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# The interplay between subduction and lateral extrusion: A case study for the European Eastern Alps based on analogue models

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ABSTRACT

A series of analogue experiments simulating intra-continental subduction contemporaneous with lateral extrusion of the upper plate are performed to study the interference between these two processes at crustal levels and in the lithospheric mantle. The models demonstrate that intra-continental subduction and coeval lateral extrusion of the upper plate are compatible processes leading to similar deformation structures within the extruding region as compared to the classical setup, lithosphere-scale indentation. Strong coupling across the subduction boundary allows for the transfer of stresses to the upper plate, where strain regimes are characterized by crustal thickening near a confined margin and dominated by lateral displacement of material near a weak lateral confinement. The strain regimes propagate laterally during ongoing convergence creating an area of overlap characterized by transpression. When subduction is oblique to the convergence direction, the upper plate is less deformed and as a consequence the amount of lateral extrusion decreases. In addition, strain is partitioned along the oblique plate boundary resulting in less subduction in expense of right lateral displacement close to the weak lateral confinement. Both oblique and orthogonal subduction models have a strong resemblance to lateral extrusion tectonics of the Eastern Alps (Europe), where subduction of the adjacent Adriatic plate beneath the Eastern Alps is debated. Our results imply that subduction of Adria is a valid mechanisms to induce extrusion-type deformation within the Eastern Alps lithosphere. Furthermore, our findings suggest that the Oligocene to Late Miocene structural evolution of the Eastern Alps reflects a phase of oblique subduction followed by a later stage of orthogonal subduction conform a Miocene shift in the plate motion of Adria. Oblique subduction also provides a viable mechanism to explain the rapid decrease in slab length of the Adriatic plate beneath the Eastern Alps towards the Pannonian Basin.

## 1. Introduction

Lateral extrusion entails the combined effects of tectonic escape and gravitational collapse of a weak orogenic wedge in response to indentation under conditions of an unconstrained (mechanically weak) lateral boundary (Ratschbacher et al., 1991a). This process results in the escape of crustal blocks along conjugate strike-slip faults towards a weak boundary (i.e. a coevally extending region) oriented at a high angle to the convergence direction. The Eastern Alps (Europe), Tibetan Plateau, and the Anatolian Plateau, for instance (Fig. 1a), have been subjected to this process with variable contributions of the collapse component (e.g., McKenzie, 1972; Ratschbacher et al., 1991a; Tapponnier et al., 1986).

Previous numerical and analogue modelling studies yielded valuable insights in the parameter space favoring escape and extrusion tectonics. These studies have shown that a weak lateral boundary is a pre-requisite for lateral extrusion to occur (Davy and Cobbold, 1988; Faccenna et al., 1996) and that the indenter only needs to be moderately strong in comparison to the indented region (Robl and Stüwe, 2005; Willingshofer et al., 2005). Other important parameters influencing the extrusion process and the resulting deformation geometries are the shape of the indenter, the convergence direction or the width and rheological variations of the indented region (e.g., Ratschbacher et al., 1991b; Rosenberg et al., 2007; Sokoutis et al., 2000).

The Eastern Alps in Europe (Fig. 1b) is one of the key examples for the study of lateral extrusion tectonics (e.g., Frisch et al., 2000; Ratschbacher et al., 1991a; Wölfler et al., 2011). There, extrusion is driven by Miocene northward indentation of the Eastern Alps lithosphere by the Adriatic microplate, which occurred simultaneously with the opening of the Pannonian Basin in the east (e.g.,

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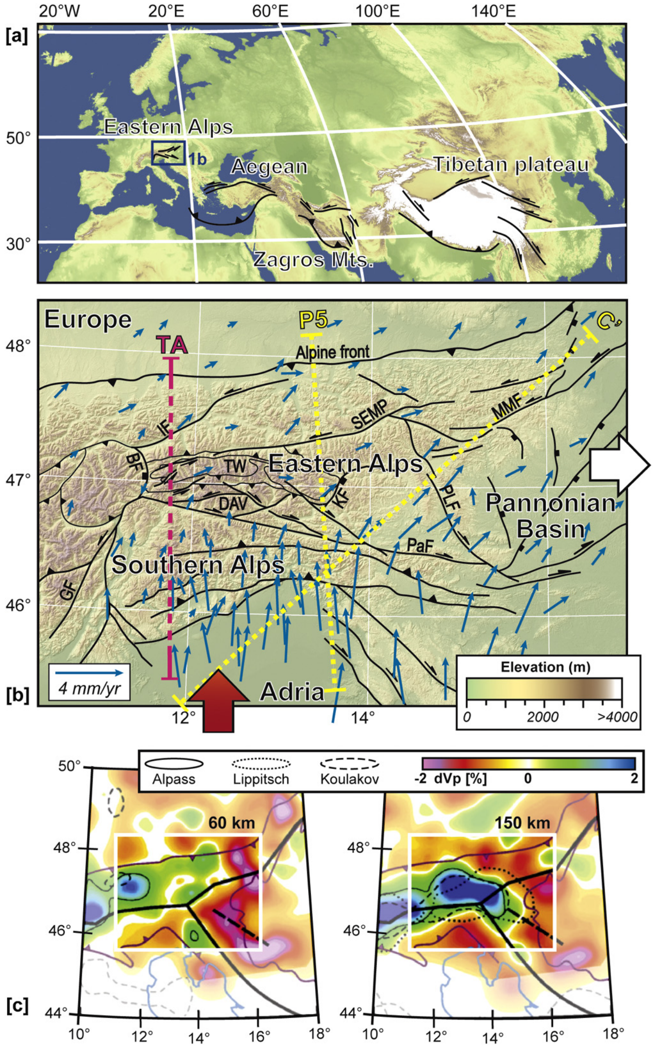

**Fig. 1.** **[a]** Topographic map showing the various regions that are affected by lateral extrusion coeval with subduction or indentation. The blue box outlines the area shown in Fig. 1b, **[b]** The elevation map of the Eastern Alps overlain by the major faults and structures associated with lateral extrusion in the Eastern Alps (modified after; Ratschbacher et al., 1991a; Schmid et al., 2004). The white arrow indicates the average direction of Pannonian back-arc extension and the red arrow indicates the direction of indentation or subduction of the Adriatic plate. The yellow dashed lines shows the location of the tomographic sections presented in Fig. 7c and the pink line show the location of the TranALP (*TA*) seismic section (Figs. 7a and b). The scaled blue arrow represent the present day GPS displacements extracted from Metois et al. (2015). **[c]** Two tomographic slices at 60 and 150 km depth by Mitterbauer et al. (2011). The highlighted area coincides with the map in Fig. 1b and the slices also show the tomographic interpretations of the area according to Lippitsch et al. (2003); Koulakov et al. (2009); Mitterbauer et al. (2011). *Abbreviations: Mur–Mürz fault* (*MMF*), *Peradriatic fault* (*PaF*), *Guidicarie fault* (*GF*), *Defereggen–Antholz–Vals fault* (*DAV*), *Pöls–Lavanttal fault* (*PLF*), *Salzach–Ennstal–Mariazell–Puchberg fault* (*SEMP*), *Brenner fault* (*BF*), *Katschberg fault* (*KF*), *Inntal fault* (*IF*), *Vienna Basin* (*VB*).

Ratschbacher et al., 1991a). The latter is related to the Carpathian slab roll-back and created the space needed for the extruding crustal blocks. Within this tectonic frame the Adriatic plate is traditionally considered as a semi-rigid indenter (Ratschbacher et al., 1991a) and marks the southern border of the weak Eastern Alps lithosphere, which is bounded to the north by the strong European lithosphere (Fig. 1b). Controversially, high-resolution teleseismic tomography as interpreted by Lippitsch et al. (2003) suggests that the Adriatic plate is not a lithosphere-scale bulldozer pushing against the Alps but has been subducting beneath the extruding Eastern Alps since about 30 Ma (Handy et al., 2015). Although interpretations of tomographic data differ (see discussion in Mitterbauer et al., 2011) (Fig. 1c), these findings raise first order questions such as: (a) how deformation is partitioned between the laterally extruding upper plate and the subducting lower plate, (b) what is the role of upper and lower plate rheology and geometry, and (c) what mechanisms control the upper plate deformation. These questions are not only relevant for the Eastern Alps but also the Tibetan Plateau, the Anatolian Plateau or the Zagros Mountains (Fig. 1a), where lateral extrusion occurs in the upper plate of a subducting continental plate.

We present results of a physical analogue modeling study that for the first time embarks on the interplay between intra-plate subduction and lateral extrusion processes, assessing the sensitivity of upper plate extrusion-type deformation in response to orthogonal and oblique continental subduction. The modelling results are primarily compared to the structural evolution of the Eastern Alps, where the extracted interferences contribute to the debate of indention versus subduction of the Adriatic plate.

## 2. Experimental approach

We present lithosphere-scale physical analogue modelling results in which we compare the results of a classical indentation-extrusion scenario with that of a combined subduction–extrusion setting with the plate geometry as an additional variable. The experiments have been designed to allow for a first-order comparison with the Eastern Alps, but are from a conceptual point of view also applicable to other regions affected by lateral extrusion coeval to indentation or subduction, such as Tibet or the Aegean.

### 2.1. Experimental set-up and rheology

The setup of the experiments (Fig. 2) incorporates continental collision perpendicular to a weak lateral confinement, where continental collision is either activated by: a) indentation (experiment 1), or b) subduction (experiments 2 and 3). The weak lateral confinement mimics the opening of the Pannonian Basin and facilitates flow of the lower crust and upper mantle of the indented region perpendicular to the convergence direction.

For the weak lateral confinement we used a low viscosity and low density silicon putty (Table 1), which is placed along the entire length of the model. Initially the weak confinement is fixated during model build-up by a 5 cm broad wooden block to prevent flow of the material. At the start of the model run the fixation is removed creating an open space that allows for the weak confinement to flow (spread) freely onto the experimental asthenosphere, thereby provoking orogen parallel extension of the upper plate (see also movies 1–3). The orogen parallel elongation coupled to coeval indentation or subduction ultimately leads to laterally extruding lithospheric material, perpendicular to the direction of shortening.

In all experiments the modeled continental lithospheres consist of a brittle upper crust, a ductile lower crust and a ductile upper mantle. Strength calculations of Willingshofer and Cloetingh (2003) suggest that the Eastern Alps lithosphere is weak in comparison to the subducting or indenting Adriatic lithosphere. This strength contrast along with the approximate crustal thicknesses obtained from the TRANSALP seismic profile (TRANSALP Working Group, 2002, see also Fig. 7b) are used to constrain the initial model setup. Note that instead of using a rigid indenter (Ratschbacher et al., 1991b; Rosenberg et al., 2007) we deploy a system where the indenter and the subducting plates have a pre-defined rheological stratification (Fig. 2) and are pushed against the deformable region through the advancement of an automated moving wall. In all experiments the rate and amount of convergence was the same, namely 1 cm/h with a total of 8 cm of shortening. The velocity