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HOW RHEOLOGY CONTRASTS CONTROL PLATE SCALE DEFORMATION: A FEM STUDY FROM THE EASTERN ALPS

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The process of a continent-continent collision is generally described with an indentation geometry: A rigid indenter is assumed to deform a significantly weaker plate. The crust in front of the indenter is thickened and forms an orogen while the indenter itself remains unaffected by the large scale deformation. This scenario is well explored by analogue- (e.g. Tapponier et al., 1982) and numerical models (e.g. England and Houseman, 1986) and has been successful in describing the India-Asia collision zone where most of the deformation is indeed partitioned into the Asian plate.

In contrast, many orogens show that substantial deformation occurs in both plates involved with the collision process. For example, in the European Alps, the Adriatic micro-plate indents the European foreland, but both plates are highly deformed. In fact, most of the seismicity in the Alpine orogen currently occurs within the Adriatic micro-plate. In two dimensions, this deformation partitioning between plates can be well-described on cross sections by employing asymmetric boundary conditions at the base (e.g. Beaumont et al., 1996). However, in plan-view, partitioning of deformation between two colliding plates can only be described by assuming a finite rheology contrast between the two plates involved. Here we present an extension of the classic thin viscous sheet model for continental collision (England and McKenzie, 1982; England and Houseman, 1986) in which we explore the influence of finite rheology contrast between indenter and foreland on the deformation partitioning. A somewhat more refined model is then applied to explore the rheology of the Adriatic micro-plate in the European Alps.

Model setup

The simple numerical model expands on the "elongate model geometry" of Houseman and England (1986). We use the finite element model of Barr and Houseman (1996) to describe thin viscous sheet deformation. A quadratic region with a dimensionless side length 1 is considered (Figure 1a). The indenter is a block of length 0.25 and variable width *w*, initially located in the center of the southern boundary of the model region. The southern boundary is moving north with the velocity U_0 over the width of the indenting block and tapers to zero outside the indenter.

In order to apply this model to the Alps we have refrained from finite strain calculations and focused on describing the present day deformation regime with incremental calculations. For this we have made the following changes to the model: (1) Potential energy was interpolated onto the finite element mesh using a filtered digital elevation model for the Alps and assuming that potential energy is directly related to topography. (2) Thin viscous sheet calculations were performed in spherical coordinates. (3) A number of regions of finite viscosity contrasts were implemented to describe realistic geological units (Figure 2b). For this a general triangulation routine was used.

Numerical model results

Within our simple model, four parameters play an important role in the deformation partitioning between the two plates. The width of the indenter *w*, the viscosity contrast between indenter and foreland , the Argand number *Ar*, and the non-linearity of viscous deformation as described by the power law exponent *n* . Figure 1b explores this parameter

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space for three pairs of *Ar* and *n* suggested to cover a characteristic range of geological settings by Houseman and England (1986). The curves shown in Figure 1b show the lines where the maximum thickening in the indenter is equal to that of the foreland. In general, crustal thickening dominates in the indenter for large *w* and small , while crustal thickening dominates in the foreland if the indenter is small and strong. For *w* = 0 the model is equivalent to that of Houseman and England (1986) and can be compared directly with their results. For a viscosity contrast of . = 3 and an indenter width of 0.15, thickening in the indenter is the same as that in the foreland and is robust towards power law exponent and Argand number.

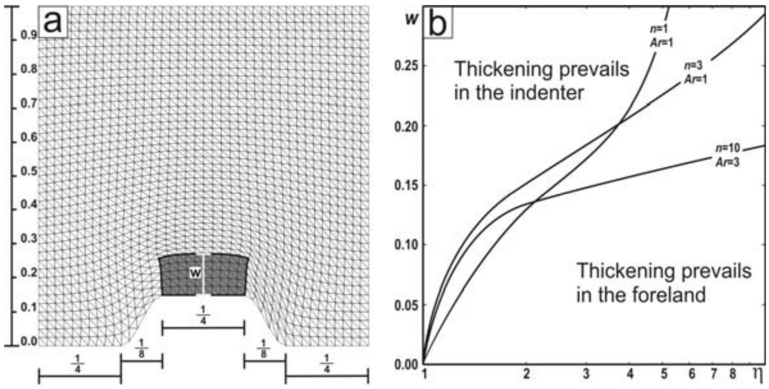

Fig. 1 Simple numerical model for the exploration of the role of indenter rheology in deformation partitioning between two plates. (a) Model set up. The dark shaded region is referred to as the "indenter", the light triangulated region as the "foreland". (b) The contours delineate the parameter space where the maximum thickening in both the indenter and the foreland are equal. . is the viscosity contrast between indenter and foreland. w is the width of the indenter. Note the logarithmic scale of the viscosity contrast.

Application to the Alps

A refined model was used to explore the indenter rheology in the Alpine orogen. For this, the region limits in the north and east were set in the aseismic European foreland and were ascribed zero velocity boundary conditions. The western boundary was placed in the central Alps where we assume symmetry of deformation across the boundary. The southern boundary is defined by zero stress and zero velocity except the boundary segment where the Adriatic plate indents into the orogenic wedge. This segment is described by an increasing north directed velocity from west to east, according to the Euler pole of the Adriatic plate at 45.36°N 9.10°E and a counterclockwise angular velocity at 0.52°/my (Nocquet and Calais, 2003). Over a width of 2° a $\cos^2$ function tapers the velocity smoothly down to zero at the eastern edge of the indenter (Figure 2a).

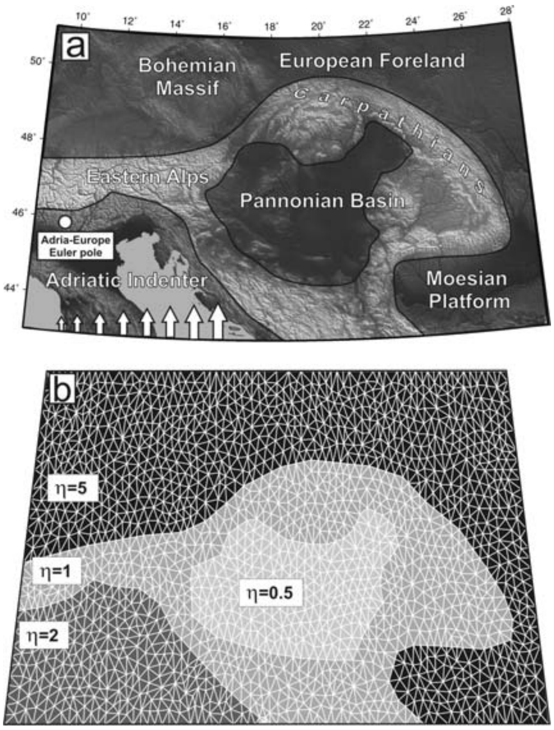

Fig. 2 Numerical model used to explore the rheology contrast between Adriatic plate and Alpine orogen. (a) Model region and boundary conditions. The arrows along the southern margin indicate the eastwards increase in north velocity. (b) Finite element grid used for the model calculations. Viscosity contrasts are labelled.

Within the modeled region we assumed 4 regions of different viscous rheology (Figure 2a). The European foreland including the Bohemian massif shows only minor internal deformation and is therefore defined arbitrarily to be 5 times more viscous than the Eastern Alps. Similarly, we assume that the lithosphere in the Pannonian basin is thin and warm and ascribe it a viscosity contrast of 0.5. The rheology of the Adriatic indenter plays a crucial role for the collision process and we explore this parameter in some detail.

Model results that match the intraplate stress field, the seismicity distribution and the GPS-determined velocity field suggest that the Adriatic indenter is 1.5 to 3 times as viscous as the Eastern Alps. While this estimate is very preliminary in our work, it is consistent with cross sectional models along the TRANSALPS profile by Willingshofer and Cloetingh (2003).

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