Extension during continental convergence in the Eastern Alps: The influence of orogen-scale strike-slip faults

Jörg Robl*, Kurt Stüwe, Stefan Hergarten, Lynn Evans
Department for Earth Sciences, University of Graz, Heinrichstrasse 26, A-8010 Graz, Austria

ABSTRACT

In the Miocene, the European Eastern Alps extruded laterally along orogen-scale strike-slip faults due to both extensional gravitational collapse and compressional tectonic forcing. Horizontal extension is most prominently evidenced by detachments east and west of the Tauern Window; it is commonly explained by a retreating slab beneath the Carpathian arc hundreds of kilometers east of the orogen. Horizontal compression is shown by north-south shortening in the Tauern Window and the entire Eastern Alps in response to the convergence of the Adriatic plate with Europe. It is interesting that analogue and numerical models for the Eastern Alps designed to describe the east-directed lateral extrusion have failed to explain the extensional regime in the region of the Tauern Window. Using a numerical model for plan-view deformation that considers internal faults, we show here that orogen-scale strike-slip faults are mechanically required to cause extension during plate convergence in the Miocene Eastern Alps. We test the idea by coupling this model with a landscape evolution model and by comparing modeled and observed drainage system geometries.

INTRODUCTION AND GEOLOGICAL SETTING

The European Eastern Alps represent a classic example for indenter tectonics: the Adriatic microplate, representing the stiff promontory of the African plate, indented the softer orogenic wedge on top of the European foreland, causing north-south shortening, crustal thickening, and east-directed lateral extrusion in front of the indenter (e.g., Ratschbacher et al., 1989, 1991a, 1991b; Frisch et al., 2000). Lateral extrusion was defined by Ratschbacher et al. (1991b) as a kinematic description for the combination of gravitational collapse and tectonic escape. In the Eastern Alps this process is controlled by activity of large orogen-parallel strike-slip fault zones, e.g., the Salzachtal-Ennstal fault in the north (Peresson and Decker, 1997; Wang and Neubauer, 1998) and the Periadriatic Lineament in the south (e.g., Viola et al., 2001) (Fig. 1A). Although the overall east-directed extrusion lasted throughout the Miocene, the stress regime changed more than once during this time. While the first stage of the extrusion was compressional, orogen-scale normal faults oriented perpendicular to the front of the Adriatic indenter formed ca. 22–13 Ma (e.g., Fügenschuh et al., 1997), extending the orogen and exhuming the Tauern window (Selverstone, 1988; Behrmann, 1988; Genser and Neubauer, 1989). This extensional phase is interpreted to be facilitated by a retreating slab within the Pannonian realm hundreds of kilometers east of the Eastern Alps (Royden et al., 1983; Ratschbacher et al., 1991b). It is assumed to have terminated again with the cessation of the subduction beneath the Carpathian arc ca. 7–10 Ma (Cloetingh and Lankreijer, 2001).

It is interesting that none of the models designed to describe the extrusion has been able to reproduce an extensional phase allowing the formation of normal faults without considering orogen-scale strike-slip faults. Numerical models of Robl and Stüwe (2005) and analogue models of Ratschbacher et al. (1991a) or Rosenberg et al. (2004, 2007) were successful in reproducing crustal thickening and lateral escape, but evidence for horizontal extension in the model region corresponding to the Tauern Window is weak or absent. A possible explanation was given by Selverstone (2005) (see also Ratschbacher et al., 1991a, 1991b), who suggested that the crustal-scale fault zones, not explicitly considered in most modeling studies, play a crucial role in causing extension by connecting the realm of the Eastern Alps and the Pannonian Basin. Here we test this idea using a numerical model that describes mechanical deformation in plan view and allows internal discontinuities to describe faults. As the formation of the drainage systems of the Eastern Alps is intimately connected with fault activity, uplift, and lateral extrusion (Frisch et al., 1998; Kuhlemann et al., 2006), we test our conclusions using geomorphological observations. We compare aspects of the present-day drainage geometry with that predicted from coupling the mechanical model used for the stress field predictions with a landscape evolution model.

MODEL SETUP AND BOUNDARY CONDITIONS

In our model we describe continental collision in plan view with a thin viscous sheet approach (e.g., England and McKenzie, 1982). Discrete structures embedded within the viscous non-Newtonian material are described as internal boundaries that allow free slip, but prevent propagation or dilation, as first described by Barr and Houseman (1996). In order to describe river incision during continental collision, we follow the most commonly used detachment limited model to describe bedrock channel erosion (e.g., Howard, 1980), assuming that the erosion rate is a power law function of slope and upstream drainage area (Robl et al., 2008b). For material constants like the erodibility of the bedrock, we use the results in Robl et al. (2008a), wherein these values were scaled for rivers in the Eastern Alps so that recent erosion and uplift rates correspond and range between 0.1 mm yr^{-1} and 1 mm yr^{-1}.

For our model calculations we define three domains of contrasting rheology inside the model region so that the Adriatic indenter, the European foreland, and the Eastern Alps have viscosity contrasts of 1.5:3:1, respectively, and a power law exponent and Argand number corresponding to the best fit estimates of Robl and Stüwe (2005). Defining an indenter with finite rheology allows partitioning of deformation between indenter and foreland and the topography-controlled development of drainages on both plates. Horizontal boundary conditions are applied on all four sides of the model region and are assumed to be constant over time: the western and northern boundaries are defined by zero velocity in normal and zero stress in a tangential direction. The southern boundary that pushes the indenter in a north direction is split into several segments with variable velocity to approximate the counterclockwise rotation of the Adriatic microplate

*E-mail: joerg.robl@uni-graz.at

as constrained by global positioning system studies (e.g., Nocquet and Calais, 2003). This leads to a maximum north-directed velocity of 10 mm yr^{-1} at the eastern edge of the indenter.

Along the eastern boundary three different sets of boundary conditions are applied to describe three different geological scenarios. Extrusion against an undeformed region in the east is modeled by closing the eastern boundary of the model region so that no material can escape. We call this the backstop boundary condition. Second, extrusion into a weak Pannonian Basin, possibly open to subduction in the east, is modeled by assuming a lithostatic eastern boundary condition that allows material to flow freely eastward. For this we assume lithostatic stresses at the margins (extrusion boundary condition). Finally, we describe subduction rollback underneath the Carpathian arc by pulling the eastern boundary with a rate of 20 mm yr^{-1} to the east (rollback boundary condition). All three sets of experiments were performed with and without internal faults. The faults are inserted corresponding in length and geometry to the Salzachtal-Ennstal, Periadriatic Lineament, Mur-Mürz, and Lavanttal faults, representing four of the most distinct fault zones in the Eastern Alps. Results are presented after 10 m.y. of convergence. As the topography of the Miocene Eastern Alps is not well constrained, we assume that there is no preexisting topography at the start of the simulations

MODEL RESULTS

During the model runs topography is built by the convergence of, and removed by, the dynamically evolving drainage systems that deeply incise the region of elevated surface following topographic gradients (Fig. 2A). Differences in crustal thickening and topography buildup between the different experiments depend predominantly on the eastern boundary condition, rather than on the faults. The highest topographic gradients and vertical strain rates are observed for the backstop boundary condition. For the extrusion experiments, there is still crustal thickening in front of the indenter, but a significant amount of material is extruded in an eastward direction, albeit in a compressive stress regime. In the rollback case the amount of crustal thickening in front of the indenter is small, but even though the east-directed pull is twice as fast as the north-south convergence imposed at the southern boundary, there is no horizontal extension north of the indenter. Vertical strain rates are positive, reflecting that there is no horizontal extension and the crust is thickening.

When inserting the four major fault zones to the models described above (Fig. 2B), the experiments show a complex vertical strain rate field causing inhomogeneous topography buildup. Rivers that follow orogen-parallel valleys at the position of the fault zones show enhanced incision rates and indicate a strong link between drainage evolution and discrete structures. For the backstop and the extrusion scenarios, topography buildup between the Periadriatic Lineament and Salzachtal-Ennstal faults is smaller than without considering faults. This is caused by significantly lower vertical strain rates. The Mur-Mürz and Lavanttal faults are characterized by the formation of topography along the eastern side, while a basin is formed in a small extending region on their western side (Fig. 2B, white arrow). Clear evidence for horizontal extension in terms of negative values in the vertical strain rate field at the position of the Tauern Window is only observed for the rollback scenario. The north-south orientation of the extending region is consistent with the orientation of the two major detachments bounding the Tauern Window, i.e., the Katschberg and Brenner detachments (Figs. 1A and 2B). We have also performed experiments without the Mur-Mürz and Lavanttal faults (not shown). Then, the extending region is even larger than that shown in Figure 2B for the rollback scenario. In summary, our experiments can successfully explain the Miocene horizontal extension in the Tauern Window in a setting of plate convergence. However, this is only possible if a retreating slab in the east is genetically linked with large active fault zones that connect the central parts of the Eastern Alps with the Pannonian realm (Fig. 2B).

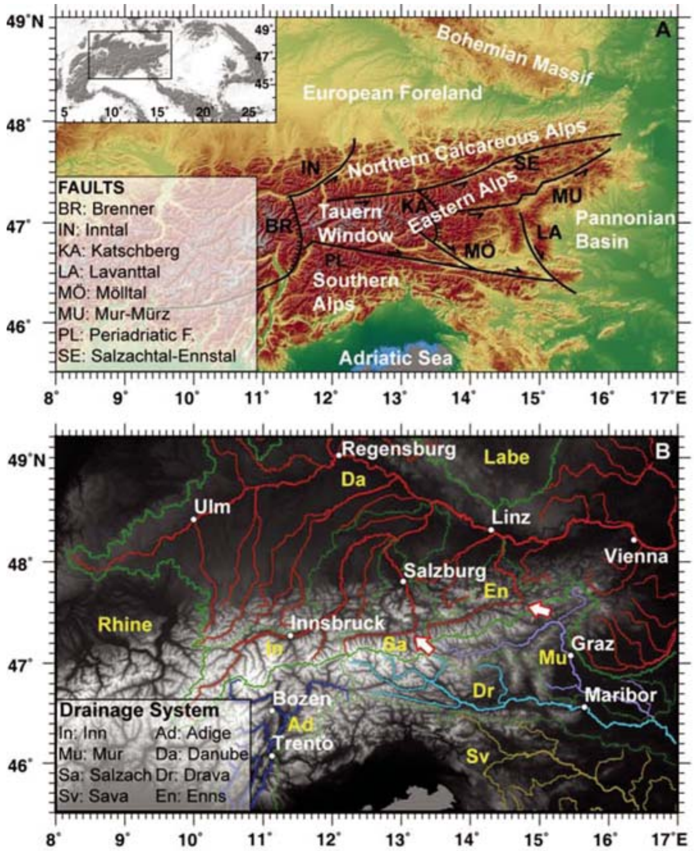

Figure 1. A: Topographic map of Eastern Alps showing major structural units and fault systems. Inset shows exact position within Alpine-Carpathian orogen. B: Drainage system of Eastern Alps. Major rivers and their tributaries are shown and line thickness is proportional to the 4th root of the upstream drainage area. Green lines indicate drainage divides. Red arrows indicate position of elbow-shaped river segments.

DRAINAGE GEOMETRY AS A TEST

The results are confirmed by a strong correlation of the first-order features of actual and modeled drainage systems. This is most obvious in the formation of large inner alpine, orogen-parallel rivers along the major fault zones (Figs. 1B and 3B). In general, indentation experiments without the consideration of faults (Fig. 3A) are characterized by numerous small rivers that follow the rather uniform topographic gradients. The highest values for stream power (defined as the product of the channel gradient and the square root of upstream drainage area as a measure for the capacity of a river to incise into the bed rock; Stüwe, 2007) coincide with the largest topographic gradients. Correspondingly, stream power values are the smallest for the rollback scenario and largest for the backstop scenario. It is interesting that the stream power does not coincide with the highest uplift rates and topography in the central parts of the orogen, indicating that there is a lag between topography formation and river incision.

When considering internal faults, the drainage system is characterized by fewer but larger rivers within the orogen, and the geometry of the model drainages bears significant similarities to the drainage pattern observed in the Eastern Alps. In particular, this includes the elbow-shaped bends of rivers that leave the orogen-parallel valleys and break through the Northern Calcareous Alps into the Alpine foreland (Figs. 1B and 3B, red arrows). Large orogen-parallel channels that follow the fault systems are characterized by significantly higher stream power values compared to the case without faults. Orogen-parallel rivers accumulate

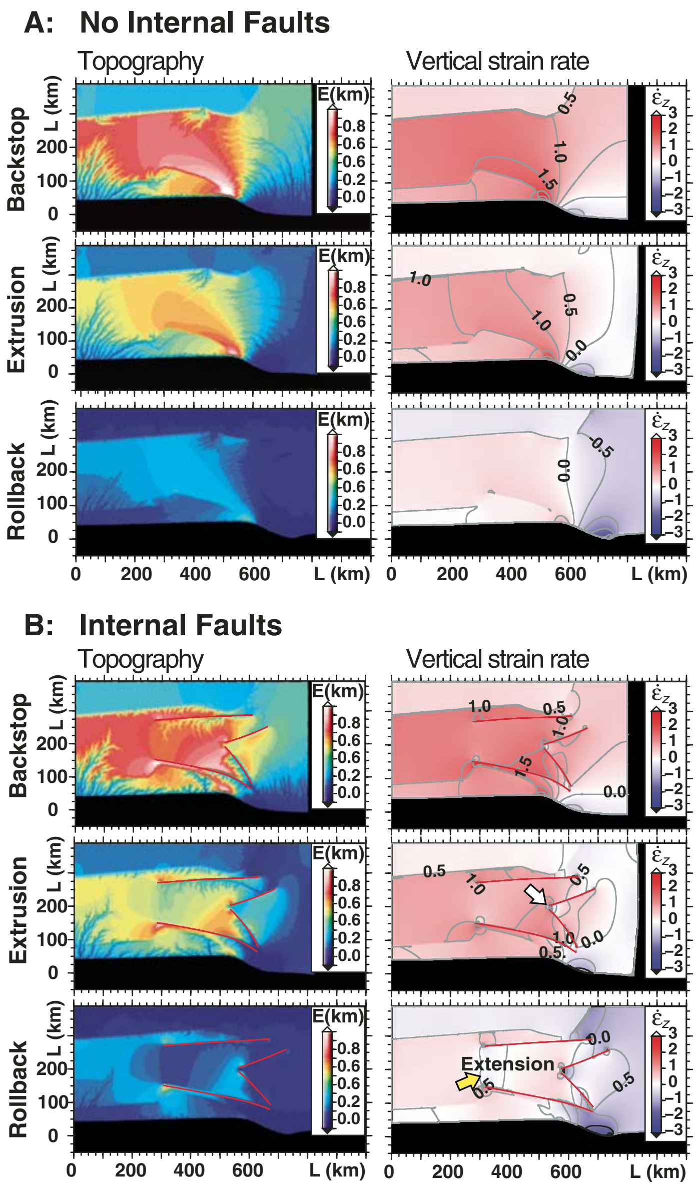

Figure 2. Topography and vertical strain rate for three different sets of boundary conditions for the eastern boundary: backstop, extrusion, and rollback. The experiments were performed without internal faults (A) and with internal faults (B), and are shown after 10 m.y. of convergence. Red shading implies horizontal compression, blue shading implies horizontal extension. Note that there is only extension in the Tauern Window in combination of faults and rollback boundary condition.

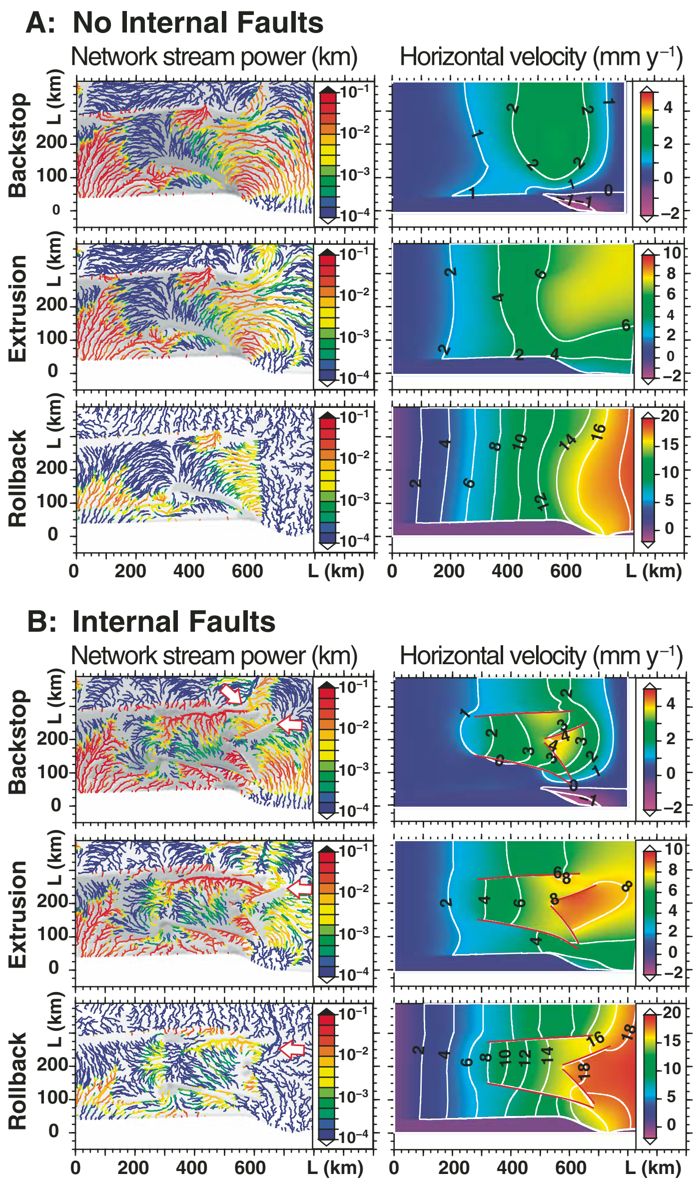

Figure 3. Drainage network configuration and stream power (color coded) of the main channels and their tributaries and the horizontal velocity field of the numerical experiments after 10 m.y. of convergence for three different conditions for the eastern boundary: backstop, extrusion, and rollback. A: Results without considering faults. B: Results considering faults. Red arrows indicate position of elbow-shaped bends of rivers.

numerous smaller channels within the orogen, increase the upstream drainage area, and are therefore characterized by higher erosion rates (Fig. 3). The elbow-shaped bends of the rivers are the consequence of the displacement along the fault systems. This also implies that there was some preexisting topography (Frisch et al., 1998), so that the major rivers of the Eastern Alps drained into the foreland before the lateral extrusion. Values for stream power are also higher in the center of the orogen compared to the scenarios without faults, indicating that the lag time between topography formation and river incision is reduced if faults are active. Differences in the modeled (Fig. 3) and observed (Fig. 1B) drainage systems may be explained in terms of pre-Miocene topography, late Miocene uplift (e.g., capture of the Mur River), and the impact of Holocene glaciations (Enns and Salzach Rivers) that caused a dramatic reorganization of the drainage system (Robl et al., 2008a).

The reason for orogen-parallel valleys, higher rates of river incision, and extension during continental collision in the rollback scenario may be seen in the horizontal velocity field. Two distinct corridors with highly increased east-directed velocity values appear between the faults. Gradients in the velocity field are compensated by changes in the crustal thickness, causing the formation of mountain ranges and basins. Our model predicts that the formation of orogen-parallel rivers is limited to a landscape with small preexisting topographic gradients, indicating that topography formation in the eastern parts of the Eastern Alps is a recent process. This is consistent with the Oligocene Augenstein surface on top of the Northern Calcareous Alps, a relic of a low-gradient topography coined by fluvial sedimentation (Frisch et al., 2001). Cretaceous to Eocene fission track ages in the Eastern Alps (e.g., Hejl, 1997) indicate that the amount of exhumation since this time was small, although recent rivers in the Eastern Alps are characterized by significant erosion rates (Robl et al., 2008a). This implies that much of the present-day topography may be a young feature and that the formation of topography was accelerated by the last inversion of the stress field (Genser et al., 2007) from extension to compression. In summary, our study has shown that Miocene horizontal extension at the position of the Tauern Window mechanically requires the simultaneous activity of orogen-scale strike-slip faults and a subduction rollback in the Pannonian Basin.

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