Available online at www.sciencedirect.com

ScienceDirect

Journal of Geodynamics 42 (2006) 12–27

JOURNAL OF GEODYNAMICS

http://www.elsevier.com/locate/jog

Implications of a visco-elastic model of the lithosphere for calculating yield strength envelopes

Andrey V. Ershov[a,*], Randell A. Stephenson[b]

[a] *Geological Faculty, Moscow State University, 119899 Moscow, Russia*
[b] *Faculty of Earth and Life Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands*

Received 18 February 2006; received in revised form 3 April 2006; accepted 8 April 2006

Abstract

The dominant deformation mechanism in the ductile part of the lithosphere is creep. From a mechanical point of view, creep can be modelled as a viscous phenomenon. On the other hand, yield-strength envelopes (YSEs), commonly used to describe lithosphere rheology, are constructed supposing creep to be mechanically plastic (note that the meaning of the term "plastic" used in mechanics and material sciences are different). Such rheological models are simple but can lead to internal inconsistencies. However, evaluating the "strength" of the lithosphere using a viscous rheology requires incorporation of the time-dependence of stresses, strains, and strain rates and also the dependence of the bulk strain rate on the total applied force. The two approaches are compared by computing stress distributions in the lithosphere for given structure, mineralogy, geotherm, and applied forces using two methods in which creep is modelled as "plastic" and "viscous" respectively. The results demonstrate the importance of the bulk strain rate of the lithosphere in determining stress distribution. Further, the bulk strain rate is not independent of the total applied force although this is an underlying assumption of the YSE-based (plastic rheology) approach. For typical plate boundary forces and normal geotherms, appropriate bulk strain rates are low, about 10^{-17} s^{-1}, indicating that lithospheric "strength" computed from YSEs using a constant bulk strain rate in the range of 10^{-16} to 10^{-14} s^{-1} is overestimated by one-half to one order of magnitude. Stresses using the YSE (plastic) approach can be significantly over- or under-estimated due to an inappropriate choice of bulk strain rate for the tectonic setting and duration of loading of forces under consideration.

Keywords: Rheology; Yield-strength envelope; Lithosphere; Stress; Strain rate; Strength

1. Introduction

The concept of a lithospheric "yield-strength envelope" (YSE) is well known in many facets of geophysical sciences (cf. Ranalli, 1995, 1997). It has been widely used in models of lithosphere deformation, such as those of sedimentary basin formation or orogen development, in which lithospheric strength—or resistance to deformation under defined loading conditions—is paramount. Several examples include Stephenson et al. (1990), Burov and Diament (1995), Fernandez and Ranalli (1997), and Lankreijer et al. (1999). The YSE concept has also been central to most quantitative estimations of stress-state in the lithosphere, including the relationship of stress-state to observed seismicity (e.g.

---

[*] Corresponding author. Tel.: +7 95 939 3865; fax: +7 95 939 3865.
E-mail addresses: and@geol.msu.ru (A.V. Ershov), randell.stephenson@falw.vu.nl (R.A. Stephenson).

0264-3707/$ – see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jog.2006.04.002

Cloetingh and Banda, 1992; Liu and Zoback, 1997), and to estimates of the strength of the lithosphere (e.g. Ranalli, 2003; Burov, 2003; Cloetingh et al., 2006).

Goetze and Evans (1979) introduced the YSE as an estimate of the upper limit of lithospheric stress (greatest possible stress given sufficient force) as a function of depth. Goetze and Evans based their calculations on experimental laboratory studies of rock mechanics, in which three main types of rock deformation are typically observed: (1) elastic, (2) brittle failure, and (3) creep. Typical experimental results can be found in Carter and Kirby (1978). In terms of mechanical theory, these kinds of observed rheological behaviours can be classified, respectively, as follows:

(1) "Elasticity"—with "elastic" deformation, being instantaneous upon loading, perfectly recoverable upon removal of the loading stress, with strain that is a linear function of stress.
(2) "Plasticity"—with "plastic" deformation, occurring only when the loading stress overcomes a critical yield value (known as the "yield strength" or "yield stress" or "critical stress"), being instantaneous (i.e. is independent of time) upon reaching the critical stress and non-recoverable upon removal of the load. Plastic deformation that results in discontinuous strain (e.g. fracturing and faulting) can be characterised as "brittle" and plastic deformation that is spatially continuous as "ductile".
(3) "Viscosity"—with "viscous" deformation or "creep", also non-recoverable but accumulating during the time in which a finite loading stress is applied (being time-dependent, therefore), with the strain rate during this time being a function of the stress, there being no ("critical") stress limit below which the deformation does not occur.[1]

In the numerous modelling and other studies in which the YSE concept has been utilised, it is generally considered to represent the profile of maximum rock strength (yield strength) with depth, this being the lesser of either "brittle strength" or "creep strength" calculated at each depth for some model of the physical properties of the lithosphere (composition, temperature, pressure) at that depth. The computed "brittle strength" is based on a brittle failure criterion such as the Coulomb-Navier failure criterion or Byerlee's law (e.g. Ranalli, 1995) whereas the computed "creep strength" is based on one of a number of laboratory-derived creep laws such as "power-law" creep or "Dorn creep" (e.g. Ranalli, 1995). As such, "creep strength" is taken to be equivalent to "creep stress"—the stress required to maintain a given rate of steady-state viscous deformation (i.e. strain rate).

Deformation at any stress below the calculated maximum rock strength at any depth in a YSE model is considered to be elastic. Stresses reaching the maximum rock strength at depths where it is defined by a brittle yield criterion are assumed to lead to brittle deformation. Stresses reaching the maximum rock strength at depths where it is defined by a creep law are assumed to lead to steady-state viscous deformation at a pre-defined bulk strain rate. In either case, therefore, plastic deformation is considered to "begin" and the stress level cannot increase any further such that it exceeds the defined critical yield value. Thus, in a YSE model, creep is considered to be a "plastic" deformation process (in the "mechanical" sense of having a yield stress below which it does not occur), whereas the laboratory data—on which the actual YSE models are based—demonstrate it to be "viscous".

The assessment of the validity of such an approximation—using viscous rheological laws to approximate a yield stress at some given strain rate—is the main objective of the present paper. In so doing, it is necessary to derive the stress state of the lithosphere in two ways: one in which deformation in the ductile part of the lithosphere is treated as truly viscous in nature, with no yield stress, and one in which deformation in the ductile part of the lithosphere is treated, as in many conventional applications, as plastic. Models with the viscous representation of creep will be referred to as to V-type models and models with plastic creep as P-type models. Neither model is "new". The general principles of the V-type model are similar to those developed by Kusznir (1982) and De Rito et al. (1986) whereas, as already mentioned above, the P-type model is based on the YSE construction according to Goetze and Evans (1979), utilised subsequently in many different studies.

Despite the wide appeal of the concepts inherent in both approaches to modelling lithosphere rheology, little attention has been given to directly comparing them. One partial exception is the work of Porth (2000) who developed

---

[1] In terms of the theoretical rheological descriptions of rock deformation, therefore, brittle failure observed in the laboratory is a form of "plasticity". However, in material sciences terminology, the words "plasticity" and "plastic flow" are used to describe inelastic deformation without rupture, as opposed to brittle deformation (inelastic deformation with rupture). In these terms, creep is a kind of plastic rock flow, an obvious source of confusion in respect of the all-important presence or absence of a critical or yield strength (stress) for a given material. Here, the word "plastic" is used in its "mechanical" (presence of a yield stress) rather than "viscous" (no yield stress) sense.