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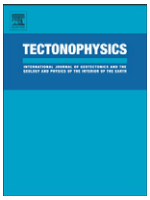

Compressive deformations and stress propagation in intracontinental lithosphere: Finite element modeling along the Dinarides–East European Craton profile

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ABSTRACT

Neotectonic stage stress and strain evolution was analyzed along a vertical lithospheric profile crossing the Dinarides, Pannonian Basin, Carpathians and East European Craton. A structural and lithological model was constructed based on distribution of seismic wave velocity along the Cel05 deep seismic sounding line. Rheological properties of each lithospheric layer were calculated as an average value for component rocks. In the applied model a highly laterally heterogeneous section of the lithosphere underwent 2.5% of shortening during 7.5 Myr, which corresponds to neotectonic inversion of the Pannonian–Carpathian–Dinaric region. The coupled viscoelastoplastic model predicts stress regime changes, within mechanically partitioned lithosphere, that together with complex rheological properties controls the deformation pattern. Long-wavelength lithospheric buckling was initiated during the first stage of inversion. It was followed by development of short wavelength minor folding in the detached upper crust. The topographic surface within the basin and over the transition to adjacent tectonic units was modified by buckling and swelling mechanisms producing folds of 800 m amplitude. Buckling, more efficient in the initial stage of inversion, was over time substituted by crustal swelling that contribute to raising anticlines at the topographic surface due to isostatic compensation. Compound mechanism of folding causes migration of anticlines at the topographic surface and synclines at Moho, which finally produces gentle pinch-and-swell pattern in the crust. Efficient mechanism of continental lithosphere buckling was described under minor shortening and a low stress level.

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1. Introduction

In the presented study response of continental lithosphere to minor tectonic contraction is examined. The 2D finite element modeling was performed on the laterally differentiated lithosphere section, which extends between the Dinarides and the East European Craton (EEC), along the CEL05 deep seismic sounding profile of CELEBRATION 2000 experiment (Grad et al., 2006) (Fig. 1). An attempt has been done to build a realistic model of lithosphere with rheological stratification. Boundary conditions reproduce the neotectonic stage of contraction resulting in partial inversion of the Pannonian Basin.

This paper is a continuation of the basin inversion study published by Jarosinski et al. (2011), in which continental lithospheric response to contraction was examined using more generic structural model of the lithosphere. The above research revealed that some general features and mechanism of deformation might be typical for contraction of intra-continental lithosphere bearing a rheologically weak segment like a rifted basin. In the recent experiment the model is more inhomogeneous and detailed due to seismically determined structure. In some segments of the model, up to seven rheologically distinct layers are distinguished. Rheological properties of these layers and asthenosphere were carefully adjusted by a mixture of several probable lithological rock varieties. Using such a composed rheological model allows checking if detachment levels, which might control deformation and stress patterns, still develop during tectonic shortening.

Although lithospheric-scale buckling has been explored by numerous studies (e.g. Nikishin et al., 1993; Cloetingh et al., 1999, 2008; Stephenson and Cloetingh, 1991) there is still an open question if folding of continents in intraplate setting really exists? Data describing such folds is never satisfactory, as seismic record of deep lithospheric structure is rare and the results are not accurate enough to depict normal size buckles and timing of their creation. In turn, more precise near-surface geological constraints, can be explained by different deeply seated processes. Until now, the rhythmic elevations of structural surfaces (e.g. Caporali, 2000; Cloetingh et al., 2002) and gravimetric anomalies (Burov et al., 1993; Jin et al., 1994; Muñoz-Martín et al., 2010; Stephenson et al., 1990) have been often taken for lithospheric folds, however due to the wavelength of several hundred

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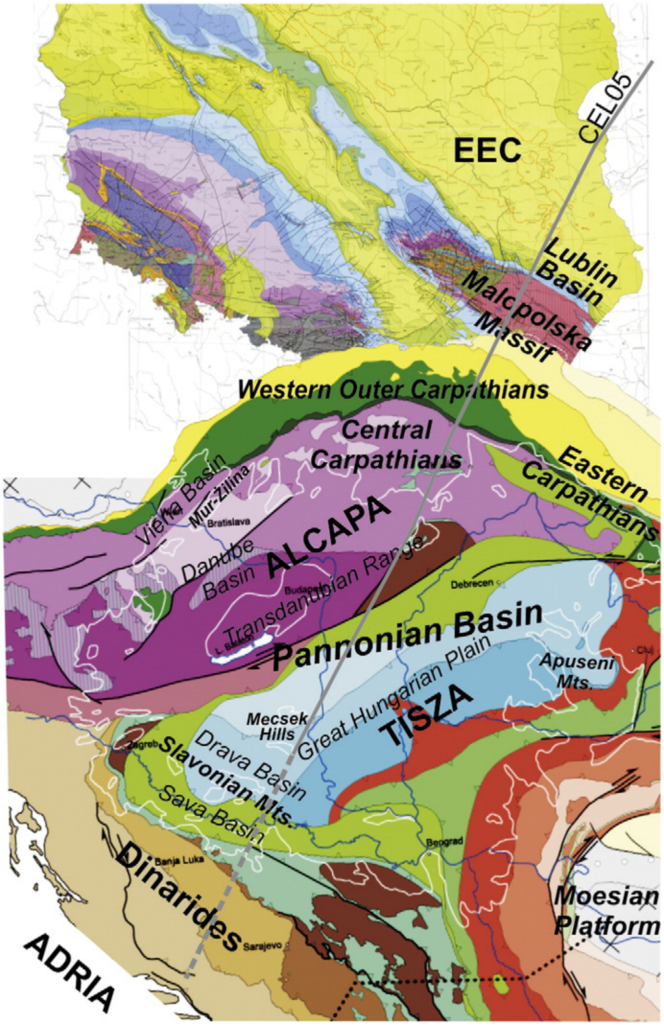

Fig. 1. Location of model cross-section at the background of tectonic maps: basement of the Pannonian Basin and surroundings and southern Poland without Cenozoic cover. Added are: mentioned in the paper the names of tectonic units and location of the Cel05 seismic profile (solid line) and its prolongation (dashed line).
Basement of the Pannonian Basin and surroundings (after Schmid et al., 2008) and southern Poland without Cenozoic cover (after Dadlez et al. 2000).

kilometers and lateral mechanical heterogeneity of continental plates these structures are in practice neither very multiple nor regular like in the cases of smaller scale folding. Usually different explanations of these phenomena are possible, among them the crustal periodic thickening in a pinch-and-swell pattern is a common alternative. This paper addresses the interplay between buckling and swelling mechanisms of lithosphere deformation and trace irregularity created by this combination.

At present, numerical modeling is the most effective method of insight in mechanical evolution of the lithosphere under tectonic loading. However, it is strongly dependent on the assumption of rheological properties and strain modes. One of the purposes of this study is to examine if the assumed "realistic" rheological model and mechanisms of deformations provide a credible solution comparable to observations. Regardless of the numerous numerical studies of lithosphere folding, so far only few concern rheologically stratified continental lithosphere (e.g. Burg and Podladchikov, 1999; Cloetingh et al., 2002; Gerbault and Willingshofer, 2004; Robin et al., 2003; Schmalholz et al., 2009). Most of them deal with deformation in orogenic context with tectonic shortening exceeding 10–20%. In recent study we address minor shortening, characteristic for intracontinental deformations, and focus on development of stresses, stress regimes and deformations in laterally heterogeneous and multilayered lithosphere.

The most visible response of the lithosphere to tectonic shortening is a change in topography (Burov et al., 1993; Cloetingh et al., 2002, Jin et al., 1994; Quigley et al., 2010), which in the case of a sedimentary basin results in inversion from deposition to erosion. Topography evolution is relatively easy to characterize by near-surface observations and because of this it can be used for model calibration. Therefore, the modeling study is focused on surface evolution and tracing its causes in deep lithosphere. An attempt has been made to decipher the changes in mechanisms and effectiveness of creating topography in time and space.

Another fruitful method of verification of the folding hypothesis is to compare the wavelength and amplitude of calculated folds with that observed in nature. To treat these parameters properly the thermomechanical model and boundary conditions have to be adjusted as carefully as possible. Earlier studies using simplified elastic mechanics raise doubts if lithosphere-scale buckling is possible due to large shear stresses necessary for instability (Ramberg and Stephansson, 1964, Turcotte and Schubert, 1982). Such stress is not expected to be generated by tectonic forces, which are limited to c.a. 10^{+13} N m^{-1} (Kusznir, 1991). More recent studies of oceanic lithosphere show that due to a more complex rheology of the lithosphere, buckling might be triggered under much lower mean differential stresses in a range of 200–400 MPa (e.g. Gerbault, 2000) or even less when additional factors, like syncline load with sediments, is taken into account (Martinod and Molnar, 1995). According to Zoback et al. (2002), cumulative tectonic forces across the lithosphere in intraplate environment might not significantly exceed $3*10^{+12}$ N m^{-1}. Under these conditions of stress and minor shortening any significant folding might be still questionable. The conditions under which lithosphere can buckle is one of the main by-products of the modeling presented here.

In general, the study is systematically focused on: (1) mechanical evolution of the lithosphere during contraction, (2) interactions between mechanically contrasting lithospheric segments, (3) formation of fold generations and its control by rheological stratification, (4) effectiveness of continental lithosphere folding, (5) interplay between buckling and swelling mechanisms of topography building. Although the model setup describes a specific part of the European lithosphere predictions of the model study might have a more widespread meaning, as minor compressive events within continental plate interiors are common and therefore could represent wide range of cases across the world.

2. Conventions and abbreviations

Systematically, acronyms are used for the lithospheric layers: UC, MC, LC stand for upper, middle and lower crust, respectively and UM and AST stand for lithospheric (uppermost) mantle and asthenosphere. Within the lithospheric layers, separated by discontinuity in P wave velocity (*Vp*) or seismic reflectors, lithological subdivisions are distinguished depending on *Vp*: slower "a" and faster "b". For model interfaces the following acronyms are used: TOPO for topographic surface, MOHO for Moho surface and LABA for lithosphere/asthenosphere boundary. Following the tectonic convention, positive values are taken for compression and negative for extension. In consequence the symbols σ_1, σ_2 and σ_3 stand for the maximum (compressive), intermediate and minimum principal stresses, respectively. In regional considerations, maximum horizontal stresses was denoted by S_{Hmax}. Normal fault (extensional), strike-slip and thrust fault (compressive) stress regimes are represented by the acronyms NF, SS and TF. The results of our modeling allow to distinguish between isostasy-driven and buckling-driven folding mechanism of the TOPO surface. Anticlines dominated by crust thickening (swelling) and isostasy are called swells while those maintained by buckling are

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