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Numerical modeling of extensional sedimentary basin formation with MATLAB: Application to the northern margin of the South China Sea

Lin Chen [a,*], Zhongjie Zhang [a], Haibin Song [b], Fei Li [c], Dieter Franke [d]

[a] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[c] Research Institute of Exploration and Development, Tarim Oilfield Company, PetroChina, Korla, 841000 Xinjiang, China
[d] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany

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ABSTRACT

The coupled simple-shear/pure-shear model (CSSPSM) with broad application for studying the evolution of continental extensional sedimentary basins was proposed by Kusznir and co-workers. It can be used to determine the geometry of sedimentary basins and their crustal structure by integration of the rheological, thermal and isostatic response of lithosphere to various loads caused by lithosphere extension. We developed a MATLAB code, MODBAS, to model extensional sedimentary basin formation based on the CSSPSM. The validity of the code was tested with a single listric fault model and a multiple-fault model. The application of the code in the Pearl River Mouth Basin (PRMB) on the northern margin of the South China Sea demonstrates (1) the effective elastic thickness of the lithosphere beneath the PRMB is very low (<5 km), which may support the idea of a very weak continental crust beneath the northern margin of the South China Sea; and (2) there are significant misfits between predicted and observed basements beneath the two high-standing areas on the profile, which was interpreted as an indication of substantial dynamic support from small-scale mantle convection.

1. Introduction

It is now generally accepted that the formation of extensional sedimentary basins is produced by continental lithosphere stretching, but the stretching process is still unclear. Two classic models, pure-shear (e.g., McKenzie, 1978) and simple-shear (e.g., Wernicke, 1985), were proposed to understand the formation of extensional sedimentary basins. The pure shear model assumes that the lithosphere undergoes uniform extension at the time of rifting, which causes thinning of the crust, surface subsidence and an increase in geothermal gradient. Subsequently, thermal contraction and isostatic re-equilibration caused by lithosphere cooling leads to thermal subsidence and further deepens the basin. The subsidence can be divided into syn-rift and post-rift components. Crustal thinning at the time of rifting leads to syn-rift subsidence and flank thermal uplift (e.g., Cochran, 1983; Buck et al., 1988), while lithosphere cooling with time produces the post-rift component. This uniform lithosphere extension model has been applied successfully to explain the subsidence history of many extensional basins in the geological record (e.g., Royden and Keen, 1980; Sclater and Christie, 1980; Barton and Wood, 1984; Clift and Lin, 2001).

The pure-shear model assumes that lithosphere behaves plastically with local Airy isostasy, that lithosphere stretching is uniform with depth, and neglects the role of basement faults during stretching. In contrast, the simple shear model (e.g., Wernicke, 1985) assumes that extension of the continental lithosphere is accommodated along a low-angle detachment fault, which cuts through the entire lithosphere. Deep seismic reflection data shows that major basement faults play an important role in the development of rifted sedimentary basins (e.g., McGeary and Warner, 1985). The major basement faults imaged on deep seismic data generally appear to be restricted to the cool, brittle topmost part of the lithosphere, corresponding to the upper crustal seismogenic layer. Beneath this layer, deformation transforms from a brittle manner into a ductile mechanism (Kusznir and Park, 1987). Within the lower crust and upper mantle, it is likely that extension can be approximated to a pure shear mechanism rather than by faulting as exhibited in the upper crust. So far, no example of a major fault or shear zone extending continuously from the surface down into the upper mantle, as suggested by the simple shear model, has been observed. This observation led Coward (1986) to suggest that the zones of upper and lower lithospheric stretching were heterogeneous and

* Corresponding author. Tel.: +86 10 82998345; fax: +86 10 82998229.
E-mail address: chenlin@mail.iggcas.ac.cn (L. Chen).

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subsequently Kusznir et al. (1987) presented a combined simple shear-pure shear model for continental lithosphere extension on the basis of this concept. This model assumes that extension within the upper crust occurs by simple shear, while the lower crust and mantle lithosphere are stretched by pure shear. The upper crustal extension by faulting is balanced at depth by pure-shear stretching within the lower crust and mantle. Simple shear and pure shear jointly lead to crustal thinning and perturbation of lithosphere temperature field. These changes combined with the subsequent lithosphere thermal re-equilibration change lithosphere density field, thus produce associated loads. The flexural response of the lithosphere to the loads controls sedimentary basin geometry and crustal structure.

The coupled simple-shear/pure shear model has been widely applied to provide insights into the evolution of a number of extensional sedimentary basins (e.g., Kusznir and Egan, 1989; Karner et al., 1992; Clift et al., 2002). In this study, we have developed an open MATLAB code, MODBAS, to model the formation of extensional sedimentary basins based on this model. The code can be used to predict sedimentary basin geometry, subsidence history and crustal structure due to lithosphere extension. The purpose of this work is to provide a useful tool for researchers to explore the processes controlling extensional sedimentary basin formation. The validity of the code is tested using two theoretical models and we present an application to the Pearl Mouth River Basin on the northern continental margin of the South China Sea.

2. The coupled simple-shear/pure-shear model

The coupled simple-shear/pure-shear model integrates the geometric, thermal and flexural isostatic consequences of continental lithosphere extension by coupling simple shear within the upper crust and pure shear within the lower crust and mantle lithosphere (Fig. 1). We acknowledge that all the following equations associated with this model are directly taken from Kusznir et al. (1987) and Kusznir and Egan (1989). In order to address our programming design clearly, the main equations are re-presented.

Simple shear along a detachment fault produces a surface depression by the hanging wall 86 collapsing onto footwall and leads to crustal thinning (Fig. 1). The size and shape of the 87 depression is controlled by the geometric shape of the crustal detachment and the magnitude of 88 extension. The detachment fault is assumed to take a listric form:

$$f_l(x) = \begin{cases} 0, & x<0 \\ z_d[1-\exp(-dx/z_d)], & x \geq 0 \end{cases} \tag{1}$$

where $f_l(x)$ is the depth of fault plane; z_d is the asymptotic depth of the detachment fault; x is horizontal coordinate ($x=0$ corresponds to the location of the footwall cutoff); and $d=\tan\theta$, where θ is the fault angle at the surface.

A fundamental assumption of the coupled simple-shear/pure-shear model is that extension within upper crust must be balanced at depth within lower crust and mantle by distributed pure-shear deformation. But the lateral distributions of these components need not be identical. The magnitude of pure shear deformation is represented by stretching factor, β (McKenzie, 1978). For convenience, a bell-shape distribution of stretching factor is assumed:

$$\beta(x) = 1+C\sin^2(\pi x/W) \tag{2}$$

where $1+C$ is the maximum stretching factor and W is the post-extension width of the pure shear zone. Conservation of cross-sectional area in the extended lithosphere is maintained by requiring that faulting within the crust is balanced by the integrated horizontal strain below the detachment. Hence:

$$E = \int_0^{W'} [\beta(x)-1]\,dx \tag{3}$$

where E is the amount of extension in the upper crust by faulting defined as horizontal heave, and W' is the pre-extension width of the pure shear zone.

Provided $W \gg E$, C takes the form as follows (Kusznir and Egan, 1989)

$$C = 2E/(W-E) \tag{4}$$

2.1. Geometric response of lithosphere to extension

Both simple shear deformation in the upper crust and pure shear deformation in the lower crust and mantle lithosphere contribute to crust thinning.

The thinning of upper crust, $s(x)$, can be given by:

$$s(x) = f_l(x)-f_l(x-E) \tag{5}$$

This equation represents the Chevron construction (e.g., Egan, 1992).

The thinning of lower crust, $p(x)$, is given by:

$$p(x) = (t_c-z_d)[1-1/\beta(x)] \tag{6}$$

where t_c is initial crust thickness.

2.2. Lithosphere temperature field

During lithosphere extension, deep hot material passively rises upwards. As a consequence, the lithosphere geothermal gradient increases. The faulting within upper crust results in cool hanging wall rock collapsing onto relatively hot footwall, which produces a temperature discontinuity across the fault.

The initial geotherm $T(z)$ before extension is given by:

$$T(z,x,t=0^-) = T(z) = \frac{z}{a}T_m \tag{7}$$

where a is initial lithosphere thickness; T_m is lithosphere basal temperature; z is vertical coordinate, which increases downward; and t denotes time.

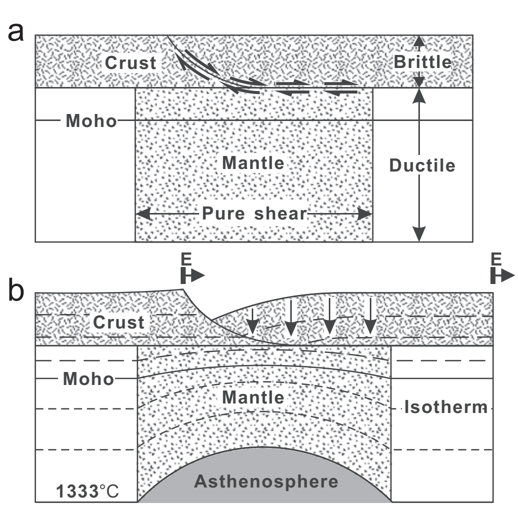

Fig. 1. Diagrammatic representation of lithosphere extension by simple shear deformation in upper lithosphere and pure shear in lower lithosphere beneath a horizontal detachment. Initial non-isostatic, geometric component of basin formation is produced by collapse of hanging wall block. The resulting lithosphere temperature perturbation is caused by both simple-shear and pure-shear components (modified after Kusznir and Egan,1989).