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Modelling recent deformation of the Pannonian lithosphere: Lithospheric folding and tectonic topography

Endre Dombrádi [a,b,*], Dimitrios Sokoutis [b], Gábor Bada [a], Sierd Cloetingh [b], Frank Horváth [a]

[a] Dept. of Geophysics and Space Sciences, Institute of Geography and Earth Sciences, Eötvös Loránd University, Pázmány Péter sétány 1/C, 1117 Budapest, Hungary

[b] Netherlands Research Centre for Integrated Solid Earth Science (ISES), VU University, De Boelelaan 1085, 1081HV Amsterdam, The Netherlands

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ABSTRACT

We investigated the role of lithospheric folding in the Quaternary inversion of the Pannonian basin by a series of analogue models. To this aim, build-up of stresses due to intraplate compression in the hot and weak Pannonian lithosphere, changes in the style of deformation and related surface processes were modelled. The primary response of the lithosphere to compression appears to be deformation in the form of large-scale folding. As a consequence of the folding, differential crustal motions occur, affecting present-day surface morphology and landscape processes. The analogue experiments examined folding mechanisms of the hot Pannonian lithosphere characterised by extremely low strengths except for a thin layer of brittle upper crust. Modelling results confirmed the existence of a large wavelength (~350–400 km) component of deformation accounting for large-scale vertical crustal motions. The amplitude of folding is sufficient to generate the amount of observed uplift and subsidence. Our analogue models, supported by the results of stress analyses, suggest that despite the low rate of convergence between the Adriatic microplate ("Adria-push") and the European plate, the weak Pannonian lithosphere has been an efficient transmitter of compression during the basin inversion. Crustal thickness variations are of key importance in governing regional deformation pattern and influence the timing and extent of the basin inversion. Effects of alternating strong and weak units in the brittle crust were also examined by means of two series of conceptual models, in which the order of thin and thick crustal blocks was opposite. Strain localisation in the brittle crust was strongly controlled by the moderate initial thickness variations. The concept gives a plausible explanation for the presence of anomalous rates of uplift and subsidence and multi-wavelength folding inside the basin. Models taking into account horizontal movements due to lateral extrusion were constructed with an oblique face of the indenter. This kinematic boundary condition resulted in a complex internal structure of the folded layers. The presented analogue experiments, together with previous numerical modelling studies, demonstrate the link between large-scale lithospheric folding and topography evolution in the Pannonian basin system.

1. Introduction

The Pannonian–Carpathian region (Fig. 1) is a key natural laboratory for studying the interaction between deep lithospheric processes, neotectonic activity and associated topographic expressions (e.g., Cloetingh et al., 2005a; Fodor et al., 2005; Bada et al., 2006). Buckling of the thinned, hot and weak back-arc lithosphere is considered to be an essential form of aseismic deformation. The Pannonian basin is often cited as a natural example of irregular lithospheric folding (Cloetingh et al., 1999), controlling the overall pattern of vertical crustal movements (Horváth and Cloetingh, 1996; Cloetingh et al., 2006; Horváth et al., 2006; Bada et al., 2007a).

Complementary to numerical modelling approaches, analogue models offer an additional tool to study the complex deformation history of this area. Crustal-scale analogue models were used to investigate fault reactivation during the formation of the Pannonian basin (Windhoffer et al., 2005). They also provided useful information on the neotectonic behaviour of strike-slip faults during basin inversion (Windhoffer and Bada, 2005).

By means of a set of analogue experiments, we focus on the compression of the whole lithosphere and the consequent subsidence and uplift anomalies observed in the Pannonian region. The geodynamic framework of the extension and subsequent compression of the Pannonian basin is reviewed first. Special emphasis is paid to recent vertical motions shaping surface morphology. Then, an overview on the process of lithospheric folding in weak intraplate continental lithospheres is given from a general perspective. This is followed by the description of the physical models implemented to tackle the coupling between the deep lithospheric processes and

* Corresponding author. Dept. of Geophysics and Space Sciences, Institute of Geography and Earth Sciences, Eötvös Loránd University, Pázmány Péter sétány 1/C, 1117 Budapest, Hungary. Tel.: +3613812191.
E-mail address: dombradi@elte.hu (E. Dombrádi).

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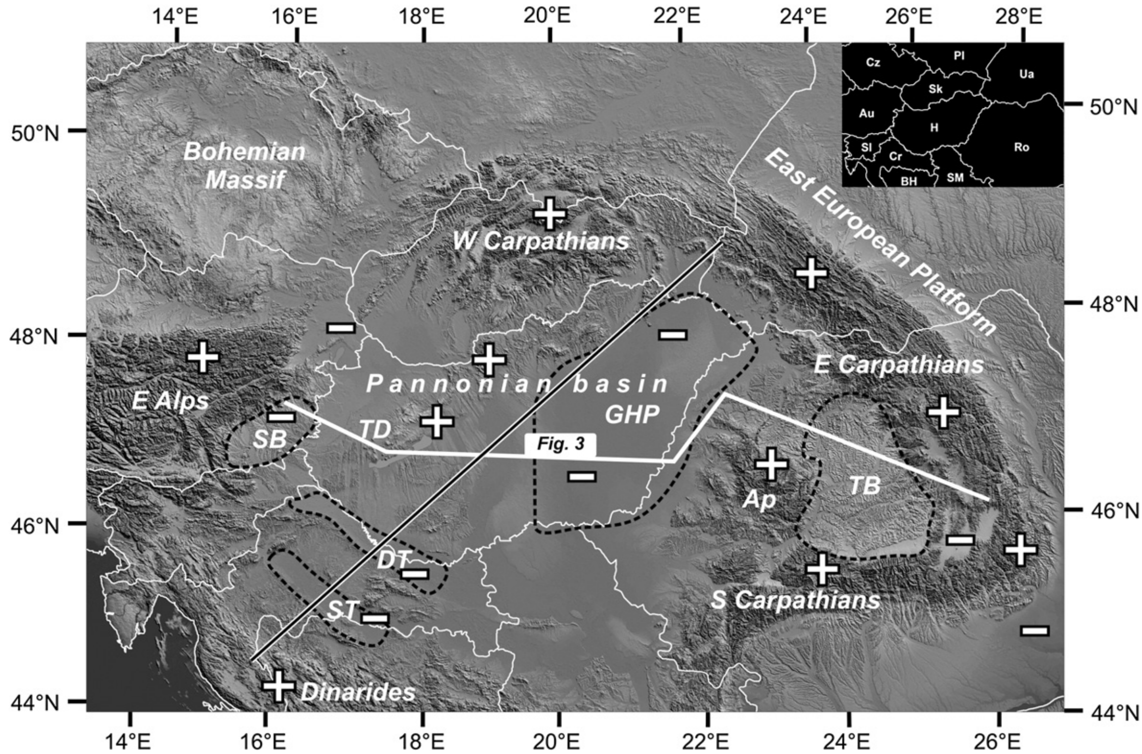

Fig. 1. Digital elevation model illustrating the topography of the Pannonian basin system and the surrounding orogens. SB = Styrian basin, TD = Transdanubia, DT = Drava trough, ST = Sava trough, GHP = Great Hungarian Plain, Ap = Apuseni Mountains, TB = Transylvanian basin. The sub-basins mentioned in the text are outlined by dashed black lines. Areas of significant Quaternary uplift and subsidence are marked by plus and minus signs, respectively. The profile presented in Fig. 3 is indicated with a solid white line. 2D interpretation of Type-1 and Type-2 models was along the solid black line representing the main direction of compression from the Adriatic indenter. The inset shows the boundaries of the countries in the wider area of the Pannonian basin (Cz = Czech Republic, Pl = Poland, Sk = Slovakia, Ua = Ukraine, Au = Austria, H = Hungary, Ro = Romania, Sl = Slovenia, Cr = Croatia, BH = Bosnia and Herzegovina, SM = Serbia).

topography. Finally, inferences gained from the analogue approach on the Quaternary to recent evolution of the Pannonian basin are discussed. In doing so, the following topics are addressed: (1) dominant wavelengths and amplitudes of lithospheric folding, (2) related vertical deformation patterns, (3) onset of the positive structural inversion, (4) the role of crustal thickness variation and (5) the influence of indenter geometry in the folding of a previously extended, hot and weak lithosphere.

Apart from the direct relevance to the evolution of the Pannonian basin, the presented results add scientific value to previous analogue models aiming at general geodynamic processes in compressional setting (Sokoutis et al., 2005) and/or the response of hot and weak lithospheres to deformation (Sokoutis et al., 2007).

2. Evolution of the Pannonian basin: from extension to compression

2.1. Formation of the Pannonian basin

The Pannonian basin, one of the hottest basins in continental Europe, is surrounded by the Alpine, Dinaric and Carpathian mountain belts (Fig. 1). The formation and extension of this back-arc basin, characterised by heterogeneous stretching of the lithosphere (Horváth, 1988; Lenkey, 1999), commenced in Early Miocene times (Horváth, 1993). Collision between Adria and the European continent led to the gravitational collapse of the eastern Alpine orogen and induced lateral, E–NE directed, extrusion of crustal blocks (Horváth, 1988; Ratschbacher et al., 1991; Tari et al., 1999; Horváth et al., 2006). The extrusion and extension were facilitated by the coeval retreating subduction in the Carpathian realm (Royden and Horváth, 1988; Horváth 1993; Bada and Horváth, 2001).

The ALCAPA (ALpine–CArpathian–PAnnonian) wedge of Alpine origin was directly driven by the N–NE directed indentation of Adria and made up the northern part of the Pannonian basement (Csontos and Nagymarosy, 1998, Fig. 2). The complex kinematic history of the southern unit, the Tisza–Dacia terrane is far less known (Csontos and Vörös, 2004). Paleomagnetic data (Márton, 2001) and structural analyses (Fodor et al., 1999) suggest strong internal deformation of the terranes during the Tertiary. By the Early Miocene, when the formation of the Pannonian basin started, however, the two terranes were already juxtaposed (Csontos et al., 1992). The present-day contact of the two blocks is marked by the Mid-Hungarian Shear Zone (see Fig. 2).

The significant stretching of the lithosphere was accompanied by pronounced asthenospheric updoming. As a result, the hot and thinned lithosphere became extremely weak and prone to subsequent tectonic reactivation related to the basin inversion (Cloetingh et al., 2005b; Bada et al., 2007a,b).

2.2. Quaternary basin inversion

In general, basin inversion is related to changes in the regional stress field (Ziegler et al., 1995, 2002) from tension controlling basin formation and subsidence to compression resulting in contraction and flexure of the lithosphere, often associated with differential vertical movements. Such major changes in the stress fields from extension, governing Miocene basin formation, to compression, controlling Pliocene to Quaternary neotectonic deformation of the Pannonian basin have been recognised (Horváth and Cloetingh, 1996; Fodor et al., 1999; Bada et al., 2001; Fodor et al., 2005; Horváth et al., 2006; Bada et al., 2007a). Consequently, positive structural inversion of the basin has been in progress accompanied by fault reactivation, related seismicity and development of tectonic topography (Horváth and Cloetingh, 1996; Bada et al., 1999; Gerner et al., 1999; Cloetingh et al., 2005a,b; Bada et al., 2007a).