Tectonophysics 668-669 (2016) 82–91

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Post-buckling relaxation of an elastic layer and its geological relevance: Insights from analogue experiments in pure shear

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ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form 3 December 2015
Accepted 8 December 2015
Available online 22 December 2015

Keywords:
Buckling
Finite length elastic layer
Viscous matrix
Strain rate
Analogue modelling
Post-buckling relaxation and unfolding

ABSTRACT

By physical modelling we investigated the buckling and post-buckling behaviour of an elastic layer hosted in a viscous medium, as analogue of the elastic response of crustal rocks. The experiments were performed by embedding thin elastic layers of finite length in a linear viscous medium, and in two successive stages: a first stage of layer-parallel shortening in pure shear, followed by a second stage of post-buckling unfolding with zero velocity at the bounding walls. The experimental results show that the fold wavelength varies inversely with applied piston velocity, following an exponential function for which the higher the piston velocity the higher the number of waves. With cessation of layer-parallel shortening, the buckled layers underwent *post-buckling relaxation* in response to the elastic strain accumulated during the buckling stage. Such relaxation reduces the number of waves by successive elimination of the lower amplitude folds. The relaxation process gives rise to larger folds of higher amplitude in the centre of the elastic layer, concomitantly with the production of a train of gentle folds in the outer domains by outward motion of the ends of the elastic layer. This means that relaxation is more efficient away from the central domain. Comparison of our experimental results with available analytical solutions reveals significant discrepancies. Finally, we suggest that a similar process of relaxation of the elastic strain, although of lower amplitude, may explain the late stage open folding and the formation of overlying extensional basins observed in past orogens like the Caledonides in western Norway.

1. Introduction

Folds are one of the most pervasive and striking tectonic features in deformed terrains, under PT conditions that can range from syn-sedimentary to high-grade metamorphic. In particular, it is common to find sinuous folds in single mechanical layers of finite length, for instance quartz veins inside slates, or pegmatite veins inside granite, gneiss or micaschist. Tectonic maps and satellite images also reveal single layer folds but at crustal scale, with wavelengths of several tens of kilometres. Studies on the mechanics of tectonic folding of single layers date back to the early nineteen sixties and seventies (e.g. Biot, 1961; Biot et al., 1961; Chapple, 1968; Cobbold, 1975; Fletcher, 1974; Hudleston, 1973; Hudleston and Stephansson, 1973; Treagus, 1973). Ramberg (1963, 1964) have shown folding as a consequence of buckling instability under layer-parallel compression, where mechanical layering plays a crucial role in controlling the onset of fold instability. According to Biot–Ramberg's theoretical model, the fold wavelength depends entirely on viscosity ratio and layer thickness. This model, however, does not account for folding in complex rheological stratifications, e.g. an elastic crustal upper layer resting upon a viscous substrate.

The buckling of a single elastic layer embedded in a linear viscous matrix has been studied both theoretically (e.g. Biot, 1961; Ramberg and Stephansson, 1964; Johnson and Ellen, 1974; Johnson and Honea, 1975a; Hunt et al., 1996; Mancktelow, 1999; Schmalholz and Podladchikov, 1999; Huck et al., 2000; Sridhar et al., 2001; Sridhar et al., 2002; Jeng et al., 2002; Schmid et al., 2004; Jeng and Huang, 2008) and experimentally (e.g. Biot et al., 1961; Bowden et al., 1998; Huck et al., 2000; Ramberg and Stephansson, 1964). Biot (1961) analysed mathematically the buckling of an elastic layer in a linear viscous medium, and derived an equation (Eq. 3.18 in Biot, 1961) that predicts the fold wavelength:

$$L_d = \pi h\sqrt{\frac{E}{(1-\nu^2)P}} \quad (1)$$

where L_d is the dominant wavelength, h is the elastic layer thickness, E is the Young's modulus, ν is the Poisson's ratio, and P is the layer-parallel compressive stress. Given that the elastic stripe was laid with the tips far from the piston and opposing wall, the compressive stress was not directly applied by the piston on the elastic layer. Therefore, the compressive stress P (external applied stress in Biot's equation) in our experiments was transmitted to the elastic layer via the viscous host,

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http://dx.doi.org/10.1016/j.tecto.2015.12.004

not directly by the piston. Given that stress is linearly related to strain rate in Newton's equation of viscosity, we conclude that P in Biot's equation depends on piston velocity. Therefore, the higher the piston velocity the higher the P transmitted to the elastic layer, and the smaller the wavelength (higher number of waves) according to Biot's equation. Strain rate does not appear explicitly in the equation, but is implicit in P because the compressive stress equates to the strain rate in the viscous matrix. Biot et al. (1961) validated the analytical solution through physical experiments.

The earlier studies discussed above dealt with the evolution of buckle folds during layer-parallel compression. It is noteworthy that crustal rocks on geological time scales show Maxwell type viscoelastic rheology (Ranalli, 1995), and thereby accumulate a significant amount of internal elastic stresses that relax during the post-contraction phases (e.g. Friedman, 1972; Tavani et al., 2014), as evident from several structures, e.g. fractures in orogenic belts. The relaxation behaviour of natural fold structures in response to such stress relaxation in the post-buckling period has remained unexplored, and comprises the main objective of this study. Sridhar et al. (2001) mathematically analysed the kinetics of buckling of a compressed film on a viscous substrate, and Sridhar et al. (2002) further developed an analytical solution to include the post-buckling kinetics of compressed thin films on viscous substrates. They concluded that "Unfortunately, no experimental data are available that show the kinetics of the evolution of the film and hence it is not possible to make direct quantitative comparisons with post buckling theory." Their theoretical analysis needs experimental validation, which is one of the main objectives of the present study. The second objective is to show the relevance of the post-buckling relaxation phenomenon in interpreting large-scale tectonic structures in past orogens like the Variscides or the Caledonides.

In this study we used analogue modelling to first investigate the influence of strain rate on the wavelength and amplitude of folds in single finite length elastic layers in a linear viscous matrix. Most importantly, our elastic–viscous models provide new insights into the folding processes in rocks, showing how a folded layer can unfold itself during the phase of tectonic stress relaxation. We simulated this post-tectonic unfolding phenomenon by analogue modelling with thin elastic layers embedded in a viscous matrix subjected to buckling under layer-parallel shortening in a first stage, and then to stress relaxation in a second phase after cessation of shortening.

Marques and Podladchikov (2009) experimentally modelled the behaviour of a thin elastic layer sandwiched between an underlying viscous layer and an overlying brittle layer. They concluded that an elastic, unbreakable layer (elastic core, e.g. Burov and Diament, 1995) may act as a restraining layer that can be buckled but is unstretchable, thus eliminating large scale brittle faulting or homogeneous thickening as available shortening modes, and so resulting in the buckling of the elastic layer. In the present study we used a similar concept, but yielding on both embedding layers was by viscous flow. Therefore, the single elastic layer in our experiments does not represent a single rock layer in nature, it represents a rock unit, kilometres thick, with a common rheological behaviour: elastic and unbreakable under layer-parallel shortening.

Given that the elastic strain is commonly assumed to be negligible when compared to typical mountain building strains, then the presence of an effectively elastic core seems to be inconsistent with large-scale lithospheric deformation. Accordingly, lithospheric deformation can only be initiated after the elastic layer has vanished, and yield conditions over the whole of the strength versus depth profile has been attained, a concept named whole lithosphere failure (WLF) by Kusznir and Park (1982). They considered a number of geodynamic scenarios 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 (e.g. Kusznir and Karner, 1985). The evolution of the intra-lithospheric elastic core can be visualized as wedging out to a vanishing point, the WLF (Fig. 1 in Marques and Podladchikov, 2009). There is another possibility for the onset of large-scale deformation while the elastic core is still present, which is buckling of the unbreakable layer resulting in structural softening of the lithosphere (Schmalholz et al., 2005). Strong layers within a shortening section of the rheologically stratified lithosphere can either fold in a creeping mode or buckle quasi-elastically (Schmalholz et al., 2002).

The main objective of this study was to use this concept of buckling while a thin effectively elastic layer is still present in the lithosphere, and how it can affect lithospheric deformation patterns during the post-buckling relaxation process. Our approach was to build a scaled experimental model in which we embedded a thin unbreakable layer in a viscous matrix. We first present and discuss model materials, boundary conditions and scaling, then we present the experimental results, and finally we discuss experimental results and large scale implications for late orogenic deformation to conclude that a relatively thin elastic layer can control large scale deformation patterns.

2. Experimental method

2.1. Basic premises

In this study we deal with a simple mechanical model to show the influence of elastic strain that accumulates through the interplay of many variables and parameters inherent to a more complex geological setting. Consequently, the present models serve mainly to illustrate the concepts of buckling and post-buckling relaxation phenomena in response to the elastic strain energy. Therefore, the mechanical model provides a firsthand approximation to more complex continental lithospheres where a brittle, weak layer overlies a viscous layer, with a thin elastic and unbreakable layer in between.

The experiments were performed in two stages: a first stage of buckling by layer-parallel shortening at different piston velocities (buckling stage or first stage); a second stage of buckling relaxation with arrested piston (piston velocity = 0, post-buckling stage). The first stage for the post-buckling relaxation experiments was carried out at maximum piston velocity (11 mm/s) and arbitrarily stopped, because we only needed to have high stored elastic energy to make the post-buckling stage vigorous enough for easier and better visualization and measurement. Different amounts of shortening were not tested, because it has long been established that the dominant wavelength (or number of waves) is determined at the first increment of shortening (Biot, 1961): the higher the compressive stress (or velocity), the smaller the dominant wavelength (or the higher number of waves). Further increase in shortening only produces smaller wavelength and larger amplitude, which is called amplification. Therefore, strain rate (or piston velocity, not the amount of strain) determines the number of waves, and the amount of strain controls amplification. It is clear that in a parallelepipedic body deforming at constant velocity by pure shear (as in the present case), the strain rate increases with time. However, this is not relevant for the process addressed here, because the number of waves is determined at the first increment of shortening. Therefore, using velocity or strain rate makes no difference.

2.2. Model materials and boundary conditions

We used polydimethyl-siloxane (PDMS — manufactured by Dow Corning of Great Britain under the trade name SGM 36) as the viscous matrix (see Weijermars, 1986, for physical properties), which has a density of ca. 965 kg/m^3, is Newtonian at the applied strain rates, and has a viscosity in the order of 10^4 Pa s. As analogues of the elastic layer, we used three types of materials, which readily fold under layer parallel shortening: (1) cellophane ca. 0.1 mm thick, with $\rho \approx 915$ kg/m^3 and Young's modulus $E \approx 5.3 \times 10^7$ Pa; (2) plasticine ca. 1 mm thick, with $\rho \approx 1320$ kg/m^3 and $E \approx 4.3 \times 10^4$ Pa (for rheological properties see e.g. McClay, 1976; Weijermars, 1986; Schöpfer and Zulauf, 2002; Zulauf and Zulauf, 2004); and (3) a low density polyethylene film (LDPE) ca.