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Does subduction polarity changes below the Alps? Inferences from analogue modelling

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ABSTRACT

The surface expression of a lateral polarity change of continental mantle lithosphere subduction has been studied by using lithosphere-scale physical models. Key parameters investigated were: the degree of lateral coupling between adjacent domains of opposing subduction polarity, the width of the zone separating the domains, and the lithosphere geometry and rheology. The model results illustrate an asymmetric lithospheric structure induced by deformation of the downgoing plates, which have been separated by a narrow transition zone. A wide and symmetric orogenic wedge overlying a region of thickened mantle lithosphere and hampered subduction characterizes this transition zone. In addition, interaction between the neighboring subduction domains caused downbending of the upper plates and resulted in the lateral termination of crustal structures and lowering of surface topography. The lateral extent of interaction between the domains strongly depends on the degree of coupling between the domains, the rheology of the mantle lithosphere and the amount of bulk shortening. The modelling results have major implications on the interpretation of seismic and tomographic data from the European Alps in terms of the crust and lithosphere geometries. It appears that an observed lateral change of subduction polarity at mantle depth can explain the variations of wedge build-up between the Western/Central and Eastern Alps.

1. Introduction

Many orogens display along-strike variations in terms of orogenic wedge geometry, the amount of shortening and/or surface uplift patterns, emphasizing that mountain building should be considered a three dimensional process. The European Alps is a good example of an orogen which contains several well studied along-strike variations. Some lateral changes are directly accessible, while others are hidden at greater depth. Examples of the former include cooling ages or exhumation patterns (e.g. Grundmann and Morteani, 1985; Hejl, 1997; Luth and Willingshofer, 2008; Rosenberg and Berger, 2009), variations in (paleo-) topography (e.g. Dunkl et al., 2005; Frisch et al., 1998; Kuhlemann, 2007; Willett et al., 2006), or the termination of tectonic units like the Austroalpine unit in the eastern Central Alps (e.g. Froitzheim et al., 1994) (Fig. 1). Additionally, the structural style varies along-strike, such as a significant amount of back-thrusting in the Central Alps versus little back-thrusting, but prominent strike-slip faulting in the Eastern Alps (e.g. Handy et al., 2005; Mancktelow et al., 2001; Ratschbacher et al., 1991). On a larger scale, the Western- and Central Alps are characterized by relatively large pro-wedges overlying the downgoing European plate and relatively narrow retro-wedges (see Fig. 3a–c in Schmid et al., 2004). In contrast, within the Eastern Alps crustal deformation is more symmetrically distributed above the colliding plates and the orogen widens reaching a maximum width along the TRANSALP profile (Figs. 1 and 11). At lower crustal levels, wedging of Adriatic lower crust has been interpreted below the Central Alps, whereas in different interpretations of the TRANSALP transect lower crustal wedging diminishes or even vanishes below the Eastern Alps (Schmid et al., 2004).

At the level of the lithospheric mantle along-strike variation in terms of a switch in subduction polarity is under debate. High resolution teleseismic tomography (Lippitsch et al., 2003) revealed southeast directed subduction of the European mantle lithosphere below the Central Alps, but a northeast dipping subduction of the Adriatic mantle lithosphere underneath the Eastern Alps (Kissling et al., 2006; Lippitsch et al., 2003) (Fig. 2). A recent tomography study (Mitterbauer et al., 2011) from the Alps and the transition to the Pannonian Basin and the Dinaric mountain chain confirmed the findings of Lippitsch et al. (2003) but differs in the interpretation of the *P wave* velocity structure. These authors interpreted the imaged *P wave* anomalies under the Eastern Alps as the subducted European lower lithosphere. In addition, oppositely dipping slabs were not derived from extensive studies of the surface geology, possibly because little is known about how lateral variations of deep lithospheric

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processes influence the crustal architecture of mountain belts. In this study we therefore investigate the surface expression of a lateral change in subduction polarity of continental mantle lithosphere through lithosphere-scale analogue modelling. Key to this study is linking mantle dynamics to deformation at crustal levels and the surface.

Lithosphere-scale analogue modelling convincingly proved to be a convenient tool investigating complex 3D geometries arising from plate convergence (e.g. Boutelier and Oncken, 2011; Davy and Cobbold, 1991; Funiciello et al., 2003; Luth et al., 2010; Regard et al., 2008; Schellart et al., 2003; Sokoutis and Willingshofer, 2011; Willingshofer and Sokoutis, 2009). In our approach special focus has been put on the crustal wedge geometry and topography, and how these might be affected by the interaction between neighboring subduction domains. The main parameters investigated were (i) the degree of lateral coupling between the domains of opposing subduction polarity, (ii) the lateral width between these domains, and (iii) the obliquity between the domains with respect to the direction of shortening. In addition, the role of vertical decoupling on crust–mantle interaction was studied by implementing a weak lower crust in both plates. Consequently, crustal deformation within the collision zone is hypothetically less influenced by deformation processes in the underlying mantle lithosphere and thus subduction polarity. Finally, implications of our modelling results for the interpretation of the lithosphere structure of the Alps are elaborated.

2. Experimental design

The rheological stratification of the modeled lithosphere comprised ductile mantle lithosphere as well as lower crust and a brittle deforming upper crust. A fluid mixture of polytungstate and glycerol represented the asthenosphere while the lithosphere was composed of strong silicon putty, weak silicon putty, and feldspar sand, respectively. In order to initiate subduction of the mantle lithosphere a 45° inclined weak zone was implemented in the mantle lithosphere similar to experiments presented in Luth et al. (2010). Plate decoupling along the weak zone was stimulated by its low viscosity differing one order of magnitude from the silicone layers constituting regular lithosphere. Dynamic and geometric scaling between model and nature was achieved by respecting the stress-scale factor:

$$\sigma^* = \rho^* g^* L^* \qquad (1)$$

where σ refers to stress, ρ to density, g to gravitational acceleration and L to the length scale. The asterisk refers to the ratio between model and nature. Considering the physical properties of the used materials and assumed values for their equivalents in nature we obtain a stress ratio of 3.3×10^{-7}, which implies a geometric scaling of 1 cm in the model to 30 km in nature. Balancing of dynamical similarities of the ductile layers involved calculation of the Ramberg number (R_m) (Weijermars and Schmeling, 1986), which represents the ratio of gravitational to viscous forces:

$$R_m = \frac{\rho g h^2}{\eta V} \qquad (2)$$

where h, η, and V are the ductile layer thickness, the viscosity, and the shortening rate, respectively.

Details on material properties and scaling parameters are described in Table 1. A lateral change of subduction polarity was implemented by juxtaposition of two domains with opposing predefined subduction directions (Fig. 3). Additionally, in experiment 1 the subduction domains were separated at mantle and lower crustal levels by a 5 mm thick weak zone (Fig. 3). Such a weak zone was absent in all the other experiments promoting strong coupling between the subduction domains (e.g. experiment 2). In experiment 3, the role of obliquity on lateral interaction and surface deformation was modeled by placing one of the two predefined plate boundary at a 60° angle with respect to the shortening direction (Fig. 3). Experiment 4 aimed for studying the effect of weak lower crust in combination with a lateral change in subduction polarity on crustal deformation. Low viscosity lower crust was implemented in both upper- and lower plates. In experiment 5, the subduction domains, with solely weak lower crust in the lower plates, were intervened by a 6 cm wide zone in where no weak plate interface existed. All experiments where shortened by a single moving wall at a constant rate of 0.5 cm/h, which scales to convergent rates of 0.5 cm/year in nature. During the experiment, top view pictures and 3D scans monitored the development of structures and topography.

3. Experimental results

3.1. Decoupled subduction domains (experiment 1)

Initial deformation produced a symmetric pop-up above the entire length of the plate interface, regardless of the predefined subduction polarity in the mantle lithosphere (Fig. 4a). Fore-thrusts (e.g. nr. 1) that verged towards the lower plates formed slightly earlier than back thrusts. Around 5% BS (bulk shortening), a second pop-up formed on the lower plates, which terminated laterally at the transition zone between the opposing subduction domains. From this moment onward a surface expression of the imposed subduction polarity at depth existed as further shortening localized along fore-thrusts of a second pop-up on the sides of the subducting plates. Meanwhile back-thrusting remained localized along the first pop-up. Hence, shortening was accommodated along the wedge margins with not much shortening between the pop-ups. From 15% BS onwards, the formation of new structures was limited to the transition zone. In here, small thrusts sprouted laterally from the lower plate and then crossed the transition zone towards the upper plates. With ongoing shortening these thrusts propagated further onto the upper plates.

During the early stage of shortening, topography development was limited to the plate boundaries and was associated with the first thrusts (Fig. 4a). From 10% BS onwards, topographic gradients developed along-strike of the orogen such that high elevations, which probably resulted from back-thrusting, bounded the low elevation of the transition zone. From 15% BS onwards, uplift mainly localized along the second pop-up, which significantly reduced towards the lateral overriding plates. Hence, surface relief within the transition zone was characterized by a lateral termination of pro-wedge associated topography. During the final stage (19% BS) wedge topography modestly increased, meanwhile the interiors of the pushed plates adjacent to the moving wall were slightly uplifted.

Comparing cross-sections, the geometry of the collision zone varies laterally (Fig. 4b). In profile 1 the amount of lithosphere subduction is high when compared with profiles through the center of the model. At crustal level two asymmetric pop-ups formed a symmetric wedge, which was thrusted onto both plates and was underlain by weak lower crust. Towards the transition zone the amount of mantle lithosphere subduction reduced and the upper plate descended more towards the plate boundary (compare profiles 1 and 2). In here, the mantle lithosphere of both plates slightly thickened. The overall symmetric upper crustal wedge was widened as small thrusts appeared on the upper plate as well. Note that these small thrusts root within strong lower crust. Profile 3 crosses through the predefined domain boundary and thus discloses weak silicon putty. Although no subduction polarity was initially predetermined within the domain boundary, a small slab dipped towards the moving wall. Upper crustal deformation resulted in a wide and symmetric collision zone comprising three pop-ups divided onto both plates. In profile 4, subduction polarity reversed showing a mirrored pattern