

Toasting the Jelly Sandwich: Rheological Effects of Shear Heating on the Earth's Lithosphere

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ABSTRACT

The rheological behaviour of the lithosphere, the outermost layer of the Earth, is still debated. While its elastic and brittle properties are well determined, the viscous properties exhibit a broad spread resulting in varying positions of the brittle-ductile transition and different relative strengths of the upper crust, lower crust, and lithospheric mantle. In our model, we incorporate shear heating and demonstrate that it is a self-regulating mechanism and a main control of the lithospheric strength and temperature. Independent tectonic driving force estimates match those of our shear heating models.

INTRODUCTION

The rheology of the rocks in the Earth is rather complex as large variations in composition, stress, temperature, and spatial and temporal scales must be considered. Here we focus on the lithosphere, the outermost, overall solid-like layer of the Earth that overlies the hot and convecting fluid-like asthenosphere. The lithosphere consists of individual pieces whose relative movement shape the surface of the Earth as described with the plate tectonic concept. For continents, the lithosphere can be further subdivided into an upper 30-50 km (with extreme cases, 20-80 km) thick crust and the compositionally different lower part, the lithospheric mantle, whose bottom interface corresponds to the 1300 °C isotherm (approx.

120 km depth, with variations of 70-200 km). These thickness values are averages and will be different for deformed lithosphere parts. The interface that separates the crust and mantle is referred to as Moho, short for Mohorovičić, a seismic discontinuity. The crust is usually again subdivided into compositionally different upper and lower parts.

The rocks of the upper crust on which we stand and build buildings and infrastructure behave as elastic solids, the properties of which are well known. If the maximum sustainable stress is exceeded, these rocks will yield by pressure sensitive shear failure that can be described by Mohr-Coulomb plasticity (tension and mixed failure modes are not relevant for this compressional study). This yield strength envelope is surprisingly insensitive to the rock type and is referred to as Byerlee's law in Earth science¹.

As we go deeper into the crust, the temperature rises and viscous creep mechanisms are activated. Direct measurement of this behaviour is impossible due to the depth of the brittle ductile transition (>10 km) and the rates of deformation ($<1 \times 10^{-12} \text{ s}^{-1}$, excluding earthquakes). Furthermore, it is complicated by linear (diffusion, Coble or Nabarro-Herring creep²) and non-linear (dislocation, power-law at high temperature/low stresses and Peierles or Dorn at low temperature/high stresses²) creep behaviour

that is affected by grain size, microstructure, composition details (rocks are always poly-phase mixtures), water content, and the strong temperature sensitivity (for extensive review see ^{3,4}). The only alternative to indirect rheology testing such as seismic and postglacial rebound studies are laboratory experiments. However, the latter are simplified and run at deformation rates that are at least six orders of magnitude faster than nature and extrapolation is therefore unreliable. Consequently, and contrasting the elastic and brittle properties, the viscous rock rheology is poorly constrained. Nevertheless, it is clear that there is a transition from one type of behaviour to the other. Depending on the rheological details and the temperature state of the lithosphere this brittle ductile transition may be repeated for all the major layers of the lithosphere, i.e. upper crust, lower crust, and lithospheric mantle.

If we plot, for an applied strain rate, the stress in the lithosphere with a simplified 1D model we obtain the Brace-Goetze strength envelope ⁵, see Fig 1a. In our models, the top of the upper crust and the top of the lithospheric mantle are stiff and strong, while the rocks in between creep viscously. Geoscientists refer to this as the “jelly sandwich” due to the correspondence of the toast (strong), jelly (weak), toast succession.

This classic model of lithospheric rheology ignores the feedback of deformation to the energy budget through shear heating. Here we elaborate on the model presented by Hartz and Podladchikov⁶ who showed that the shear heat caused by deformation is of first order importance for the temperature distribution in the lithosphere (geotherm), potentially overprinting the influence of parameters typically incorporated in thermal models such as heat flux from the interior,

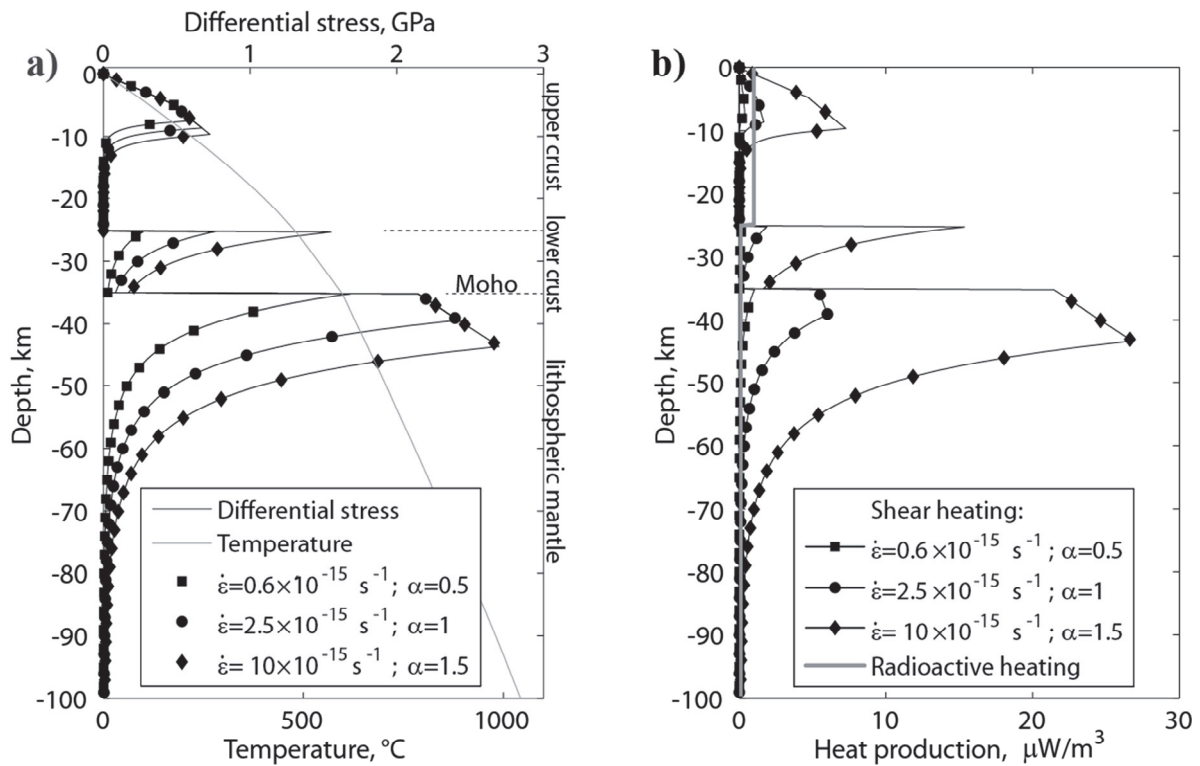


Figure 1. (a) Initial differential stress (Brace-Goetze strength envelope) and temperature profiles for chosen cases. The stress profiles differ by varying strain-rate, $\dot{\epsilon}$, and the rheological parameter, α . (b) Shear heating rates for three chosen cases. The radioactive heat production rate is presented for comparison.

radiogenic heating, conductive rock properties, and the surface conditions. That in turn may significantly reduce lithosphere strength by approximately one order of magnitude and therefore be more important than varying rheological parameters within their uncertainty.

SHEAR HEATING: A NATURAL CONSEQUENCE OF DEFORMATION

Shear heating as such is widely acknowledged in the geological community based on numerous observations of frictional melts near brittle faults⁷ or near grand-scale ductile shear zone⁸, and incorporated in two- and three-dimensional numerical models of a complexly deforming lithosphere⁹⁻¹³

One-dimensional models naturally lack the refinement and detail of the models mentioned above. However, due to their simplicity 1D-models allow for identifying and isolating key factors of deformation. For example, Hartz and Podladchikov⁶ showed that the Brace-Goetze envelope directly yields the amount of shear heating by multiplying it by the strain rate used to calculate the strength. Thus, without adding new assumptions it can be demonstrated that shear heating caused by lithospheric deformation yields 10 to 25 $\mu\text{W}/\text{m}^3$. This is one order of magnitude larger than radioactive heating in the Earth (Fig. 1b), which is usually considered the main source of heat in the continental lithosphere.

SHEAR HEATING IN COMPRESSION

In the following series of experiments we follow the model set-up of Hartz and Podladchikov⁶ and analyse the evolution of stresses needed to deform the lithosphere and the resulting evolution of the geotherm. We study the influence of different strain rates and viscous strengths on models with (WSH) and no shear heating (NSH).

We vary the rate of thickening, $\dot{\epsilon}$, from 3×10^{-16} to $1 \times 10^{-14} \text{ s}^{-1}$ resulting in a 100% thickening within 2 to 35 My, thereby in-

cluding all realistic rates of continental collision and thickening. We mimic variations of the viscous creep rheology of the lithosphere by introducing α . This parameter simply acts as multiplier of the viscosity, making the lithosphere stronger for $\alpha > 1$, and weaker for $\alpha < 1$. $\alpha = 1$ corresponds to rheology as derived by laboratory testing (see⁶ for complete list of rheological parameters). α does not affect the brittle part of the model lithosphere, but significantly changes the differential stresses in the ductile parts of the lithosphere, resulting in 2-3 fold variations in the integrated lithospheric strength (for α between 0.5 and 1.5, Fig. 1a). The strength multiplier α does not reflect any particular experimentally derived rheology, but reflects the large number of, often contrasting, experimental datasets and rheological laws.

NUMERICAL MODELLING RESULTS

Through the twofold thickening, the initial lithospheric strength profile (Fig 1a) develops into Fig 2a (NSH) and 2b (WSH). Relative to the initial situation the NSH models increase in strength whereas the opposite is true for WSH, resulting in substantial strength differences at the end of the deformation. The reason for this is the temperature rise caused by the shear heating (see perturbed geotherms Fig 2b). For example, two intermediate NSH and WSH models with $\alpha = 1$ and $\dot{\epsilon} = 2.5 \times 10^{-15}$ show temperature differences of up to 80 °C. The inferred strength decrease due to this rise in temperature is fivefold.

Another interesting effect is that for NSH models the variations in strain rate and α yield massively different strength profiles (Fig. 2a). These differences are greatly reduced through the introduction of shear heating (Fig 2b). The reason for this is that shear heating in the context of lithospheric deformation is a self-regulating process where the high stress models also thermally weaken the most. One can compare the

stress evolution for two end-member WSH models. Starting from more than 2GPa difference (Fig. 1a) the stress difference reduces to less than 0.5GPa at the end of the thickening (Fig. 2b).

A key parameter for lithospheric deformation is the integrated strength, which provides an estimate of the required driving forces. Estimation of the integrated stresses in the final stage of the models (Fig. 2 b and c) shows that NSH and WSH differ significantly. NSH models require integrated stresses of around 10^{14} N·m, which is one order of magnitude larger than the WSH model. Only the forces in models with shear heating are compatible with independent estimations of available driving forces of plate tectonic deformation, e.g. ¹⁴.

Even though the results of this section utilise specific initial, boundary and rheological conditions, the conclusions are gen-

eral. We have tested the whole range of Earth-like conditions and the conclusions prevail.

CONCLUSIONS

Shear heating is of first order importance for the temperature and strength of the deforming lithosphere. Shear heating may reduce differential stress by one order of magnitude due to the high temperature sensitivity of viscous creep. Hence, the effect of shear heating is of equal or larger importance than the variation of other parameters, e.g. rheological laws, variations in experimental data, and water fugacity, within their uncertainty limits. Temperature rise due to shear heating reduces the strength of the lithosphere and thus the rate of heat production. Hence, this is a self-regulating mechanism maintaining a moderate integrated lithospheric strength, essentially irre-

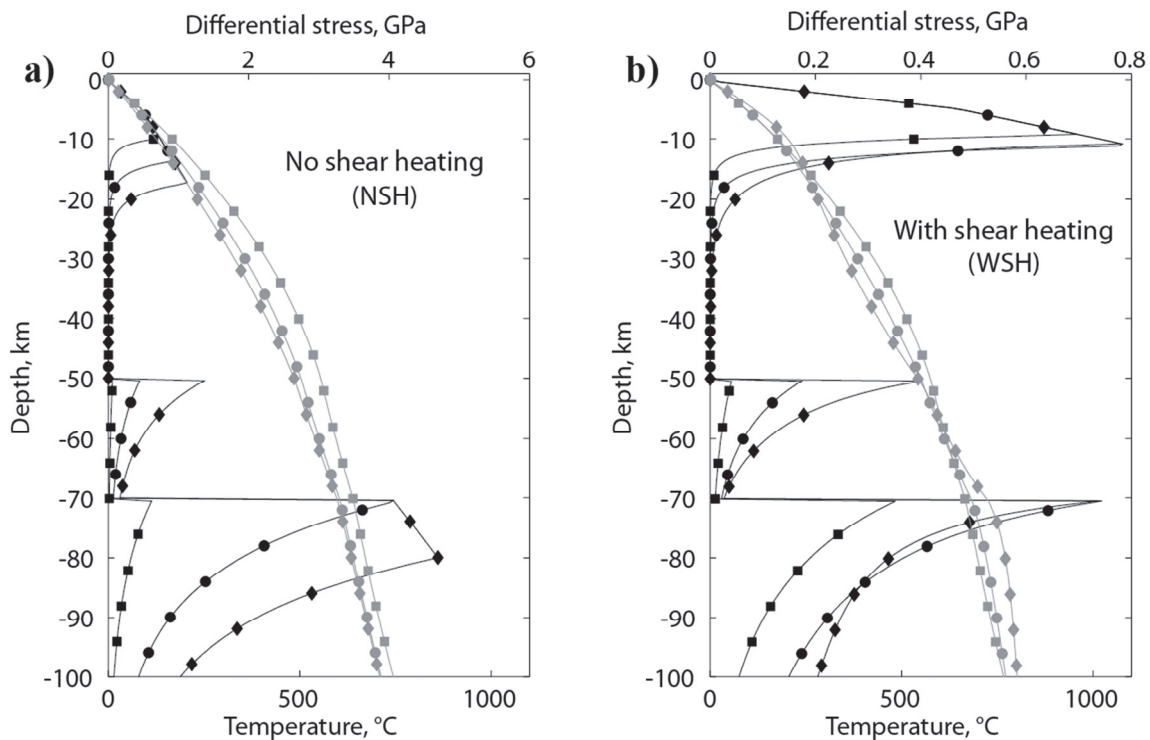


Figure 2. Differential stress (black lines) and temperature (grey lines) profiles after 100% thickening for models with no shear heating (NSH, a); and for models with shear heating (WSH, b). See parameters and marker coding on Fig. 1. Note different scales for stress between panels.

spective of applied strain rate and viscous strength laws and compatible with independent estimations of forces driving plate tectonics.

ACKNOWLEDGMENTS

Research is funded by the “TectoNorthSea”-project grant from Det norske oljeselskap to Sergei Medvedev and Daniel W. Schmid. The Norwegian Science Council provided basic funding through a “Centre of Excellence” grant to Physics of Geological Processes, and Statoil and Det norske viteskapsakademi is thanked for a Vista grant to Alban Souche. Yuri Podladchikov and Arild Saasen are thanked for persistent discussions.

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