since body and surface forces in the lithosphere were scaled homogeneously. However, the flow in the mantle and its action on the plates were not implemented, which can lead to situations where the dynamics in the model is controlled by unscaled parameters and therefore becomes unrealistic (Boutelier and Cruden, 2013). To include the dynamical interaction with the mantle, it is necessary to increase the viscosity of the fluid representing the upper mantle, without changing significantly the scaling of densities. This is because any significant change in scaling

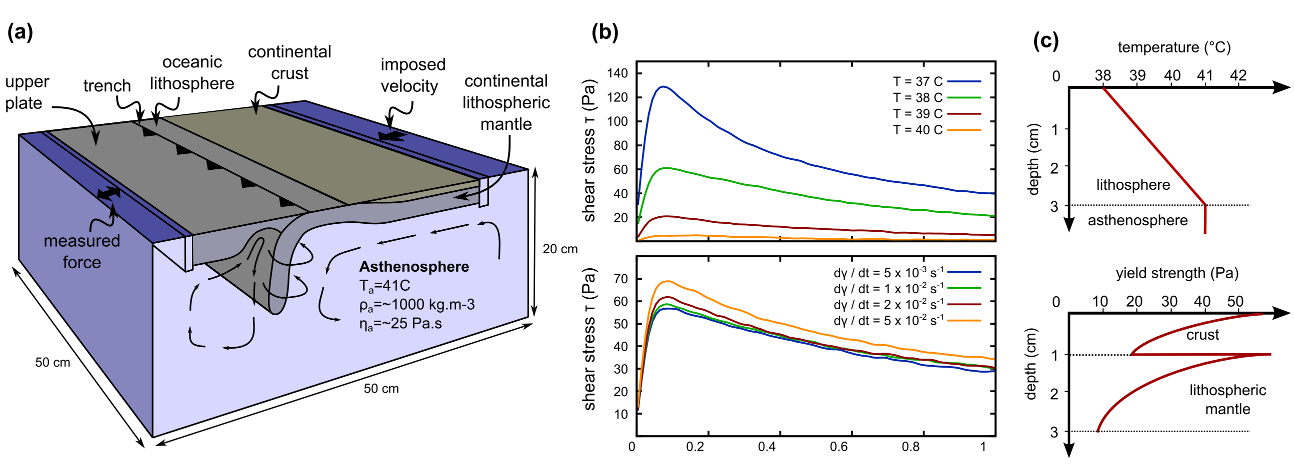

Fig. 1. Illustration of a modelling setup for which a fluid with specific physical properties (viscosity and density) must be engineered because of existing scaling relationships. **(a)**, schematic drawing of the experimental apparatus with the solid lithospheric plates made of hydrocarbons resting on viscous asthenosphere. The similarity criteria obtained from the scaling of the physical properties of the lithosphere constrain the scaling of the mantle viscosity. **(b)**, the materials employed for the lithosphere are ductile elasto-plastic with strain softening (Boutelier and Oncken, 2011). The rate of deformation does not change the yield stress significantly, whereas a small temperature change strongly affects both the yield stress and the amount of softening after failure. **(c)**, a vertical conductive gradient is imposed in the lithosphere prior to deformation to generate a rheological stratification. The scaling of rate and time, allows scaling of relative heating and therefore relative strength reduction during deformation.