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3D Modelling and Retrodeformation of the Western Helvetics: Insights from the swissAlps 3D Project

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3D geological modelling is an essential tool for visualization, interpretation and retrodeformation of orogenic systems. Cross-sections restoration allows improved correlations between present-day structures and their paleogeographic evolution. Despite such advantages, accurately representing polydeformed orogenic belts remains challenging due to their structural complexity, large spatial extent, and multiphase tectonic histories.

To address these challenges, the swisstopo-funded swissAlps 3D (SA3D) project (2024–2030) aims to develop a consistent, large-scale 3D geological model of the major lithostratigraphic and structural boundaries of the Swiss Alpine region. As part of SA3D, the Helvetics 3D (HL3D) project focuses on the 3D reconstruction of the Swiss Helvetic domain. This work focuses specifically on the 3D geometry of the External Crystalline Massifs (ECM), from the Aar Massif to the Aiguilles Rouges–Mont Blanc massifs and the overlaying Helvetic nappe stack.

The Helvetic nappes overlying the ECM – composed of allochthonous Mesozoic marine limestones, marls, shales, and sandstones – experienced multiple deformation phases from ~39 Ma to the present (Burkhard, 1988). These events produced complex structural geometries, including recumbent and isoclinal folds and major thrust systems, making the Helvetic domain a key natural laboratory for verifying and reconstructing 3D geological structures.

The elaborated 3D model is based on 2D geological datasets, interpreted and re-validated cross-sections, borehole data, other published 3D geological models, and geophysical datasets. Except for the Aar Massif (Musso Piantelli et al. 2026), most of the Helvetic realm is characterized by limited subsurface constraints, with sparse borehole information, seismic profiles, and mainly geological cross-sections. To address this limitation, we developed a workflow combining explicit and implicit 3D modelling techniques, preserving the accuracy of detailed geological observations while increasing modelling efficiency.

Here, we present the preliminary results from the HL3D project, illustrating the 3D modelling of the ECMs in the westernmost Swiss Helvetic domain and their progressive retrodeformation from the present-day configuration back to the Miocene Grindelwald deformation phase (Handegg, Oberaar, and Pfaffenhopf phases; Herwegh et al., 2023). The 3D geometry of this area indicates the ECMs as elongated domes, with the long axes of the Aiguilles Rouges/Mont-Blanc and Aar/Gastern massifs respectively, plunging to the ENE and WSW. Their histories characterized by differential uplift, combined with an a-cylindrical and en-echelon arrangement of the basement units, affected the overlaying Helvetic nappe stack, and continues to control large-scale structures such as the Rawil depression.

The retrodeformation of this Miocene uplift shows that the Rawil depression formed in response to the inversion of a complex paleogeographic geometry of the former European passive margin during late-stage collision between the Adriatic and European plates. In this context, the ECMs and the overlying nappe stack experienced an uplift exceeding 8 km (Herwegh et al., 2023; Mercier et al., 2023).

In summary, this first HL3D model and its retrodeformation (i) provides new insights into the geometry and structural evolution of the western ECM, (ii) demonstrates the necessity and strength of 3D modelling in unravelling Alpine complex tectonic evolution, and (iii) reveals the initial extent and paleogeographic configuration of the central part of the European passive continental margin.