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The Structural Topology model: integrating topology and ontology in 3D geological modelling

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Three-dimensional geological modelling is increasingly used to analyze and investigate the geological evolution of complex areas, offering advantages over classical 2D maps and cross-sections, to test and validate geometries and structural (topological) relationships against sparse field data.

Within this context, 3D modelling in polymetamorphic belts poses different challenges, first the absence of formally defined stratigraphic surfaces that are transposed and cancelled by multi-stage tectono-metamorphic events. Alternative tectonostratigraphic or tectonometamorphic units are used when mapping in these environments, but the non-formal definition of these units and of their boundaries can lead to topological ambiguities and even inconsistencies in geological legends, that in turn lead to geo-ontological deficiencies in the modelling process – i.e. deficiencies in the explicit and formal shared conceptualization of the geological meaning and role assigned to units and boundaries.

To address these issues, it is essential to explicitly integrate topological and ontological reasoning into the modelling workflow, building a consistent geological legend, in order to generate valid 3D models both in implicit and explicit modelling approaches.

Here, we present the Structural Topology model (STm), a workflow grounded in classical structural geology's thinking and field mapping knowledge, which systematically analyses scale-dependent topological relationships between surfaces and volumes to reconstruct a geologically valid and internally consistent 3D legend based on the concept of a generalized structural polarity. This is a vector that, depending on the geological environment and modelling purpose, can be defined as the younging direction (when relative or absolute ages are available), but also structural position with respect to some convenient reference, and cross-cutting relationships allowing to constrain a sequence of geological events. In this framework, units are classified as tectonometamorphic (TMU), tectonostratigraphic (TSU), stratigraphic (SU), intrusive (IU), or shear zone (SZ) according to their origin and evolution. Their boundaries may be conformal to the main foliation (in the broadest sense, including bedding) or discordant, e.g. at some tectonic contacts, shear zones and

unconformities.

The formal definition of units with internal polarity, conformal vs. discordant boundaries with polarity, and cross-cutting relationships, allow connecting geological ontology with a topological model that can be implemented in a 3D model. In addition, properly defining polarity for each model entity allows using implicit surface methods (that operate by interpolating a scalar field whose gradient is the polarity) at each stage of the modelling workflow.

Here we present an implementation of the STm within the PZero open-source software (<https://github.com/gecos-lab/PZero>), including a lightweight graphical interface that enables the construction of STm-based geological legends from a Polarigram, where units are plotted against polarity. Examples from complex polymetamorphic areas in the Alps demonstrate that geological topology can be robustly defined even when geological ontology remains ambiguous and scale-dependent, providing a consistent foundation for 3D geological modelling.