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A thin elastic core can control large-scale patterns of lithosphere shortening

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ABSTRACT

Peak lithospheric strength should reside in the rocks that, under the applied stress, cannot either creep (due to low temperature) or break (due to high confining pressure). The greatest resistance comes from dry olivine/pyroxene-rich upper mantle/lowermost crust at Moho conditions (400–600 °C and >1 GPa). We have conducted laboratory experiments to investigate the importance of the unbreakable core of the lithosphere in between its brittle and ductile parts and conclude that it can control the large-scale lithospheric deformation pattern under shortening. Regardless of the thickness of the unbreakable core, it acts as a restraining layer that is easily flexed but is unstretchable. This eliminates large scale brittle faulting or homogeneous thickening as available shortening modes and results in irregular wrinkling of the unbreakable layer. We discuss geodynamic implications of our laboratory experiments and advocate studies of large scale buckling of the lithosphere as a relevant shortening mode.

1. Introduction

Deforming rocks exhibit complex rheological responses ranging from strong quasi-rigid-like- to weak quasi-fluid-like-effective behaviour as a function of temperature, stress, fluids and/or rock composition. Therefore, there is a need for a simplified rheological model that can serve as analogue of the complex heterogeneous lithosphere, while capturing its effective large-scale rheological behaviour. A widely used conceptual model of the lithosphere is the yield strength envelope (YSE — Fig. 1), introduced by Goetze and Evans (1979) and based on laboratory rock experimental data (see also Brace and Kohlstedt, 1980; Kirby, 1980). This model incorporates both brittle rock strength, increasing with pressure (depth), and viscous rock strength, which is a function of rock properties, strain rate, and temperature, and generally decreases with depth (Fig. 1). Rocks are assumed to fail by the weaker of the two criteria, resulting in a branched strength envelope. For a standard parameter set, the YSE includes effectively elastic cores between brittle and ductile layers. Effectively elastic layers should exist if the stress level is smaller than the brittle yield and viscosity is too high to allow creep and relaxation of differential stresses (e.g. Kirby, 1983). The argument is that olivine and pyroxene (or respective aggregates) are very strong, so that at Moho temperature (400–600 °C depending on thermal gradient) they cannot creep or break for differential stresses lower than 1 GPa, even when the strain rate is corrected to geologically acceptable values, in the order of 10^{-15} s^{-1} (e.g. Griggs et al., 1960; Avé Lallemant, 1978; Goetze, 1978; Evans and Goetze, 1979; Kirby and Kronenberg, 1984; Karato, 1997; Dorner and Stöckhert, 2004; Li et al., 2004; Boettcher et al., 2007; Renshaw and Schulson, 2007; Korenaga and Karato, 2008). The validity of great extrapolation from laboratory length and time scales have been frequently questioned, and rock strength at geological time scales has been suggested to be significantly weaker (Rutter and Brodie, 1991). However, all quantified weakening mechanisms, such as grain size reduction, are inefficient at low temperatures and small strains, the conditions prevalent in stable lithosphere (e.g. Chopra and Paterson, 1981, 1984; Karato, 1984; Tsenn and Carter, 1987; Karato and Wu, 1993). Moreover, the direct evidence for long-term integrated strength of the stable lithosphere, which does not significantly relax differential stress on geological time scale, has been inferred by persistence of density anomalies causing large-scale gravity anomalies in old terrains (e.g. Artemjev and Artyushkov, 1971; Burov et al., 1998), or by rheology independent topographic force balance at active mountain belts (e.g. Jeffreys, 1959), or by absence of expected viscoelastic topography adjustments in various tectonic settings, such as foreland basins or depressions of the oceanic lithosphere loaded by volcanic islands (e.g. Watts and Talwani, 1974; Watts and Cochran, 1974; Watts and Burov, 2003;Watts and Zhong, 2000).

Since elastic strain is assumed to be negligible compared to typical mountain building strains, then the presence of an effectively elastic core seems to be inconsistent with large-scale lithospheric deformation. This can only be initiated after the elastic layer has vanished and yield conditions over the whole of the strength versus depth profile to be attained, a concept named whole lithosphere failure (WLF) by Kusznir and Park (1982). They considered a number of geodynamic scenarios

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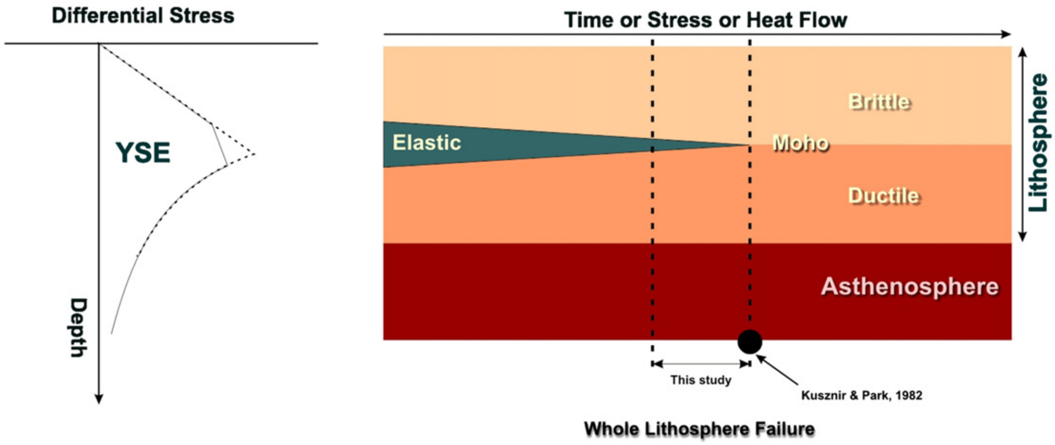

Fig. 1. Sketch with the YSE for compression of oceanic lithosphere prior to (solid line) and after WLF (dashed line).

possibly responsible for the vanishing of the quasi-elastic core of the lithosphere and identified major controlling parameters like duration of loading, stress level and heat flow. The evolution of the intra-lithospheric elastic core can be visualized as wedging out to a vanishing point, the WLF (Fig. 1). It was not the aim of this study to investigate mechanisms that can lead to WLF, or lithospheric deformation under WLF.

There is another possibility for the onset of large-scale deformation while the elastic core is still present. The unbreakable layer can be wrinkled or folded away to allow for shortening of the horizontally compressed plates, a concept named structural softening of the lithosphere by Schmalholz et al. (2005). Strong layers within a shortening section of the rheologically stratified lithosphere can either

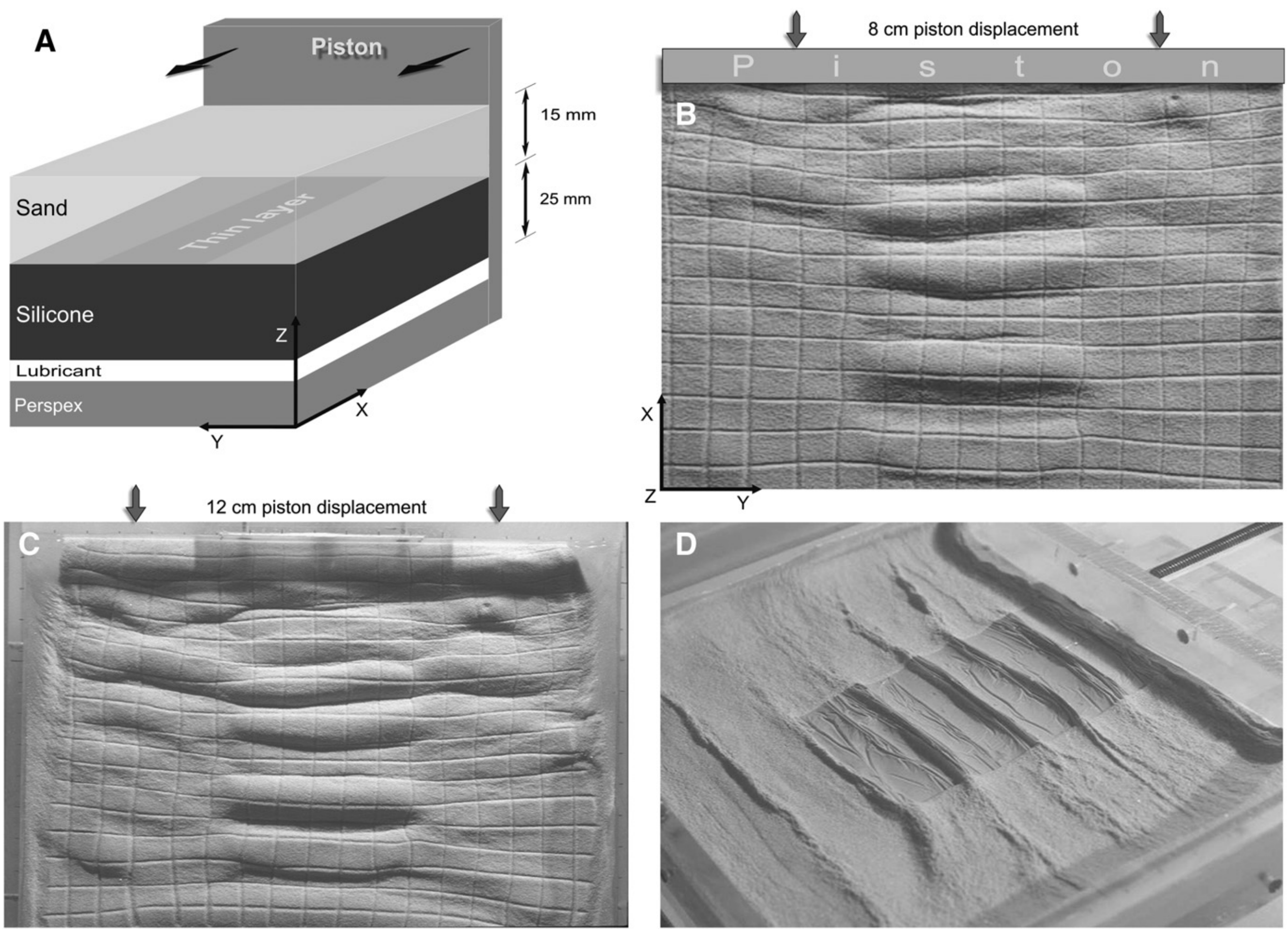

Fig. 2. A — sketch of typical geometry and layer distribution in the experimental models. B to D — Top views of two stages of deformation of Model 1 (LDP thin layer). Images show upper surface of models: B — intermediate stage; C — final stage; D — oblique view of PDMS top surface after sand removal. Comparison with *c* shows that fold frequency in the elastic layer is much greater than in sand, especially in the antiformal, acute hinges.