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Symmetry during the syn- and post-rift evolution of extensional back-arc basins: The role of inherited orogenic structures

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ABSTRACT

Rheological heterogeneities in the lithosphere have first order control on the topographical expression of tectonic processes. Pre-existing orogenic suture zones localise extensional deformation resulting in asymmetric basins. Such crustal geometries are often in contrast with the more symmetric regional lithospheric structure observed beneath extensional basins. We study such (a)symmetries and their controlling parameters by conducting a series of 2D thermo-mechanical numerical experiments of the extension of an overthickened, hot lithosphere that contains a weakness zone. The modelling shows that syn-rift subsidence is low to moderate creating asymmetric half grabens where extension migrates in space and time, grouped in an overall symmetrical appearance on a larger scale. The initial lithospheric mantle asymmetry is attenuated by the lateral heat conduction and further dynamic evolution of the thermal anomaly during the "post-rift" phase, resulting in differential vertical movements of the crust including additional 2–3 km subsidence in the basin centre. The modelling shows that the initial crustal and lithospheric thicknesses, rate of extension and surface processes strongly control the thermo-mechanical evolution of the extensional system. The numerical modelling yields new insights into the mechanics of coupling between near-surface kinematics and the evolution of deep lithospheric structure in the Pannonian basin and the Aegean, two of Europe's largest back-arc systems.

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1. Introduction

The evolution of extensional basins is controlled by multiple internal and external forcing factors and parameters, such as variable plate divergent rates, surface processes, coupled or decoupled crustal and lithospheric configurations, evolution of asthenospheric thermal anomalies and associated mantle dynamics (e.g., Huismans and Beaumont, 2003; Burov, 2007; Liao and Gerya, 2014). Moreover, rheology is a key parameter influencing the geometry of extension, strength contrasts and degree of brittle–ductile coupling (e.g., Brun, 1999; Burov and Poliakov, 2001). It also controls localisation of deformation and its subsequent evolution (Dunbar and Sawyer, 1988; Sokoutis et al., 2007; Li et al., 2011). The extension rates also control the style of extension, for instance low divergence rates or tectonic quiescence periods may lead to rift migration (Van Wijk and Cloetingh, 2002; Naliboff and Buiter, 2015), critical for the formation of hyper-extended margins (Brune et al., 2014). Furthermore, low extension rates favour the formation of asymmetric basins, resulting in the creation of high lateral offsets between the locations of maximum crustal and lithospheric thinning (e.g., Huismans and Beaumont, 2003). Analogue models infer that different extension rates also have considerable impact on strain localisation. An increase of plate divergence rate increases the strength of the ductile layers and therefore enhances the coupling between the brittle and ductile layers resulting in more distributed extension (Brun, 1999; Corti et al., 2003).

The symmetry of extension, in terms of crustal and lithospheric thinning and its evolution with time, and the degree of rheological coupling between different lithospheric layers are particularly important when extension affects a pre-existing nappe stack (e.g., Ziegler and Cloetingh, 2004). In orogenic settings, nappe contacts provide critical rheological contrasts. In particular, subduction and suture zones formed during the amalgamation of continents provide the possibility of large lithospheric scale reactivations (e.g.,

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Dunbar and Sawyer, 1988; Sokoutis et al., 2007). Such conditions are most often met in extensional back-arc domains, where asymmetric (i.e., simple shear) extension reactivates suture zones and nappe contacts shortly after orogenic build-up, affecting an overthickened, hot and weak lithosphere (Le Pourhiet et al., 2004; Tirel et al., 2008; Huet et al., 2011; Menant et al., 2016). Back-arc extension reactivates thrust contacts and exhumes rocks previously buried at great depths, such as in the Apennines or Aegean system (e.g., Brun and Faccenna, 2008). In these settings deformation occurs at high strain rates, controlled by the interplay between subduction and plate convergence velocities, such as typically observed in Mediterranean back-arcs. Extension was variable in time and space with average velocities of 2–3 cm/yr for the last 30 My, of course short periods of very slow and fast extensional pulses are inferred (Faccenna et al., 2014).

The role of evolving thermal anomalies, phase transformations and migration of deformation in space and time associated with variable subsidence rates are important in understanding the evolution of extensional basins, in particular in back-arc settings (Cloetingh et al., 2013; Menant et al., 2016). Numerical models have demonstrated the close feedback between stretching, evolution of thermal anomalies and basin formation (Huismans and Beaumont, 2003; Burov, 2007). However, their relationship with the extensional back-arc basin infill, in terms of symmetry, evolution and migration of deformation in time and space, is less understood.

In this study, we investigate the influence of large scale rheological weakness zones during the formation and evolution of back-arc extension using 2D thermo-mechanical numerical modelling calibrated by geological and geophysical observations. A key element in our model is the implementation of a lithospheric weakness zone, simulating the influence of a pre-existing suture or major nappe contact during extension. We conducted a series of numerical models to test the controls of key parameters, such as the initial crustal and lithospheric thicknesses, weakness zone geometry, extensional velocities applied at the model sides and rate of erosion and sedimentation. Our study focuses on analysing the influence of these parameters on the interplay between the extensional symmetric versus asymmetric crustal deformation and mantle structure, and the formation and evolution of the overlying sedimentary basins. Our numerical modelling results are compared to observations in two of Europe's largest extensional back-arc areas, the Pannonian and Aegean basins of the Mediterranean region.

2. Modelling methodology

Thermo-mechanical numerical modelling is particularly well suited to study the mechanics of extension and the evolution of associated sedimentary basins (e.g., Burov and Poliakov, 2001; Huismans and Beaumont, 2003). We have employed the thermo-mechanically coupled 2D finite element code Flamar v12 (e.g., Francois et al., 2013; Burov and Gerya, 2014), based on the earlier Flac-Para(o)voz algorithm (e.g., Poliakov et al., 1993). Because of its capability to solve for large strains and its free upper surface boundary condition, this method is especially suitable to monitor the surface vertical movements during basin (de)formation (Fig. 1). The numerical algorithm explicitly takes into account elasto-visco-plastic properties of different lithospheric layers and the asthenosphere. The implemented constitutive laws include linear elasticity, Mohr–Coulomb failure criterion for brittle deformation (faults) and pressure–temperature and strain-rate dependent viscous deformation (Ranalli, 1995). Linear cohesion softening is used for effective localisation of plastic deformation (e.g., Huismans and Beaumont, 2003). Our modelling setups involve a 2D section of 1000 km wide and 450 km deep. Constant lateral velocities are applied at the sides, while the upper boundary is a free surface (Burov and Poliakov, 2001). Pliable lithostatic pressure (Winkler basement) is applied at the bottom of the model, which implies vertical normal stresses proportional to vertical displacement of the boundary, multiplied by the density contrast (see also Burov, 2007; Francois et al., 2013). The horizontal grid resolution is 2 km and the vertical grid resolution varies between 1.2 up to 3 km, with higher resolution in the upper part of the crust and the overlying sedimentary basin (Fig. 1). The accuracy of vertical displacements is in the order of 10 meters based on a series of sensitivity analyses (see Appendix and Francois et al., 2013).

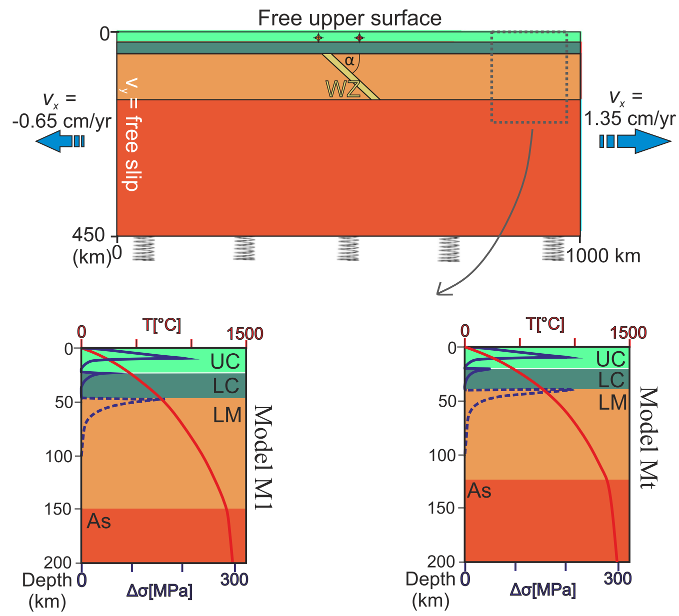

Fig. 1. Initial setup of the numerical model. The upper model boundary is a free surface. Springs indicate lithostatic pressure (Winkler basement) applied at the base of the model. Constant lateral velocities are applied at the sides of the model (blue arrows). An initial tilted rheological weak zone (WZ) is defined in the lithospheric mantle. Two crustal marker points are plotted on the phase configuration showing the evolution of extension with time in Fig. 2. The initial geotherms and strength profiles were calculated for model M1 (left) and Mt (right) based on the rheological parameters of Table 1. UC: upper crust, LC: lower crust, LM: lithospheric mantle, As: asthenosphere. The lithospheric mantle is relatively weak (dashed line) due to the high geotherm and has no strength at the weakness zone at such high temperature values. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

The experiments are specifically designed to simulate the fast extension of a hot and overthickened lithosphere that is common to many back-arc areas preceding extension, for instance in the Alpine-Carpathian region (Fig. 1; Faccenna et al., 2014). Our modelling procedure includes the implementation of a reference model (model M1, Table 1) and further analysis of the effects of variable parameters, such as rate of erosion and sedimentation, lithospheric weakness zone dip angle, initial crustal and lithospheric thickness and the rate of extension. A setup with an initial crustal thickness of 48 km, lithospheric thickness of 150 km, lithospheric weakness zone dip angle of 50 degrees with lateral velocities of 0.65 cm/yr left and 1.35 cm/yr right has been defined as a reference model for comparison with other scenarios (Figs. 1 and 2, Table 1). Similar to other numerical models (Burov and Poliakov, 2001), surface processes in terms of erosion and sedimentation were simulated by a linear diffusion law, where different erosion coefficients (k_e) correspond to different erosion rates (Table 1). Such an approach allows us to consider the dependence of erosion and sedimentation rate on the smoothness of the relief (i.e. surface curvature). The influence of the surface processes is simulated by a variable erosion coefficient (k_e) between 0 to 750 $m^2\,yr^{-1}$.

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