DEFORM – Deformation patterns in relation to the deep configuration of the lithosphere of the Alps and their forelands

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Present-day surface deformation in the Alps in terms of uplift and crustal seismicity has been attributed to surface (i.e., climatic) and tectonic processes (i.e., subduction, slab detachment/break-off, mantle flow). Quantifying the relative contribution of these forces and their interplay is fundamental to understand their role in mountain building. The present-day 3D configuration of the lithosphere and upper-mantle is a prerequisite to assess the contribution of tectonic processes.

In the first phase of 4D-MB, INTEGRATE project produced a multidisciplinary data-integrated crustal model of the Alps and its forelands (Spooner et al., 2019, 2020, 2022). In the follow-up project DEFORM, we use these results to quantify how the active forces originating from the internal heterogeneity in the lithosphere and upper-mantle (i.e., lithospheric thickness and slabs in the asthenosphere) can provide some insights into the present-day mechanical set-up of the study area. To objectively interpret the upper-mantle configuration, we convert the results of regional shear-wave tomography models to temperature using an in-house developed tool (Kumar, 2022) based on Gibbs-free energy minimization algorithm (Connolly, 2005). Our results showcase a shallow/attached slab in the Northern Apennines as a common feature in the different tomography models, as also consistent with recent AlpArray seismic data-derived tomography models. They also highlight some differences among the different tomography models beneath the Alps. We quantitatively address these differences by statistically clustering tomography models into three end-members corresponding to the mean and 67% confidence intervals. These end-member models represent scenarios ranging from shallow/attached slabs to almost no slabs in the northern Apennines and Alps.

End-member scenarios of the mantle configuration are tested with the new pan-Alpine gravity anomaly by 3D density modelling (IGMAS+, Götze et al., 2023), surface uplift from GNSS, AlpArray seismicity catalogue, mantle flow inferred from the shear-wave splitting measurements of the AlpArray seismic experiment, and resulting topography. As a first step, we model topography and deformation velocities as resulting from buoyancy-forces driven by a quasi-instantaneous flow resulting from the first-order rheological structure of the lithosphere-asthenosphere system using the open-source geodynamic simulator LaMEM (Kaus et al., 2016). We found that detached slab beneath the Alps, but attached beneath the Northern Apennines captures first-order patterns in topography, vertical surface velocities, and mantle flow (Kumar et al., 2022). The presence of an attached slab beneath the northern Apennines can also explain the observed sub-crustal seismicity compared to the upper-crustal seismicity in the Alps.

Data-derived scenario-based modelling approach allowed us to capture the first-order characteristics of the lithosphere and upper-mantle configuration in the Alps and corresponding forelands. Although we have been able to explain first-order observations with respect to the end member variations in viscosity and density contrasts, we additionally carried out a global sensitivity analysis to quantify associated uncertainties as well as the degree of parameter correlation within a solid density-effective viscosity phase space. This was done using physics-preserving surrogate models (model order reduction via reduced basis, Degen et al., 2022) to effectively run ensemble models of the dynamic state of the system (Denise et al., 2023). Using surrogate models, we explore deformation velocities and stresses, guiding boundary conditions to reconstruct the loading/unloading history of the last glacial cycle.

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