



The Structural Topology Model: A Topology–Ontology Framework for Assigning Geological Legends in 3D and 2D Geomodelling

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Abstract. Three-dimensional geological modelling of orogenic belts and other highly deformed complexes remains challenging, especially in metamorphic complexes, where the obliteration of stratigraphy complicates the definition of units, boundaries, and their relations. In such contexts, approaches inherited from modelling in sedimentary basins often lead to ambiguous definition of the legend (and the units represented therein) and topologically inconsistent 3D models. Here, we present the Structural Topology Model (STM), a conceptual framework designed to formalise the construction of consistent geological legends by making explicit the relations between units, bounding surfaces, and their structural roles, according to the concept of oriented topology (based on the properties of continuity and conformability). Central to STM is the concept of the Structural Level, which integrates absolute ages, relative ages, and structural relations into a scalar field used to define an ordered sequence of geological units and events, even where chronological constraints are incomplete or ambiguous. STM was conceived for 3D modelling, but it could be applied also in 2D to geological maps and cross-section providing useful constraints and tools to validate topological relationships and conceptual models. The method is illustrated with two case studies in the Helvetic units of the Aar Massif (Helvetics, Central Swiss Alps) and in Penninic units of the Gressoney Valley (Western Italian Alps). In both examples, STM enables the construction of topologically consistent volumetric models that preserve internal structures, foliation patterns, and cross-cutting relationships, while providing an unambiguous framework for labelling units and boundaries. STM, already implemented in the open-source PZero 3D modelling platform, is independent of specific software implementations or interpolation techniques and could be potentially applied in a wide range of geological settings and software. In this way, limitations of implicit 3D modelling in complex polydeformed areas are reduced substantially.



1 Introduction

30 3D geological modelling techniques have seen a constant development since the early '90s, thanks to a concurrent development of hardware and software (Mallet, 1988, 1997, 2002). Originally their applications were focused on oil and gas reservoirs (Gartrell et al., 2004; Power et al., 2001), mining (Sides, 1997; Vollgger et al., 2015; Wang et al., 2018), underground repositories and research facilities (Schneeberger et al., 2017, 2018) and in some case on geothermal exploration (e.g. Witter and Phillips, 2012). This range of applications reflects the high capital intensity of these industries, where the financial value
35 of subsurface targets justifies substantial investment in 3D/4D data acquisition and analysis, and therefore in software and hardware (Hartman and Mutmanský, 2002; Jahn et al., 2008). More recently, 3D modelling is becoming common in many other fields of geology, thanks to cheap high-performance 3D graphics hardware, new techniques and algorithms that are constantly under development, sustained both by specialised software houses but also by a growing community of open-source developers (de la Varga et al., 2019; Bistacchi et al., 2021; Grose et al., 2021; Lyu et al., 2021; Hillier et al., 2023; Malard et al., 2023; Monti et al., 2024; Kamath et al., 2026). These applications now routinely include geothermal projects (Guglielmetti et al., 2013; Milicich et al., 2014), nuclear waste repositories (Bossart et al., 2017), civil or industrial underground facilities (Bistacchi et al., 2008; Xiong et al., 2018), and fluid reservoirs in the framework of the energy transition (Kaufmann and Martin, 2008; Vo Thanh et al., 2019). The diffusion and improvement of 3D geomodelling technologies has also suggested an
45 increasing number of national geological survey agencies the possibility to complement the classic 2D map representation with 3D models of the surface and sub-surface geology (Maxelon and Mancktelow, 2005; Baumberger et al., 2022; Musso Piantelli et al., 2022; Pizzella et al., 2022; Arienti et al., 2024; Dal Piaz et al., 2025a, b; Lopez et al., 2025), with the long-term goal to help managing – in synergy with other geosciences experts – geological hazard, water and geothermal resources, mineral deposits, and subsurface storage applications (Kaufmann and Martin, 2008).

As 3D geological models are increasingly used to support geological interpretation and decision-making, assessing and
50 communicating their reliability becomes increasingly important. Any 3D geological model represents an interpretation of incomplete and spatially heterogeneous geological information and is therefore inherently affected by uncertainty. Such uncertainty may involve both uncertainties associated with input data and model geometry, and those related to alternative geological interpretations or modelling scenarios (Wellmann et al., 2010; Wellmann and Regenauer-Lieb, 2012; Schneeberger et al., 2017; Baumberger et al., 2022). The explicit representation of geological knowledge and of the assumptions underlying
55 a model is therefore an important component of model evaluation and comparison.

The traditional paradigm used to represent geological bodies in 3D geomodelling is the so-called “boundary representation” (BREP)(Mallet, 2002). In this framework, geological units are defined as finite-size hollow volumes bounded by their boundaries (i.e. stratigraphic, tectonic, and intrusive contacts) represented by discretised surfaces (e.g. triangulated surfaces). Geological units in BREP models are a partition of the volume occupied by the model itself, which in turn is a partition of the



60 whole 3D space (Mallet, 2002). The boundary surfaces are therefore the key element in BREP, and the meaning of the model (the “legend” of the model in geological jargon) is strictly connected to the meaning of the boundary surfaces.

In order for a BREP partition to be unambiguous, the volumes must be “watertight”, in the sense that the boundary surfaces must be perfectly sealed one to another and do not allow any connection between different units or leave undefined volumes within the modelling domain (Caumon et al., 2004). This topological condition is even more fundamental if the purpose of a 65 3D geological model is not just qualitative visualisation, but to make available the geometry and properties of different volumes for further analysis or modelling downstream (e.g. Cacace and Blöcher, 2015; Kastner et al., 2017; Nguyen et al., 2017; Hussain et al., 2026). To produce a sealed model, discretised boundary surfaces must be connected along intersection polylines, with no undefined spaces or overlapping domains between the different units (i.e. “meet and contain” topological contacts according to the 9-intersections model, as in Egenhofer et al., 1993; Zlatanova et al., 2004; Wang et al., 2016). In common 70 geological terms, this means that stratigraphic boundary surfaces must be perfectly sealed to other stratigraphic boundaries, faults, or the outer model boundaries, while faults could have free borders when their tip-lines (null displacement lines) fall within the model domain (hereafter referred to as “finite faults” in the sense that they do not extend to the whole model extent). In computer graphics jargon, this assembly of watertight discretised surfaces and intersection polylines is called a Piecewise Linear Complex (PLC)(Cacace and Blöcher, 2015; Tierny et al., 2018; Hussain et al., 2026).

75 In a traditional 3D geomodelling workflow - known as “explicit approach”, the discretised surfaces that contribute to a BREP are modelled, one-by-one, with several different tessellation and interpolation algorithms, that are not specifically the object of this contribution (see for example Lévy and Mallet, 1998; Mallet, 2002; Caumon et al., 2004), and in a second step all their intersections are calculated, sometimes with a mesh-refinement or resampling step allowing to ensure perfect sealing (e.g. Cacace and Blöcher, 2015; Hussain et al., 2026).

80 More recently, implicit modelling methods have been introduced, that use potential field-type functions (Lajaunie et al., 1997; Mallet, 2004; Caumon and Mallet, 2006; Caumon et al., 2007; Tertois, 2007; Calcagno et al., 2008; Hillier et al., 2014) to produce volumetric scalar field(s) representing the “stratigraphy” (more details are given in the following) from which the boundary surfaces are extracted a-posteriori (hence indicated as “implicit”). Implicit interpolation dramatically reduces user interaction and interpolation times, and increases the reproducibility of the model, since the whole model, including all 85 different units, is interpolated in a single step, ensuring mathematical consistency and the watertight requirement (Tertois, 2007).

Whatever the interpolation methods used are, since many applications of 3D geological modelling are focused on hydrocarbon reservoirs or mining, the kind of geological structures involved are usually relatively simple (e.g. sedimentary basins with limited deformation), or sometimes more complex but condensed in a small volume (e.g. fault zones in mines). By contrast, 90 when developing 3D models at the scale of the sheets of official national maps, at scales between 1:25.000 and 1:50.000 and for areas between 300 and 600 km², modellers are forced to deal with very large study areas. Moreover, in metamorphic or fold and thrust belts, structures become more complex (Arienti et al., 2024; Musso Piantelli et al., 2026). The model may include both sedimentary cover and metamorphic and/or basement units, and these may be overturned, repeated, or completely



transposed, lithological boundaries may not correspond to stratigraphic ones, and temporal relationships are often uncertain or
95 entirely obliterated. As a result, the construction of 3D geological models relies heavily on conceptual geological frameworks,
in which geological objects are framed within a coherent geological history involving multiple processes (e.g. sedimentation,
erosion, deformation, magmatic, metamorphism, etc.). In these contexts, the standard stratigraphic practice, as defined by the
International Commission of Stratigraphy (Salvador, 1994), does not always apply or is not practically applicable, and defining
target modelling units poses problems that must be solved according to different criteria and interpretative standards (Williams,
100 1985; LeMaitre et al., 2002; Gillespie et al., 2008; Fettes et al., 2011; North American Commission on Stratigraphic
Nomenclature, 2021; Simonetti et al., 2024).

In a partial attempt at solving this class of problems, Grose et al., 2021 introduced "time aware" geological modeling – a
generalized version of implicit modeling, but in some complex geological environments the problem of defining a valid and
practically usable geological legend is still open, and we believe that it is rooted into a general ontological problem¹, i.e. a
105 problem concerning the possibility to define an explicit conceptual, formal and yet practically applicable classification of
geological units, for both 2D maps and cross-sections, and 3D models.

In an attempt at tackling this kind of problems, in this contribution we focus on 3D modelling in metamorphic poly-deformed
mountain belts, combining basement and cover – possibly the hardest situation in terms of structural and tectonic complexity,
but our aims are also more general and we propose a framework – the Structural Topology Model (STM) - that might be
110 applicable to a multitude of geological scenarios, from simpler to extremely complex, independently from interpolation
methods, despite being inspired by implicit modelling, and valid both in 2D and 3D models, hence strengthening the
connections between data (2D map) and interpretation (2D cross-sections and 3D models).

2 The Structural Topology Model

The Structural Topology Model (STM) is a conceptual and topological framework for representing geological architectures,
115 including spatial and temporal relationships. The goal of STM is to enable geologists to schematise legends based on concepts
derived from standard stratigraphic and structural practice, since they are familiar to all geologists, while formalising these
concepts into an ontology – an explicit and formal machine-readable conceptualisation applicable to 3D geological models,
2D maps, and cross-sections.

2.1 Structural Scalar Field and Structural Polarity

120 In implicit modelling, as originally proposed by Mallet, 1989 and Lajaunie et al., 1997, and implemented by (Mallet, 2004;
Caumon and Mallet, 2006; Tertois, 2007; Caumon et al., 2007; Calcagno et al., 2008), a scalar field representing the value of

¹ Ontology in philosophy is the most general study of reality and entities, where knowledge structures and categories are
created to organise reality and the relationships between entities. By extension, the term ontology is used in information
science as "a formal, explicit specification of a shared conceptualisation" that can be used by computers (i.e. it can be used
in practice and is unambiguous)(Gruber, 1993)



stratigraphic time (e.g. absolute or relative age of rocks) is interpolated from points bearing observations (i.e. outcrops of rocks with a given age). In this framework, iso-surfaces of the volumetric scalar field are time-surfaces that can be matched, choosing a specific age value, to standard stratigraphic boundaries (Mallet and Tertois, 2021). One key property of the scalar field used in implicit methods is that it is defined as a potential field, i.e. a field that is continuous and differentiable (Mallet, 1989; Lajaunie et al., 1997; Mallet, 2002; Tertois, 2007; Calcagno et al., 2008). Thus, it always has a gradient (first spatial derivative) defined as a vector field that is everywhere – by definition – orthogonal to equipotential iso-surfaces, hence to stratigraphic boundaries and more generally to bedding. Observations of layering can be therefore used as further constraints for interpolation of the scalar field, increasing very much the volume of data that can be used in these methods. The most relevant commercial implementations of this general concept are found in GeoModeller® (<https://www.brgm.fr/en/software/geomodeller-3d-geological-modelling-software>; Calcagno et al., 2008) and SKUA® (<https://www.aspentech.com/en/products/sse/aspen-skua>; Mallet and Tertois, 2021; Tertois, 2007), the first being the first commercially available software for implicit methods, the latter including the GeoChron model, where a system of paleo-coordinates is used, with the vertical paleo-coordinate axis representing geological time in a stratigraphic sense. Notable open-source implementations are represented by LoopStructural (<https://loop3d.org/LoopStructural>; Grose et al., 2021) and GemPy (<https://docs.gempy.org/installation.html>; de la Varga et al., 2019), both including very up-to-date algorithms but lacking a graphical user interface, thus posing a usability barrier to many geologists.

In our contribution, we generalise the implicit framework by reformulating it as an a-priori modelling ontological construct, aimed at extending its applicability beyond the stratigraphic age concept, to a broader class of geological concepts and settings, while preserving the underlying implicit representation of scalar potential fields. Thanks to this ontology (Fig. 1), it is possible to correlate maths, geology and topology, satisfying both the need for a clear geological meaning, and that for a rigorous mathematical definition (allowing a general implementation). Within STM, the scalar field is defined as a structural scalar field that represents a general Structural Level (SL), which includes stratigraphic level (i.e. age), but also geological levels defined by a set of reference surfaces or horizons, such as foliation or metamorphic isograds, as well as by continuously varying quantities such as crustal depth or any other planar structure. The gradient of SL is defined as the Structural Polarity (SP), which may represent the younging direction when SL is used as a stratigraphic level, or other structurally significant vector fields, such as the normal to foliation in metamorphic units (more examples afterwards in Fig. 2). This provides a unified mathematical and topological framework for defining coherent relationships among geological observables and the model, regardless of the geological processes they represent. Where geological discontinuities are present, such as unconformities or intrusive boundaries (i.e. stratigraphic discontinuities), or faults and tectonic boundaries (i.e. tectonic discontinuities), the SL scalar field (or the stratigraphic scalar field of previous implementations) is made discontinuous (with different techniques, depending on the specific interpolation method; Fig. 1). Depending on the geological situation, a discontinuity can completely disconnect two sub-regions of the model (resulting in two disconnected SL fields, for example across a major fault separating two distinct structural domains), or end within the domain, as in the case of finite faults (as define above) or of unconformities



155 passing laterally to continuity. Notably, only the interpolation method implemented in SKUA® can at the moment deal with finite discontinuities (Tertois, 2007).

It is a common observation in complex terrains that the internal layering, bedding and/or foliation within map units (that can be easily measured in the field, thus providing large datasets of planar data) can be either parallel (i.e. concordant) or form an angle (i.e. discordant) with stratigraphic and tectonic boundaries. Concordance vs. discordance is obviously also a key concept, and source of data, in stratigraphy. To frame this kind of observation in STM, we introduce the concept of oriented topology, where the continuity and conformability of a boundary define the possibility to use planar constraints within units on both sides of the boundary (“intraformational constraints”) to define the geometry – i.e. interpolate – the boundary itself. Within this framework, four end-member topological relationships can be distinguished for boundaries: (1) continuous and conformable, (2) discontinuous and conformable, (3) discontinuous and conformable on one side only, and (4) discontinuous and unconformable on both sides. As evidenced by the sketches in Fig. 1, these end-member relationships are very general and can represent sequential stratigraphy concepts, or relationships typical of both magmatic and metamorphic basement complexes. Noteworthy, their mathematical formulation remains general and can be applied to a wide range of geological settings (Fig. 2), as well as to any combination of the end-member cases and where different domains meet (e.g. at the unconformity separating basement from cover sequences).

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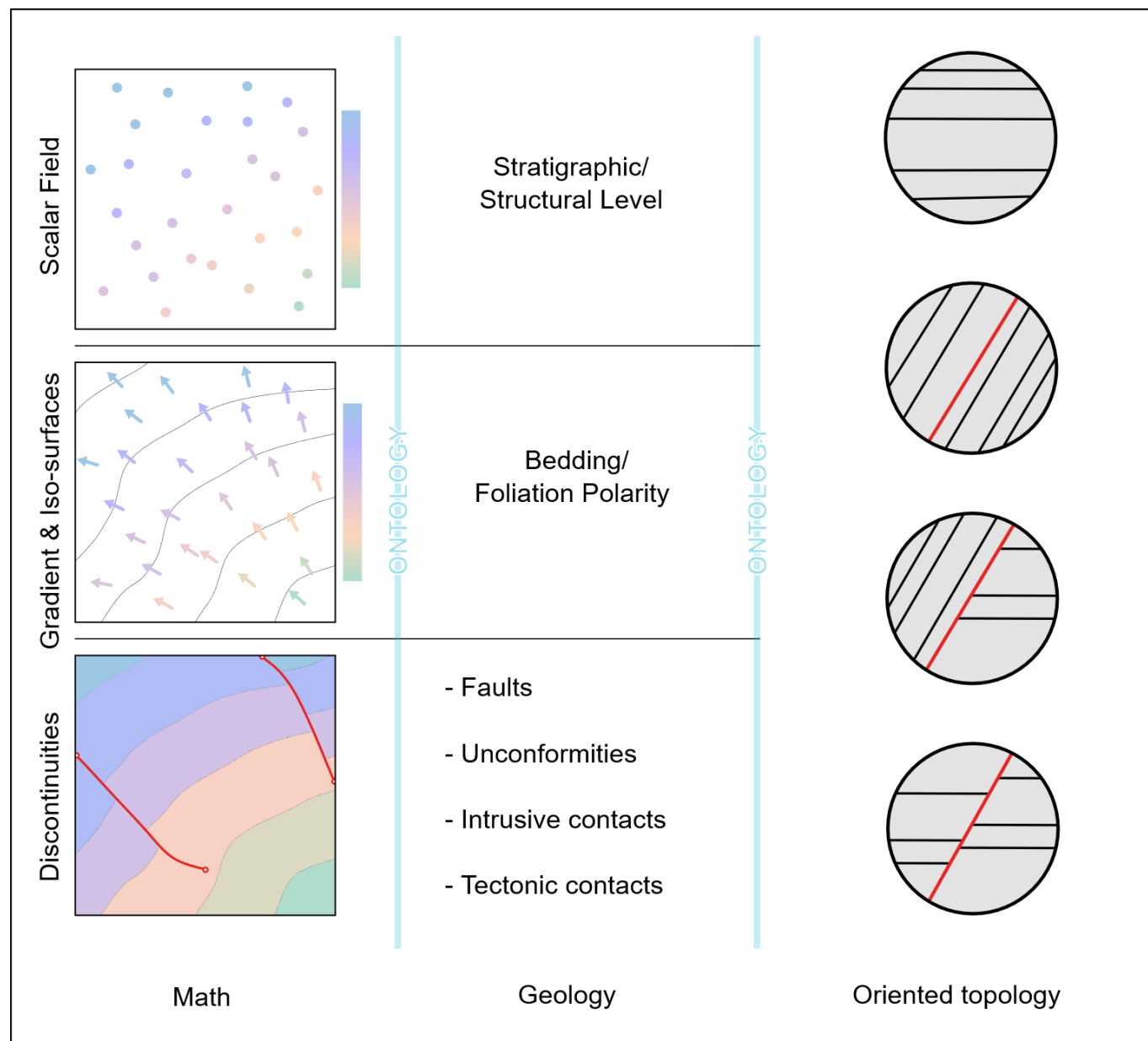


Figure 1: Ontological relations between math (SL, scalar field, gradient and iso-surfaces, and discontinuities), geology and oriented topology are the building bricks of STM. Stratigraphic and structural levels are fundamental components for constraining the SP. On the right, from top to bottom, the four end-member classes of boundaries are shown: continuous and conformable (absence of discontinuities), discontinuous and conformable (e.g. in depositional hiatus or thrust), discontinuous and conformable on one side only (e.g. in erosive contacts or tectonic contacts), and discontinuous and unconformable (e.g. faults).

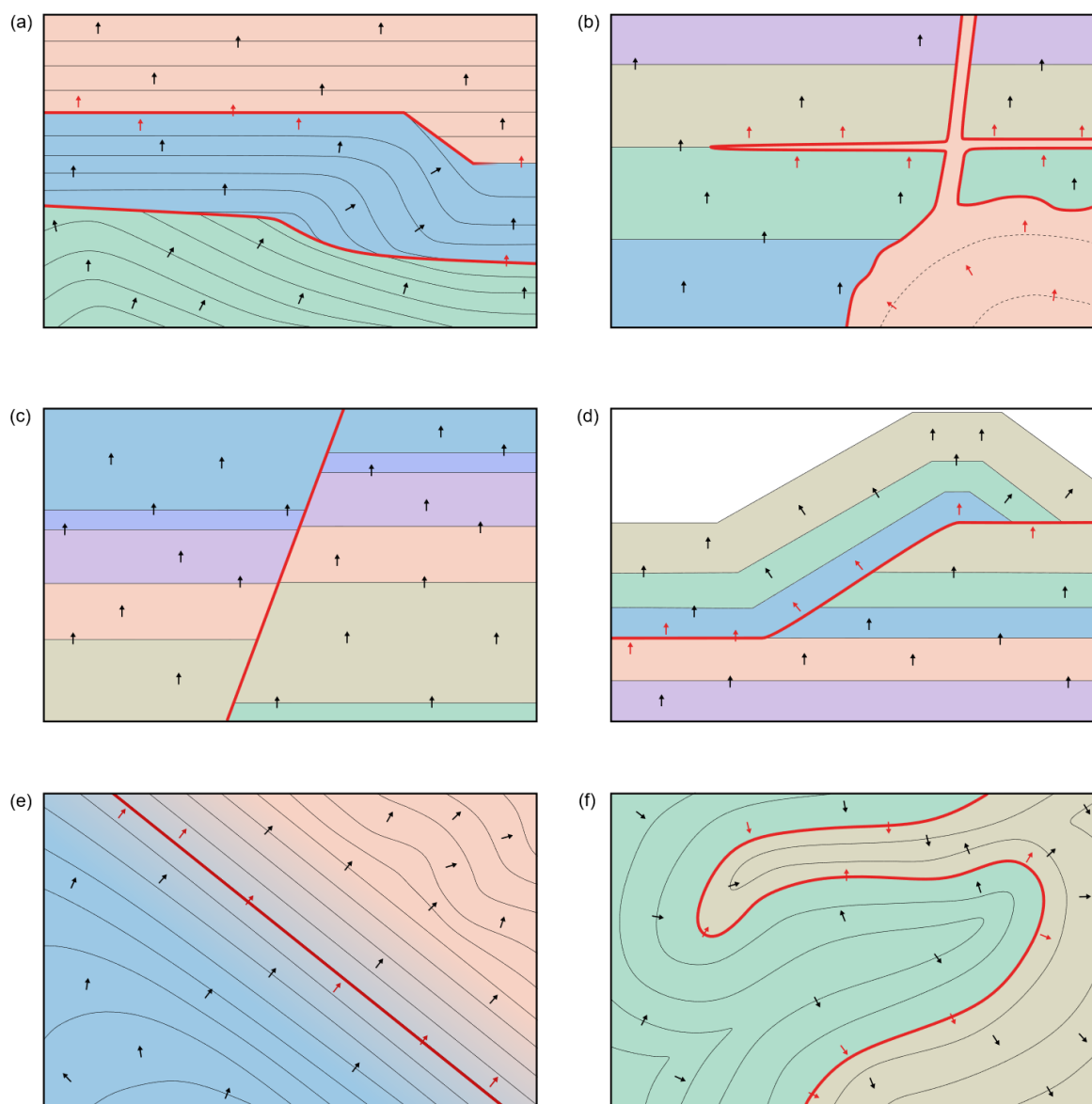


Figure 2: Example of relationships between the SL scalar field, its gradient SP, and discontinuities in different geological settings. Colour represents SL, black arrows represent SP, red ones refers to areas where the gradient is conformable with the geometry of the discontinuities: (a) erosional truncation, onlap, downlap, toplap, and depositional hiatus as in sequential stratigraphy conceptualisations, where all kinds of oriented topologies occur; (b) dyke (unconformable), sill (conformable) and plutonic intrusion (if igneous rocks are foliated or layered, these planar structures may be coherent or not with the pluton boundary surface); (c) a simple fault with complete unconformability with the host rocks; (d) a ramp and flat thrust system with conformability in footwall and hanging wall flats, and unconformability in ramps; (e) a ductile shear zone gradually overprinting the foliation of the surrounding units (conformable); (f) a folded tectonic contact conformable to both units.



2.2 Units and their boundaries

Similar to generation of a legend at the start of a field mapping project, the first step when creating a 3D model is the ontological definition of the geological units to be represented. The definition of these units depends on the scale and resolution of the model or map, and its intended purpose, but also fundamentally on geological criteria such as the origin of each unit, the rocks it includes, and the way its boundaries are defined. The assignment of a geological volume to a specific unit type is therefore scale- and purpose-dependent, and must rely on parameters that are observable, interpretable, and mappable at the scale of representation. It is therefore very common for a geological legend suitable for mapping at, for example, a 1:10.000 scale to require generalisation when creating a 3D model at a 1:50.000 scale. According to approaches followed by geological survey agencies worldwide (Gillespie et al., 2008; Simonetti et al., 2024), we classify geological units as: Tectonic Units (TUs), Stratigraphic Units (SUs), or Intrusive Units (IUs).

TUs are units primarily defined by tectonic and/or metamorphic features at the scale of representation. They commonly include crystalline basement domains, metamorphic complexes, or tectonic slices, but also tectonised sedimentary or volcano-sedimentary units, either metamorphosed or not. When preserved, original lithological associations or stratigraphic elements may contribute to their interpretation and, at finer scales, may allow internal subdivisions within the broader TU. Some authors further differentiate between Tectono-Stratigraphic (TSU) and Tectono-Metamorphic (TMU) Units (Battaglini et al., 2022). TUs are bounded by tectonic contacts (i.e. faults and ductile shear zones) that may be either conformable or unconformable. Depending on surrounding units, also unconformities and intrusive contacts may contribute to bounding TUs.

SUs are used within sedimentary or volcanic sequences showing preserved stratigraphic relationships, primary structures, and depositional architecture, undeformed or only mildly deformed. These units retain well-preserved primary structures and stratigraphy, such as those found in foreland basins, preserved rift sequences, stable platform domains, or volcanic successions with recognisable stratigraphic organisation. SUs are typically bounded by conformable tops and bases, but may also be confined by unconformable boundaries such as erosive surfaces, unconformities (which may be conformable for instance in pyroclastic fall deposits) and faults.

IUs include intrusive bodies such as dykes, plutons and batholiths. They are distinguished by their intrusive nature and by their cross-cutting relationships with surrounding units. However, when post-emplacement deformation and metamorphism affect an intrusive body together with its host rock, obliterating its intrusive features, it may be more appropriately classified as a TU. IUs are typically bounded by intrusive contacts, which may be conformable with the IUs in the presence of a magmatic foliation or layering. Despite their cross-cutting nature, intrusive contacts may also be conformable with the host-rock fabric or structures when these control the geometry of the intrusion (as e.g. in a sill or laccolith).

A specific case of TUs, occurring where deformation is distributed across a volume rather than localised along discrete structural boundaries and involving geological domains not necessarily corresponding to formal units, is represented by what we call Structural Domains (SDs). These are volumes that can be used to capture structural features of interest, e.g. the damage



zone of a brittle fault zone, a shear zone characterised by progressive dragging of foliation in a finite volume, etc. (Fig. 3).
 This kind of unit is therefore scale-, resolution- and purpose-dependent: the brittle fault system in Fig. 3a/b may be represented
 as a volumetric geological object, rather than simple surfaces, when the modeller chooses to define an envelope that
 encompasses the entire fault system, explicitly accounting for damage zones, strain gradients, uncertainty domains, or fluid-
 flow-related processes (Fig. 3c). Also ductile shear zones (Fig. 3e) can be represented as SDs with a well-defined volume (Fig.
 3f), either when upper and lower boundaries are clearly identifiable or when the modeller chooses to define a certain threshold
 intensity of deformation or metamorphic recrystallisation, based on fabric observation (e.g. Fossen and Cavalcante, 2017).
 Following the same approach, mélanges, DSGSD, and recumbent fold limbs can be represented with SDs, as well as systems
 of other pseudo-planar, deformation-related objects, such as dykes, sedimentary dykes and mineralised veins.

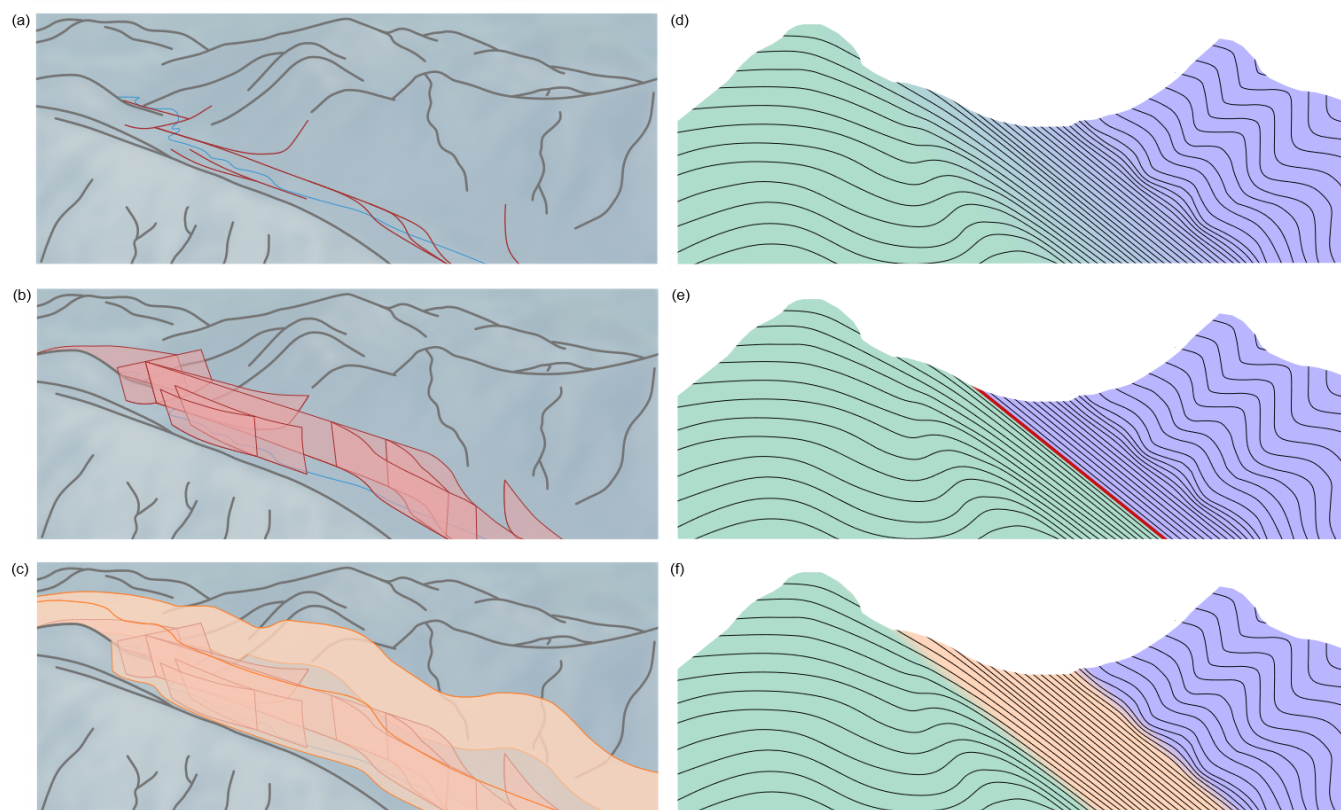


Figure 3: Classification of SDs depending on the model's scale, resolution and purpose. On the left, a fault system in a mountain valley (a) can be represented in the classic way with single surfaces (b), preserving cross-cutting relations and fault geometries, or as a SD volume (c), encompassing all the faults and defining a fault zone volume. On the right, a ductile shear zone, which does not show sharp or clearly defined boundaries (d), can be represented either as a single surface defining the tectonic contact between units (e), or as a volumetric SD (f), where upper and lower boundaries are identified based on a strain intensity or metamorphic recrystallisation threshold.



Depending on the geological setting and the scale and resolution of the model, a specific boundary may represent the top of a SU (typically preferred in stratigraphic successions), the bottom of any kind of unit, or a discontinuity – such as a tectonic, intrusive or erosional contact. Within this framework, it is important to consider that changing the label or structural role of a surface – while keeping its geometry unchanged – may completely alter the interpretation of the geological evolution and the relations among units, as shown in Fig. 4. Geometrically correct but semantically ambiguous surfaces may obscure the expected orientation of the foliation, the stratigraphy, or the deformation patterns within the units. This can lead to misinterpretation of the structural and stratigraphic framework and evolution. In implicit modelling, these semantic ambiguities could also compromise the efficacy of using dip data as constraints for interpolation.

For these reasons, when possible, assigning a single conformable boundary to each unit (consistent with the oriented topology) helps to maintain clarity in the model and supports the transition from surfaces to volumetric representations, as illustrated in Fig. 2. However, some geological bodies are not characterised by an internal foliation and others only show non-conforming boundaries. A typical example is non-foliated IU, which are defined solely by their intrusive contact, which cross-cuts planar structures in host rocks, and has no useful relationships with the internal isotropic fabric. Similarly, not all tectonic contacts can serve as a reference surface conformable to internal structures, e.g. when a tectonic contact does not produce any foliation at the scale that is relevant for modelling (e.g. the Combin Fault in Fig. 10).

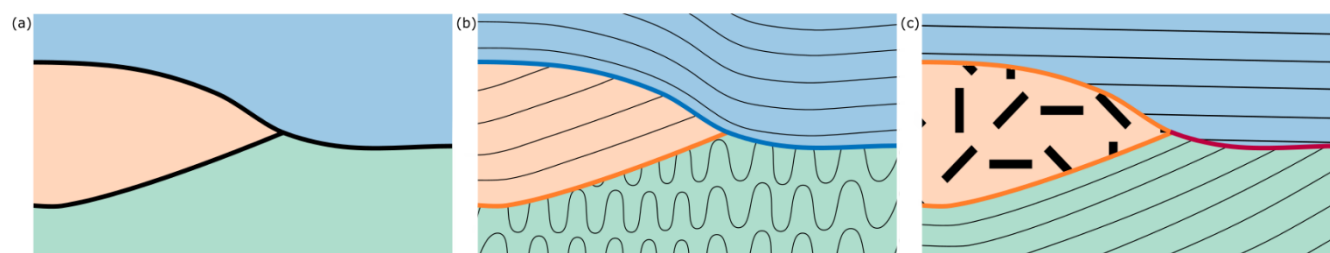


Figure 4: Starting from a neutral case study (a), where black lines represent unlabelled contacts, different ontological interpretations of the same contacts can lead to completely different geological settings, while preserving the same geometric configuration from (b) cross-cutting relations to (c) an intrusion along an unconformity.

The hierarchical meaning of units and boundaries may also change across scales, suggesting the use of super-units composed of several units that are only relevant at lower hierarchic level and that can be modelled only locally at high resolution. In STM, hierarchical levels are defined by the relationships among geological objects: higher-order boundaries subdivide larger domains, while lower-order boundaries further partition the resulting units. Intersection and truncation relationships between boundaries can therefore be used to establish their relative hierarchical order at the scale considered. For example, in regional geological maps it is common to have large higher-order TUs or SUs that include several smaller lower-order units, as in the case for instance of two TUs, composed of several SUs and IUs, overlain (on top of a regional unconformity) by a SU (Fig. 5).

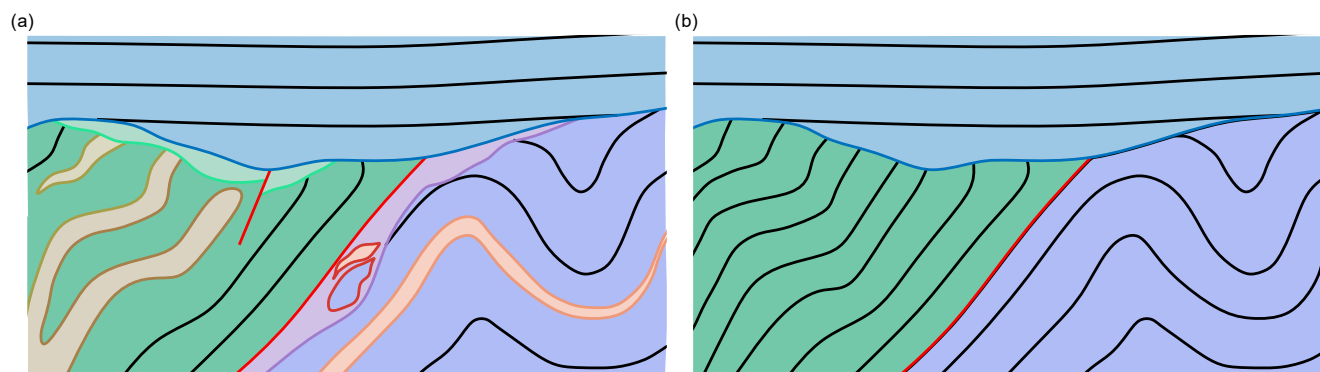


Figure 5: TUs (green and purple) with their lower-order metasedimentary covers (light green and purple) and transposed intrusive bodies (a). These SU and IU can be included in the higher order TUs (b).

Similarly, a regional boundary (higher-order) may be subdivided into smaller portions (lower-order) when it changes its meaning laterally, as in the case of an unconformity becoming conformal towards the basin (Fig. 2a). In all these cases, maintaining topological and polar consistency across scales and hierarchic levels is essential to ensure that the boundaries remain geologically meaningful and that the transition from 2D (map data and conceptual interpretation in cross-section) to 3D preserves the reasoning and interpretation from data to model.

2.3 STM

Building on the concepts described in the previous paragraphs, we have developed graphical tools to facilitate building the STM, and we have implemented these tools in PZero (<https://github.com/gecos-lab/PZero/releases>; Monti et al., 2026). To illustrate how this works, we consider the synthetic case shown in Fig. 6a, where two tectonic units (TU_1 and TU_2) are juxtaposed and share a common deformational history, resulting in conformable relationships along their common boundary (Bnd_A). TU_1, TU_2, and Bnd_A are truncated by Bnd_B, which separates them from TU_3, located at a higher structural level (no assumption about the age of its rocks). Bnd_B is conformable with the foliation in TU_3 but crosscuts the foliations in TU_1 and TU_2, as implied by the conformable relationship between Bnd_A and the internal foliations of these units. Finally, the Bnd_C unconformity marks the base of SU_1, which transgressively overlies the eroded basement units. In order to build an interpretative and geometric scheme that defines the relations among these units, structural relations must be made explicit, highlighting cross-cutting and unconformable vs. conformable contacts between the different units.

Each unit included in the model corresponds to a range of values of the structural scalar field SL, increasing upwards in a structural sense and bounded by values at the boundaries (see vertical axis marked SL), while the gradient SP of SL defines its polarity and the relationships across boundaries are defined in terms of oriented topology (Fig. 6b). Starting from the lowermost structural levels (lower part of the graph), Bnd_A shows a continuous and conformable relationship with TU_1 and TU_2, which can be assigned to a single domain or super-unit that shares the same continuous scalar field SL. This super-unit,



comprising TU_1, TU_2 and Bnd_A, is then cross-cut by Bnd_B, which is discontinuous and conformable on the TU_3 side only. Finally, Bnd_C is discontinuous and unconformable on both sides and SU_1, showing the higher range of SL values, is not conformable to any boundary within the modelling domain. These relationships are schematised in the graph in Fig. 6b, where units and boundaries are represented in two different columns, at an elevation corresponding to relative values of SL (growing upwards) and continuous lines represent conformal relationships in oriented topology, while dashed lines indicate non-conformity.

In addition to geological boundaries, in the graph in Fig. 6 also the modelling region boundaries are shown, that must be used to limit generate units with a finite volume.

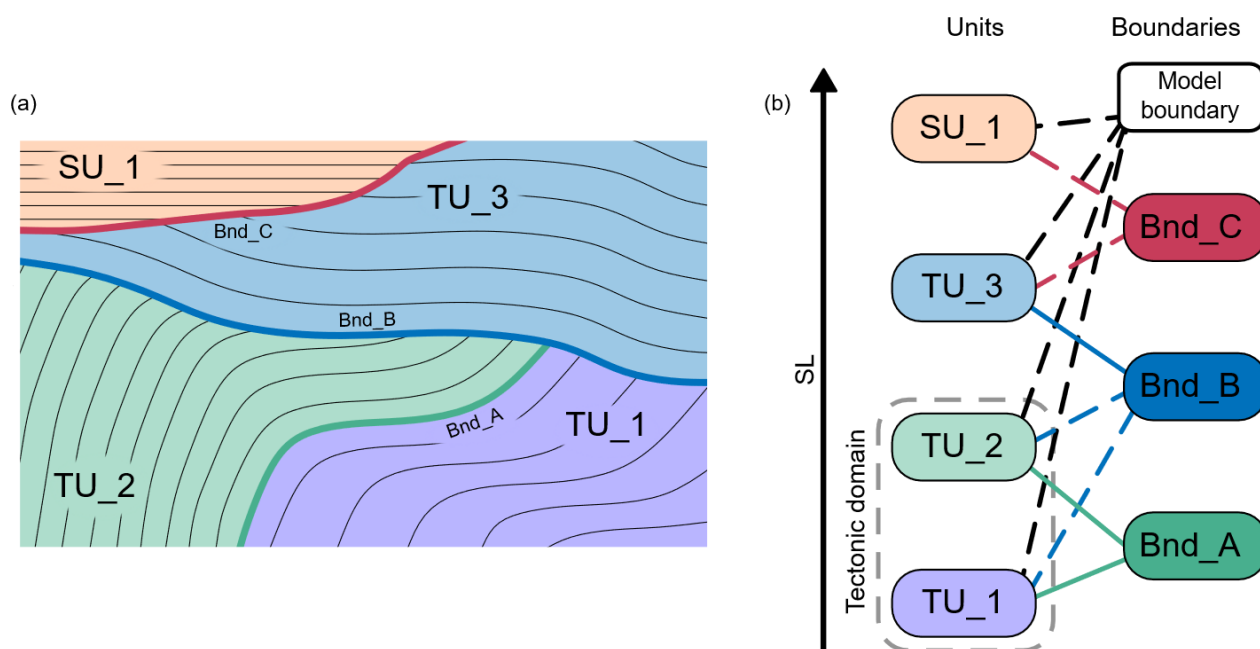


Figure 6: Synthetic case study to explain the ontological architecture of the STM. (a) Cross-section with units, boundaries and foliations and bedding; (b) Components of the STM arranged in the graph discussed in the text and implemented in PZero.

3 Case studies

Here we present two case studies from the Alps (general overview in Dal Piaz et al. 2003) that played different but complementary roles in the development and application of the STM.

The goal of the first case study was to model several basement units and the Mesozoic cover as a whole in the Helvetic domain of the Aar Massif (Swiss Central Alps). Here a regional-scale 3D geological model has already been published by Musso Piantelli et al., (2026), which was reconstructed with classical explicit methods. The initial goal for us was to test to which extent reprocessing with implicit methods would be capable to generate a valid 3D model, in a faster and less manpower demanding way compared to explicit modelling. During this process, the complexity of the geological units and their structural



relationships revealed ontological ambiguities and topological relationships that could not be represented unambiguously within standard implicit frameworks, ultimately motivating the development of STM.

The second case study includes Penninic units outcropping in the upper part of the Gressoney Valley (Italian Northwestern Alps), at the foot of the Monte Rosa massif. This study area has been selected to test and generalise the approach in a different tectonic setting with both basement and ophiolitic units, and different kinds of boundary surfaces.

For the purposes of this paper, the two case studies are illustrated through a single representative geological cross-section from each 3D model (Fig. 9 and Fig. 10). However, the topological relations encoded in the STM are valid at the scale of the entire 3D models and not limited to the cross-section 2D representation, and in fact are valid also in 2D maps or in any other representation. This means that STM encodes structural and stratigraphic relationships that are valid irrespective of the representation – an abstraction level that is typical of topological representation, which lies at a more abstract level than geometry.

Before discussing the case studies, it is important to briefly analyse examples where the SL scalar field and its gradient SP do not represent geological time in a stratigraphic sense (as in standard implicit methods), and the alternatives we have to define it in the more general structural level sense. In Fig. 7a the green unit is metamorphic and polydeformed, and a stratigraphic younging direction cannot be defined. This can be defined, on the other hand, within the orange and blue cover units, but there is no way to define a unique younging direction at the scale of the whole model. Therefore we can define an SL scalar field based on the structural level (deep to shallow) in the present configuration, highlighted by the black arrow, and use it and its gradient SP to interpolate our model. In Fig. 7b all units are from the crystalline basement and tectonically juxtaposed, therefore no younging direction can be defined, and the structural level is not really defined, being the boundaries vertical. The interpreter is free to use SL oriented right to left (black arrow) or left to right (grey arrow). Finally in Fig. 7c we show a mid-ocean ridge environment (Nicolas, 1995) that can be used as a model for ophiolitic sequences (used later on in the Gressoney case). Here all rocks have roughly the same age, but they occur at different crustal levels: green serpentinites at the deeper level, then blue sheeted dykes, intruded by brown gabbros, all overlain by pale blue ocean-floor basalts. In this case we suggest to use the original crustal level at the ridge as a suitable choice for SL and SP.

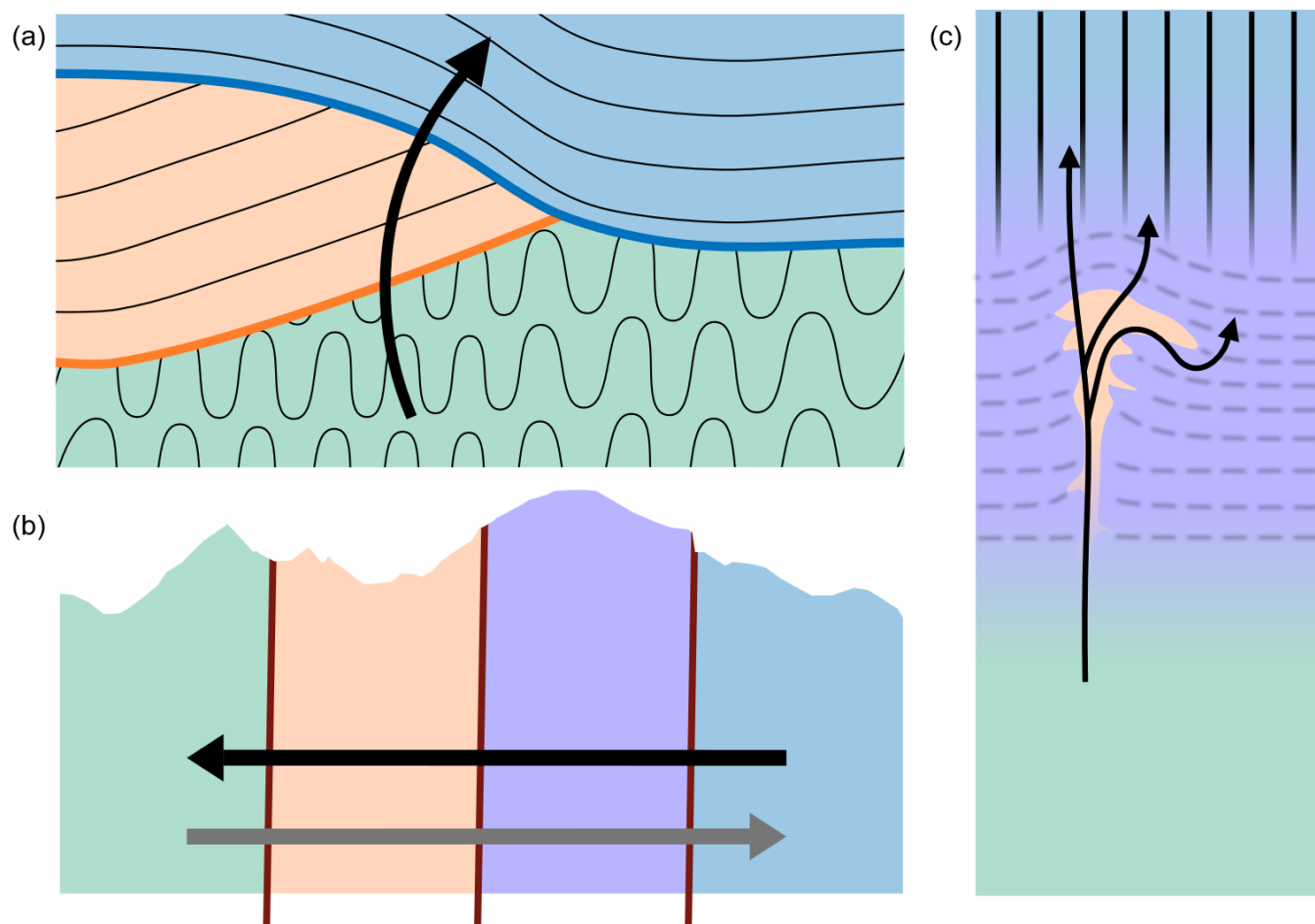


Figure 7: Orientation of the SP (black arrows) in different geological contexts: (a) cross-cutting relations between basement and cover units; (b) basement units vertically juxtaposed; (c) ophiolitic complex (modified after Nicolas, 1995). Discussing in main text.

3.1 Helvetic of the Aar Massif

The Aar Massif – an NE-SW trending elongated dome exposing the European basement– is one of the External Crystalline Massifs of the Helvetic domain in the Central Alps of Switzerland (Piaz et al., 2003). It is composed of pre-Variscan gneisses and migmatitic basement units intruded by Variscan to post-Variscan plutons after their coupling and it was affected by Permo-Carboniferous transtensional tectonics (Schaltegger and Corfu, 1992; Berger et al., 2017; Ruiz et al., 2022). The overlying Doldenhorn Nappe is composed of Mesozoic cover units derived from the European passive continental margin, and was emplaced during basin inversion and nappe stacking in the Oligocene (Abrecht, 1994; Berger et al., 2017; Herwegh et al., 2017; Musso Piantelli et al., 2026). Subsequent Alpine deformation of the Aar Massif included vertical extrusion (~22–12 Ma)



and later NW-directed thrusting (Herwegh and Pfiffner, 2005; Herwegh et al., 2017, 2020; Berger et al., 2017). Starting from cross-sections of the published structural model by Musso Piantelli et al. (2026), we created the STM of the area, which includes the same geometries but now includes a complete definition of topological relationships schematised in the graph of Fig. 8. The six basement units of the massif have been grouped into a macro-domain of TUs with SL representing the structural position, oriented from SSE (Clavaniev Zone) to NNW (Innertkirchen–Lauterbrunnen Zone) following the tectonic units of Berger et al. (2017). This orientation reflects the SP derived from the regional metamorphic gradient and deformation pattern (Herwegh et al., 2017, 2020).

The early Variscan volcano-sedimentary Cavardiras Group TU follows as a younger unit, with cross-cutting relations with the basement units. Similarly, the early Variscan Rötifirn Group IU follows, intruding both the basement units and the Cavardiras Group. The Fruttstock IU (middle Variscan) and the Diechtermgletscher–Tscharren and Lötschen–Mandranertal Groups TUs do not intersect each other, but their absolute ages allow their SL to be defined.

The late-to-post-Variscan Haslital Group IU presents two key aspects: (1) although labelled as a single group, it is composed by the main body of the Haslital Group and by the Gastern Granite, which is spatially separated from the former; (2) the NNW boundary of the Haslital Group coincides with the contact between its host unit (Sustenhorn Zone) and the Ferden–Guttannen Zone, without intruding the latter, since the contact has been reactivated during Alpine collision (Wehrens et al., 2017).

The Oberaar–Furka Zone is a tabular unit composed of pre-Variscan protoliths, showing cross-cutting relationships with the younger Haslital Group, due to an Alpine deformational stage. Its tabular geometry and mylonitic foliation make it more appropriately classified as a SD unit (a shear zone).

Finally, the Mesozoic cover of the massif is represented by a TU overlying the entire structural stack through a higher-level boundary (Fig. 9), providing a stratigraphic reference for the younger evolution of the massif, and the internal stratigraphic units are not further differentiated in this model (but they can be potentially differentiated following the hierarchic approach discussed above).

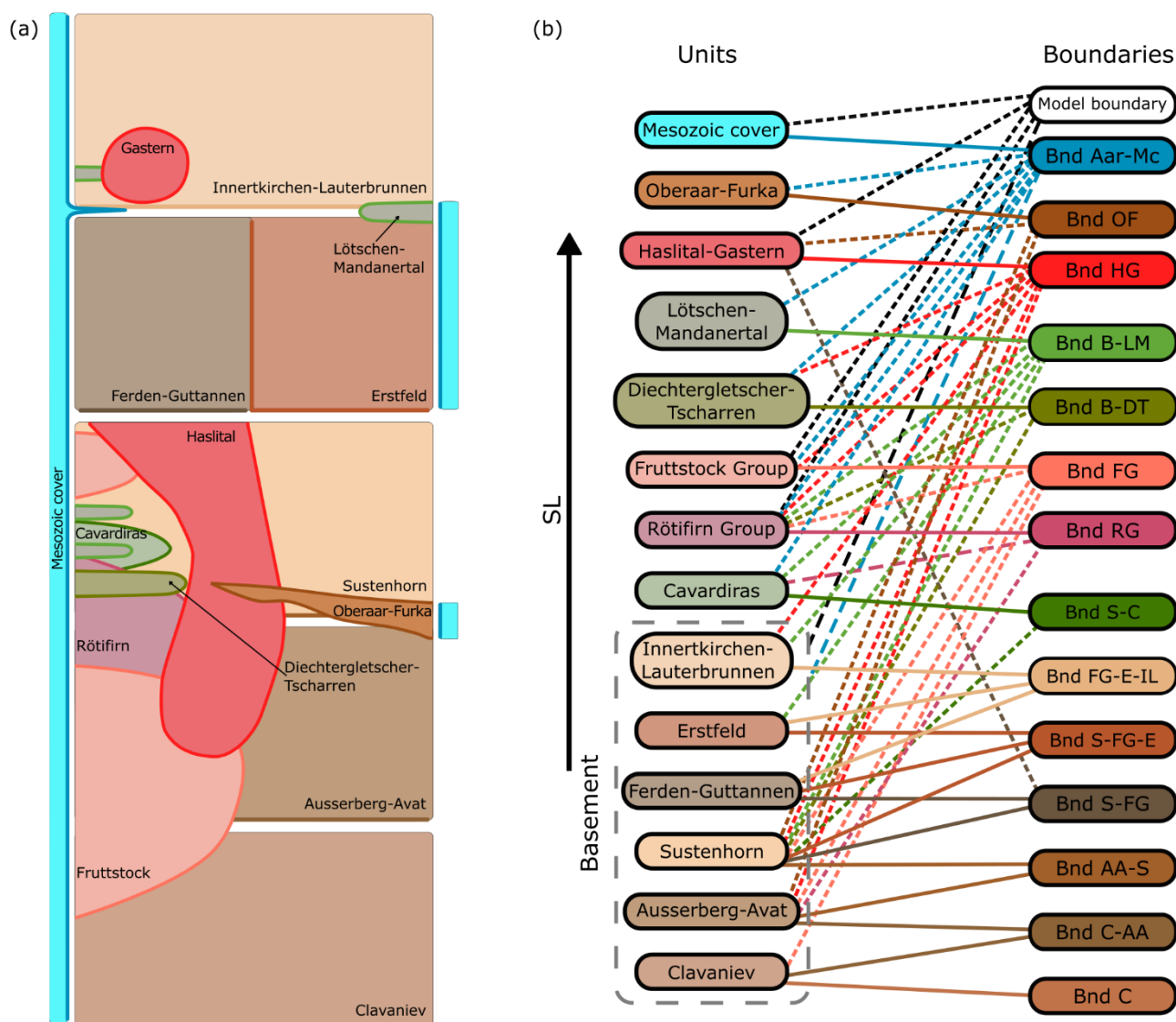


Figure 8: A schematic non-georeferenced representation of the Aar Massif (a). The topological relation between units and boundaries are represented in the graph (b), where boundaries labels are assigned based on shortened names of the main units they bound (exceptions to this rules are the intrusive contacts that only refers to the related IU, and the some contacts with relations with groups of basement units, B, or with the entire massif, Aar). Continuous lines represent conformable relations, and dashed lines represent unconformable one. For graphical simplification the topological connections between the basement units the cover or the model boundary are unified in single lines from the basement domain to the boundaries.

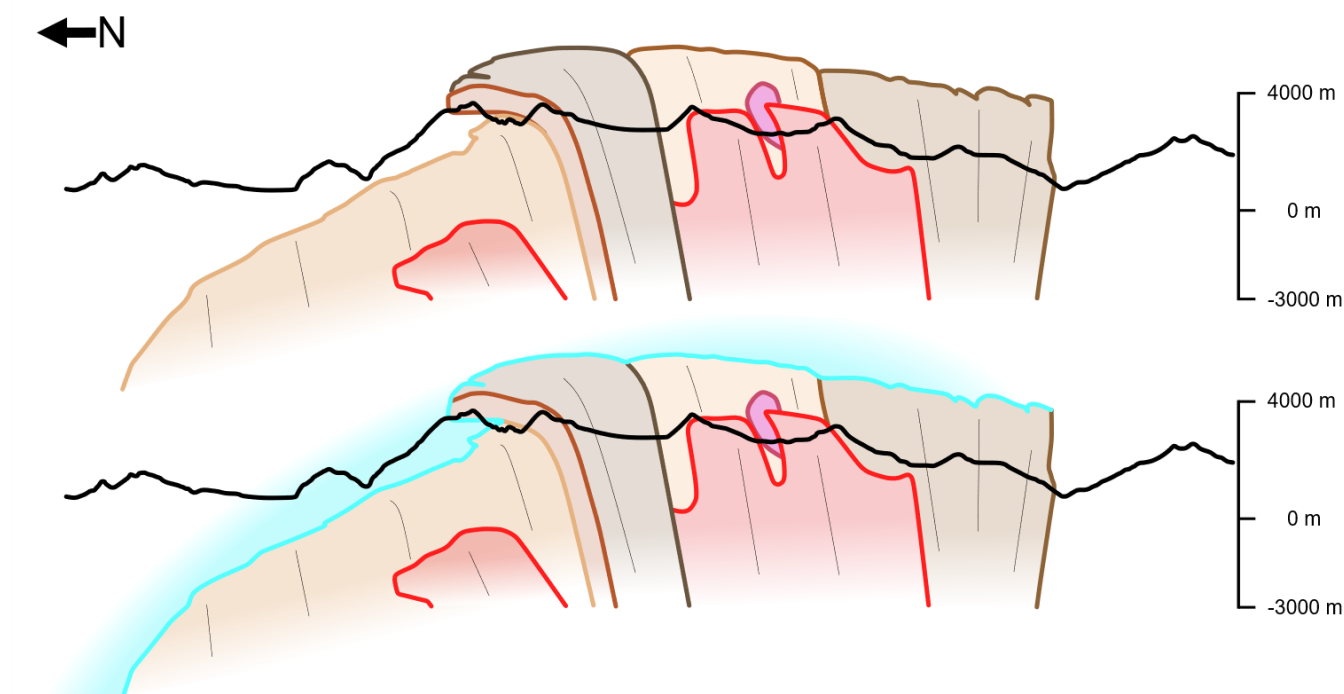


Figure 9: A comparison of the interpretation of the surfaces in a cross-section of the 3D model of the Aar Massif (Musso Piantelli et al., 2026) before STM (above) and after STM (below), where surfaces have been split in accordance with oriented topology avoiding the use of shells. See the graph in Fig. 8 for colours legend. The main foliation of the units is represented by thin black lines.

3.2 Penninic of the Gressoney Valley

In the upper Gressoney Valley (northwestern Alps, Italy), the oceanic suture between the European continental crust—represented by paragneisses and orthogneisses of the Monte Rosa Nappe—and the overlying Piedmont Ligurian oceanic lithosphere—including the Zermatt–Saas and Combin ophiolitic units—is well exposed (Balleivre and Merle, 1993; Reddy et al., 2003; De Giusti et al., 2003; Dal Piaz, 2010). This area has been considered a natural laboratory for studying subduction, collision and exhumation processes since the introduction of plate tectonics (Chadwick, 1974). The Monte Rosa and Zermatt–Saas units reached eclogite-facies (possibly UHP) conditions in the Eocene (Rubatto et al., 1998; Lapen et al., 2006) and were then exhumed following the same decompression path, under epidote-amphibolite and greenschist facies conditions (Ernst and Dal Piaz, 1978; Dal Piaz and Lombardo, 1986). Since also mylonites at their boundary (Monte Rosa–Zermatt boundary in the following) followed the same path, Lapen et al., (2006) suggest that these units were coupled in an early stage of the exhumation path and then were exhumed as a whole. The Combin unit, which never reached the eclogite facies and is mostly characterised by greenschist-facies assemblages (Manzotti et al., 2021), was tectonically juxtaposed to the Zermatt–Saas and Monte Rosa assembly in a much later stage, under greenschist facies conditions, with tectonic elision of a thick section of the collisional belt along the extensional Combin fault (Balleivre and Merle, 1993; Reddy et al., 2003).



For the sake of this methodological study, the STM (Fig. 10) was reconstructed as follows (different solutions might apply to studies at different scales). At the higher hierarchical level we have three TUs: from lower structural levels (lower SL scalar value) to higher levels (higher SL) the Monte Rosa, Zermatt-Saas and Combin units. The Zermatt-Saas unit has been further split into two units with lower hierarchic level: serpentinites and metabasalts, with SL growing from serpentinites to the metabasalts as proposed above. The internal boundary between serpentinites and metabasalts is locally cross-cut by the higher-order tectonic boundary between Monte Rosa and Zermatt-Saas. This might suggest a discordant topology along this boundary with respect to foliations within both units. However, this mylonitic zone and its host rocks were characterised by continuing shear during and after juxtaposition of Monte Rosa and Zermatt-Saas, resulting in transposition of original lithological layering and attraction of all fabrics towards parallelism with the boundary itself in a thick volume around it. Therefore, we define the Monte Rosa-Zermatt boundary as conformable on both sides, and the lower-order boundary between serpentinites and metabasalts as unconformable (however small the angle between these boundaries can be, if one crosscuts the other they cannot be all conformable for topological reasons). From this perspective, polarity is oriented from the Zermatt-Saas unit toward the Monte Rosa Nappe, even though, chronologically, the Jurassic ophiolites are younger than the pre-Mesozoic paragneiss. This contact is strongly deformed due to the competence contrast between serpentinites and paragneisses, locally developing cusped-lobate folds.

Continuing upwards, the Combin fault exhibits a rather planar geometry, truncating the folded foliations of both units in the hanging wall and footwall, therefore it is modelled as unconformable on both sides.

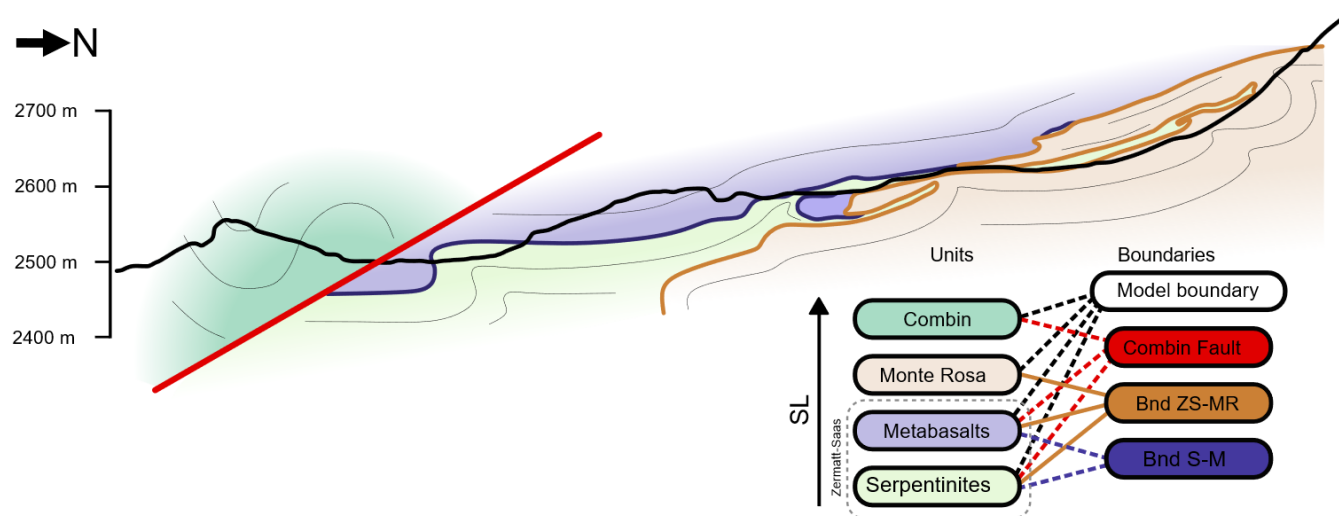


Figure 10: A cross-section from the 3D model of the Gressoney Valley and the related graph. See extended discussion in main text.



4 Discussion and conclusion

STM is a conceptual topological modelling method aimed at formalising and making explicit, in a machine-readable ontology, geological concepts and reconstructions, including structural, stratigraphic and petrographic observations and processes. In more complex settings, such as metamorphic belts where stratigraphy is unreliable, building an STM graph allows reconstructing unambiguous topological relationships between units, their internal foliation or layering, and their boundaries, also considering hierarchic relationships between these elements in 3D and 2D.

In addition to being fundamental for 3D modelling, STM allows building geological legends that clearly represent the stratigraphic and tectonic evolution. Therefore, this approach could be greatly helpful even if 3D modelling is not the goal.

Although the method has been developed to be applicable to both explicit and implicit surface modelling workflows, the SL scalar field, and its SP gradient, represent key elements in STM since they lead to the concept of oriented topology and a proper classification of topological relationships between the internal foliation/layering of units and their boundaries. Applying STM to 3D modelling with explicit methods is possible; however, in this case, these topological relationships are not intrinsically encoded by the modelling framework and therefore need to be defined and maintained separately. An implication of this framework concerns the use of structural observations (e.g. orientation data) as constraints in implicit modelling, since existing implicit interpolation methods can already incorporate different types of structural constraints in addition to geometrical information from interpreted cross-sections. STM provides the conceptual and topological framework for assigning such constraints according to the oriented topology between unit boundaries and internal foliation or layering. In structurally complex settings, this may allow structural observations to be exploited more consistently and potentially reduce the dependence on dense networks of interpretative cross-sections. The extent to which this potential can be exploited in practice depends on the capabilities and implementation of the modelling software adopted.

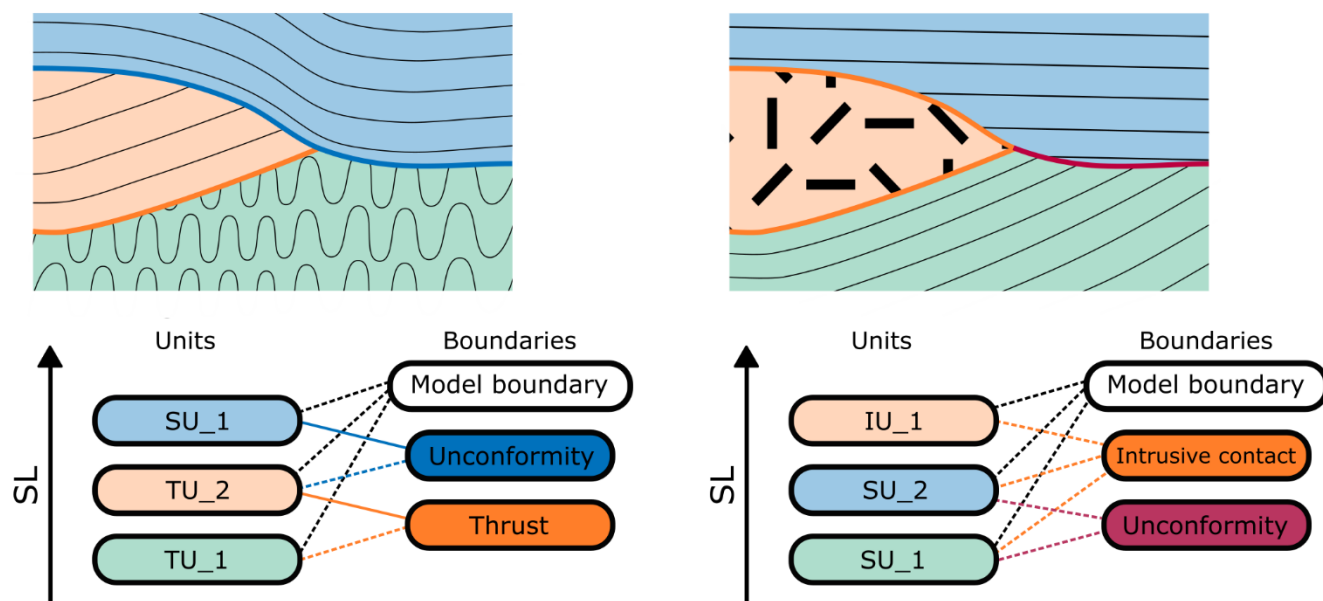
The assignment of a geological object to a specific STM class is not absolute, but depends on the scale, resolution, and purpose of the model. The same geological entity can therefore be represented as a higher-order domain bounded by its main boundaries at a regional scale, and as a hierarchy of lower-order units and associated local boundaries at finer scales. This flexibility relies on simple geological criteria (which are often directly recognisable in the field), such as the structural position of units, defined by their boundaries and characteristic internal content, and the intersection and truncation relationships among boundaries, which establish their relative hierarchy. This scale-dependent representation does not imply a change in the underlying geological interpretation, but rather its progressive refinement, provided that the topological and polar relations between hierarchical levels are preserved.

The Aar Massif and Gressoney Valley case studies demonstrate how to apply STM in different geological contexts. Both areas are well-investigated geological systems, and in both cases the main challenge is not the lack of geological knowledge, but the difficulty of translating complex and heterogeneous geological relationships into a formal and unambiguous representation. The Aar Massif is the case where STM was originally conceived, emerging as a response to unresolved topological problems



440 encountered in standard implicit and explicit modelling. In this setting STM enables the identification of structural domains
and the definition of coherent SL and SP fields, solving ambiguities typical of classical methods. The Gressoney case study
illustrates the broader applicability of the approach beyond its original scope, demonstrating that the method is not case-specific
but can be extended to geological systems characterised by strong deformation, shear zones, and an evolution in time that is
clear (after 60 years of detailed studies) but not expressed in terms that can be formalised according to standard stratigraphic
445 codes. Taken together, the two case studies show that STM can accommodate geological systems in which the main challenge
is not the absence of geological knowledge, but the difficulty of translating complex and heterogeneous geological
relationships into a formal and unambiguous representation.

A critical aspect of the method is its dependency on the purpose of the model itself and on expert interpretation. However, this
dependency is intrinsic to geological modelling and does not represent a limitation specific to STM. Three-dimensional models
450 are not just interpolated geometries, but also experts' interpretations guided by hypotheses and geological knowledge. Within
STM, these hypotheses and modelling decisions are explicitly represented through the workflow and the ontological legend,
providing a traceable link between geological interpretation and the resulting digital model. This also provides a framework
for exploring interpretational uncertainty through alternative modelling scenarios. Different geological hypotheses may, for
example, imply alternative classifications of boundaries and units, different hierarchical relationships, or different topological
455 relationships between geological objects. As illustrated in Fig. 4, the same geometrical configuration may therefore result in
different ontological representations and corresponding STM graphs when different geological meanings are assigned to its
elements (Fig. 11). These alternatives can be represented as distinct STM scenarios and compared while explicitly preserving
the assumptions underlying each reconstruction.



460 **Figure 11: Alternative interpretations of the same geometrical configuration and their corresponding STM representations. The geological examples introduced in Fig. 4b/c are here associated with their respective STM graphs, showing how different geological meanings assigned to the same geometrical elements result in different ontological classifications and topological relationships. STM therefore allows alternative interpretative scenarios to be explicitly formalised and compared.**

The aim of STM is not to eliminate interpretation or to provide a quantitative estimate of uncertainty, but to make it explicit, traceable, and testable in a formal ontological legend, with topological relationships between units, their internal layering or foliation, their boundaries, and possibly a hierarchy from sub- to super-units, clearly represented by the STM graph.

The formal structure of the STM graph also makes the ontology machine-readable and suitable for computational implementation. In this context, STM has been implemented in the geological modelling software PZero (this topic will be covered in a future publication), where the formalised topology supports model construction and validation while preserving the imposed geological relationships. STM is therefore not intended to replace geological interpretation, but to provide a formal framework in which such interpretation can be explicitly expressed, structured, compared, and computationally tested.



Code availability

PZero, the geological modelling environment mentioned in this study, is open-source and available at <https://github.com/gecos-lab/PZero> under the GNU Affero General Public License v3.0.

Author contributions

480 RM conceived the study, developed the theoretical framework, developed the 3D geological model of the Gressoney Valley, analysed and interpreted the results, prepared the visualizations, and wrote the original draft. AB supervised the research and contributed substantially to the conceptualization and development of the theoretical framework, interpretation of the geological observations and models, and extensive review and editing of the manuscript. RM and AB also contributed to field investigations in the Gressoney Valley. WH contributed to the methodological development, interpretation and validation of
485 the results, and scientific discussions throughout the development of the study. BM and GDP contributed their long-standing geological expertise and knowledge of the study area and regional geological framework, supported the development and validation of the theoretical interpretation. MH supervised the research conducted during the research stay abroad and contributed to the conceptual and methodological development of the study, interpretation of the results, and review and editing of the manuscript. SD and MF contributed to the methodology and workflow of the 3D geological modelling, as well as to the
490 interpretation and discussion of the models. FMP developed the Aar Massif 3D geological model and contributed to its interpretation and visualization, as well as to review and editing of the manuscript. All authors discussed the results and approved the final version of the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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References

- Abrecht, J.: Geologic units of the Aar massif and their pre-Alpine rock associations: a critical review : The pre-Alpine crustal evolution of the Aar-, Gotthard- and Tavetsch massifs, in: Geologic units of the Aar massif and their pre-Alpine rock associations: a critical review : The pre-Alpine crustal evolution of the Aar-, Gotthard- and Tavetsch massifs, 5–27, <https://doi.org/https://doi.org/10.5169/SEALS-56328>, 1994.
- Arienti, G., Bistacchi, A., Caumon, G., Dal Piaz, G., Monopoli, B., and Bertolo, D.: Regional-scale 3D modelling in metamorphic belts: An implicit model-driven workflow applied in the Pennine Alps, *Journal of Structural Geology*, 180, 105045, <https://doi.org/10.1016/j.jsg.2023.105045>, 2024.
- Ballèvre, M. and Merle, O.: The Combin Fault: compressional reactivation of a Late Cretaceous–Early Tertiary detachment fault in the Western Alps, *Schweizerische Mineralogische und Petrographische Mitteilungen*, 73, 205–227, <https://doi.org/10.5169/seals-55570>, 1993.
- Battaglini, L., Carta, R., Cipriani, A., Consorti, L., D’Ambrogio, C., Di Manna, P., D’Orefice, M., Falcetti, S., Fiorentino, D., Fiorenza, D., Lettieri, M., Lo Faro, S., Martarelli, L., Muraro, L., Orefice, S., Papasodaro, F., Pieruccioni, D., Radeff, G., Silvestri, S., Simonetti, M., Troccoli, A., and Vita, L.: Aggiornamento e integrazioni delle linee guida per la realizzazione della Carta Geologica d’Italia alla scala 1:50.000 – Progetto CARG, Quaderni serie III, 15, ISPRA – Servizio Geologico d’Italia, Rome, <https://doi.org/10.15161/oar.it/212546>, 2022.
- Baumberger, R., Herwegh, M., and Kissling, E.: Remote Sensing and Field Data Based Structural 3D Modelling (Haslital, Switzerland) in Combination with Uncertainty Estimation and Verification by Underground Data, in: *3D Digital Geological Models*, John Wiley & Sons, Ltd, 159–197, <https://doi.org/10.1002/9781119313922.ch10>, 2022.
- Berger, A., Wehrens, P., Lanari, P., Zwingmann, H., and Herwegh, M.: Microstructures, mineral chemistry and geochronology of white micas along a retrograde evolution: An example from the Aar massif (Central Alps, Switzerland), *Tectonophysics*, 721, 179–195, <https://doi.org/10.1016/j.tecto.2017.09.019>, 2017.
- Bistacchi, A., Massironi, M., Dal Piaz, G. V., Dal Piaz, G., Monopoli, B., Schiavo, A., and Toffolon, G.: 3D fold and fault reconstruction with an uncertainty model: An example from an Alpine tunnel case study, *Computers & Geosciences*, 34, 351–372, <https://doi.org/10.1016/j.cageo.2007.04.002>, 2008.
- Bistacchi, A., Arienti, G., Pecorella, E., and Soldo, L.: PZero: a new open-source Python geomodelling platform, in: 2021 RING Meeting, 2021 RING Meeting, 14, <https://hdl.handle.net/10281/325209>, 2021.
- Bossart, P., Bernier, F., Birkholzer, J., Bruggeman, C., Connolly, P., Dewonck, S., Fukaya, M., Herfort, M., Jensen, M., Matray, J.-M., Mayor, J. C., Moeri, A., Oyama, T., Schuster, K., Shigeta, N., Vietor, T., and Wiczorek, K.: Mont Terri rock laboratory, 20 years of research: introduction, site characteristics and overview of experiments, *Swiss J Geosci*, 110, 3–22, <https://doi.org/10.1007/s00015-016-0236-1>, 2017.
- Cacace, M. and Blöcher, G.: MeshIt—a software for three dimensional volumetric meshing of complex faulted reservoirs, *Environ Earth Sci*, 74, 5191–5209, <https://doi.org/10.1007/s12665-015-4537-x>, 2015.
- Calcagno, P., Chilès, J. P., Courrioux, G., and Guillen, A.: Geological modelling from field data and geological knowledge, *Physics of the Earth and Planetary Interiors*, 171, 147–157, <https://doi.org/10.1016/j.pepi.2008.06.013>, 2008.
- Caumon, G. and Mallet, J.-L.: 3D Stratigraphic models: representation and stochastic modelling, IAMG 2006, Int. Assoc. for Mathematical Geology XIth International Congress, <https://hal.univ-lorraine.fr/hal-01795303>, 2006.



- 540 Caumon, G., Lepage, F., Sword, C. H., and Mallet, J.-L.: Building and Editing a Sealed Geological Model, *Mathematical Geology*, 36, 405–424, <https://doi.org/10.1023/B:MATG.0000029297.18098.8a>, 2004.
- Caumon, G., Antoine, C., and Tertois, A.: Building 3D geological surfaces from field data using implicit surfaces, <https://www.ring-team.org/research-publications/ring-meeting-papers?view=pub&id=956>, 2007.
- 545 Chadwick, B.: Glaucophane Fabric in the Cover of the Monte Rosa Nappe, Zermatt–Saas Fee, Southwest Switzerland, *GSA Bulletin*, 85, 907–910, [https://doi.org/10.1130/0016-7606\(1974\)85%3C907:GFITCO%3E2.0.CO;2](https://doi.org/10.1130/0016-7606(1974)85%3C907:GFITCO%3E2.0.CO;2), 1974.
- Dal Piaz, G. V.: The Italian Alps: a journey across two centuries of Alpine geology, *J.Virt.Ex*, 36, <https://doi.org/10.3809/jvirtex.2010.00234>, 2010.
- Dal Piaz, G. V. and Lombardo, B.: Early Alpine eclogite metamorphism in the Penninic Monte Rosa-Gran Paradiso basement nappes of the northwestern Alps, in: *Blueschists and Eclogites*, edited by: Evans, B. W. and Brown, E. H., Geological Society of America, 249–266, <https://doi.org/10.1130/MEM164-p249>, 1986.
- 550 Dal Piaz, G. V., Bistacchi, A., Gianotti, F., Monopoli, B., Passeri, L., and Dal Piaz, G.: Carta Geologica d’Italia - Foglio 68 Monte Bianco, ISPRA - Servizio Geologico d’Italia, <https://progetto-carg.isprambiente.it/cartografiaCARG/>, 2025a.
- Dal Piaz, G. V., Bistacchi, A., Gianotti, F., Monopoli, B., Passeri, L., and Dal Piaz, G.: Carta Geologica d’Italia - Foglio 69 Gran San Bernardo, ISPRA - Servizio Geologico d’Italia, <https://progetto-carg.isprambiente.it/cartografiaCARG/>, 2025b.
- 555 De Giusti, F., Dal Piaz, G. V., Massironi, M., and Schiavo, A.: Carta geotettonica della Valle d’Aosta, Carta geotettonica della Valle d’Aosta, <https://hdl.handle.net/10281/38785>, 2003.
- Egenhofer, M. J., Sharma, J., and Mark, D. M.: A critical comparison of the 4-intersection and 9-intersection models for spatial relations: Formal analysis, in: *Auto-Carto 11: Eleventh International Symposium on Computer-Assisted Cartography*, Minneapolis, Minnesota, 1–11, ISBN 1-57083-001-0, 1993.
- 560 Ernst, W. G. and Dal Piaz, G. V.: Mineral parageneses of eclogitic rocks and related mafic schists of the Piemonte ophiolite nappe, Breuil-St. Jacques area, Italian Western Alps, *American Mineralogist*, 63, 621–640, <https://pubs.geoscienceworld.org/msa/ammin/article-abstract/63/7-8/621/40933/Mineral-parageneses-of-eclogitic-rocks-and-related>, 1978.
- 565 Fettes, D. and Desmons, J. (Eds.): *Metamorphic Rocks: A Classification and Glossary of Terms – Recommendations of the International Union of Geological Sciences Subcommission on the Systematics of Metamorphic Rocks*, Cambridge University Press, Cambridge, ISBN 978-0-521-33618-5, 2011.
- Fossen, H. and Cavalcante, G. C. G.: Shear zones – A review, *Earth-Science Reviews*, 171, 434–455, <https://doi.org/10.1016/j.earscirev.2017.05.002>, 2017.
- 570 Gartrell, A., Zhang, Y., Lisk, M., and Dewhurst, D.: Fault intersections as critical hydrocarbon leakage zones: integrated field study and numerical modelling of an example from the Timor Sea, Australia, *Marine and Petroleum Geology*, 21, 1165–1179, <https://doi.org/10.1016/j.marpetgeo.2004.08.001>, 2004.
- Gillespie, M. R., Stephenson, D., and Millward, D.: BGS classification of lithodemic units: Proposals for classifying units of intrusive rock, British Geological Survey Research Report RR/08/05, British Geological Survey, Nottingham, UK, 31 pp., ISBN 978-0-85272-624-2, <https://nora.nerc.ac.uk/id/eprint/5226/>, 2008.



- 575 Grose, L., Ailleres, L., Laurent, G., and Jessell, M.: LoopStructural 1.0: time-aware geological modelling, *Geosci. Model Dev.*, 14, 3915–3937, <https://doi.org/10.5194/gmd-14-3915-2021>, 2021.
- Gruber, T. R.: A translation approach to portable ontology specifications, *Knowledge Acquisition*, 5, 199–220, <https://doi.org/10.1006/knac.1993.1008>, 1993.
- 580 Guglielmetti, L., Comina, C., Abdelfettah, Y., Schill, E., and Mandrone, G.: Integration of 3D geological modeling and gravity surveys for geothermal prospection in an Alpine region, *Tectonophysics*, 608, 1025–1036, <https://doi.org/10.1016/j.tecto.2013.07.012>, 2013.
- Harry E. Wheeler (2): Time-Stratigraphy, *Bulletin*, 42, <https://doi.org/10.1306/0BDA5AF2-16BD-11D7-8645000102C1865D>, 1958.
- 585 Hartman, H. L. and Mutmansky, J. M.: *Introductory Mining Engineering*, 2nd ed., John Wiley & Sons, Hoboken, NJ, 592 pp., ISBN 978-0-471-34851-1, 2002.
- Herwegh, M. and Pfiffner, O. A.: Tectono-metamorphic evolution of a nappe stack: A case study of the Swiss Alps, *Tectonophysics*, 404, 55–76, <https://doi.org/10.1016/j.tecto.2005.05.002>, 2005.
- Herwegh, M., Berger, A., Baumberger, R., Wehrens, P., and Kissling, E.: Large-Scale Crustal-Block-Extrusion During Late Alpine Collision, *Sci Rep*, 7, 413, <https://doi.org/10.1038/s41598-017-00440-0>, 2017.
- 590 Herwegh, M., Berger, A., Glotzbach, C., Wangenheim, C., Mock, S., Wehrens, P., Baumberger, R., Egli, D., and Kissling, E.: Late stages of continent-continent collision: Timing, kinematic evolution, and exhumation of the Northern rim (Aar Massif) of the Alps, *Earth-Science Reviews*, 200, 102959, <https://doi.org/10.1016/j.earscirev.2019.102959>, 2020.
- Hillier, M., Wellmann, F., de Kemp, E. A., Brodaric, B., Schetselaar, E., and Bédard, K.: GeoINR 1.0: an implicit neural network approach to three-dimensional geological modelling, *Geoscientific Model Development*, 16, 6987–7012, <https://doi.org/10.5194/gmd-16-6987-2023>, 2023.
- 595 Hillier, M. J., Schetselaar, E. M., de Kemp, E. A., and Perron, G.: Three-Dimensional Modelling of Geological Surfaces Using Generalized Interpolation with Radial Basis Functions, *Math Geosci*, 46, 931–953, <https://doi.org/10.1007/s11004-014-9540-3>, 2014.
- 600 Hussain, W., Cacace, M., Bistacchi, A., and Monti, R.: PyMeshIt: An Open-Source Python modelling engine in PZERO and a standalone software for Conforming Tetrahedral Mesh Generation, EGU26-16992, Copernicus Meetings, <https://doi.org/10.5194/egusphere-egu26-16992>, 2026.
- Jahn, F., Cook, M., and Graham, M.: *Hydrocarbon Exploration and Production*, 2nd ed., Developments in Petroleum Science, 55, Elsevier, Amsterdam, 444 pp., ISBN 978-0-444-53236-7, 2008.
- 605 Kamath, A. V., Thiele, S. T., Moulard, M., Grose, L., Tolosana-Delgado, R., Hillier, M. J., Wellmann, F., and Gloaguen, R.: Curlew 1.0: Spatio-temporal implicit geological modelling with neural fields in python, *Geosci. Model Dev.*, 19, 3455–3475, <https://doi.org/10.5194/gmd-19-3455-2026>, 2026.
- Kastner, O., Norden, B., Klapperer, S., Park, S., Urpi, L., Cacace, M., and Blöcher, G.: Thermal solar energy storage in Jurassic aquifers in Northeastern Germany: A simulation study, *Renewable Energy*, 104, 290–306, <https://doi.org/10.1016/j.renene.2016.12.003>, 2017.



- 610 Kaufmann, O. and Martin, T.: 3D geological modelling from boreholes, cross-sections and geological maps, application over former natural gas storages in coal mines, *Computers & Geosciences*, 34, 278–290, <https://doi.org/10.1016/j.cageo.2007.09.005>, 2008.
- Lajaunie, C., Courrioux, G., and Manuel, L.: Foliation fields and 3D cartography in geology: Principles of a method based on potential interpolation, *Math Geol*, 29, 571–584, <https://doi.org/10.1007/BF02775087>, 1997.
- 615 Lapen, T. J., Johnson, C. M., Baumgartner, L. P., Piaz, G. V. D., Skora, S., and Beard, B. L.: Coupling of oceanic and continental crust during Eocene eclogite-facies metamorphism: evidence from the Monte Rosa nappe, western Alps, *Contrib Mineral Petrol*, 153, 139–157, <https://doi.org/10.1007/s00410-006-0144-x>, 2006.
- LeMaitre, R. W., Streckeisen, A., Zanettin, B., Le Bas, M. J., Bonin, B., Bateman, P., and International Union of Geological Sciences: *Igneous Rocks: A Classification and Glossary of Terms 2nd Edition* | Cambridge University Press & Assessment, <https://doi.org/https://doi.org/10.1017/CBO9780511535581>, 2002., 2002.
- 620 Lévy, B. and Mallet, J.-L.: Non-distorted texture mapping for sheared triangulated meshes, in: *Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, 343–352, <https://doi.org/10.1145/280814.280930>, 1998.
- Lopez, S., Clausolles, N., Brogaard Pedersen, C., Calcagno, P., Colomer, M., d’Ambrogio, C., Kearsey, T., Heerema, C., Herms, I., Hölzel, M., Marin Lechado, C., Palotai, M., Pizzella, L., Spoerlein, T., Stafleu, J., Stepien, U., Svagera, O., Szynkaruk, E., Terrington, R., and Wiese, M.: Towards a common geomodelling toolbox: sharing practices among European Geological Surveys, <https://doi.org/10.5194/egusphere-egu25-13319>, 2025., 2025.
- Lyu, M., Ren, B., Wu, B., Tong, D., Ge, S., and Han, S.: A parametric 3D geological modeling method considering stratigraphic interface topology optimization and coding expert knowledge, *Engineering Geology*, 293, 106300, <https://doi.org/10.1016/j.enggeo.2021.106300>, 2021.
- 630 Malard, A., Dörfliger, N., Jeannin, P.-Y., and Laube, S.: Contribution of the dynamic visualization of a 3D hydrogeological conceptual model to the participatory management of groundwater resources, *Comptes Rendus. Géoscience*, 355, 231–244, <https://doi.org/10.5802/crgeos.152>, 2023.
- Mallet, J. L.: Three-dimensional graphic display of disconnected bodies, *Math Geol*, 20, 977–990, <https://doi.org/10.1007/BF00892974>, 1988.
- 635 Mallet, J. L.: Discrete modeling for natural objects, *Math Geol*, 29, 199–219, <https://doi.org/10.1007/BF02769628>, 1997.
- Mallet, J.-L.: Discrete smooth interpolation, *ACM Trans. Graph.*, 8, 121–144, <https://doi.org/10.1145/62054.62057>, 1989.
- Mallet, J.-L.: *Geomodeling*, Applied Geostatistics Series, Oxford University Press, Oxford/New York, ISBN 978-0-19-514460-4, 2002.
- Mallet, J.-L.: Space–Time Mathematical Framework for Sedimentary Geology, *Mathematical Geology*, 36, 1–32, <https://doi.org/10.1023/B:MATG.0000016228.75495.7c>, 2004.
- 640 Mallet, J.-L. and Tertois, A.-L.: 3D Restoration of sedimentary terrains: The GeoChron Approach, <http://arxiv.org/abs/2105.06137> (last access: 21 November 2024), 14 May 2021., 2021.
- Manzotti, P., Ballèvre, M., Pitra, P., and Schiavi, F.: Missing lawsonite and aragonite found: P–T and fluid composition in meta-marls from the Combin Zone (Western Alps), *Contrib Mineral Petrol*, 176, 60, <https://doi.org/10.1007/s00410-021-01818-0>, 2021.
- 645



- Maxelon, M. and Mancktelow, N. S.: Three-dimensional geometry and tectonostratigraphy of the Pennine zone, Central Alps, Switzerland and Northern Italy, *Earth-Science Reviews*, 71, 171–227, <https://doi.org/10.1016/j.earscirev.2005.01.003>, 2005.
- Milicich, S. D., Bardsley, C., Bignall, G., and Wilson, C. J. N.: 3-D interpretative modelling applied to the geology of the Kawerau geothermal system, Taupo Volcanic Zone, New Zealand, *Geothermics*, 51, 344–350, <https://doi.org/10.1016/j.geothermics.2014.03.002>, 2014.
- Monti, R., Bistacchi, A., and Zanchetta, S.: 3D Geomodelling of Alpine structures: the Misox Shear Zone (Swiss), EGU24-21804, Copernicus Meetings, <https://doi.org/10.5194/egusphere-egu24-21804>, 2024.
- Monti, R., Bistacchi, A., Hussain, W., Favaro, S., Herwegh, M., Drvoderić, S., Furlan, M., Piantelli, F. M., Piaz, G. D., and Monopoli, B.: The Structural Topology model: integrating topology and ontology in 3D geological modelling, EGU26-18878, Copernicus Meetings, <https://doi.org/10.5194/egusphere-egu26-18878>, 2026.
- Musso Piantelli, F., Mair, D., Berger, A., Schlunegger, F., Wiederkehr, M., Kurmann, E., Baumberger, R., Möri, A., and Herwegh, M.: 4D reconstruction of the Doldenhorn nappe-basement system in the Aar massif: Insights into late-stage continent-continent collision in the Swiss Alps, *Tectonophysics*, 843, 229586, <https://doi.org/10.1016/j.tecto.2022.229586>, 2022.
- Musso Piantelli, F., Nibourel, L., Berger, A., and Herwegh, M.: From a Continental Margin to an Alpine Dome: 4D Geodynamic Evolution of the Aar Massif, *Tektonika*, 4, 1–27, <https://doi.org/10.55575/tektonika2026.4.1.105>, 2026.
- Nguyen, B. N., Hou, Z., Bacon, D. H., Last, G. V., and White, M. D.: Analysis of a Complex Faulted CO₂ Reservoir Using a Three-dimensional Hydro-geochemical-Mechanical Approach, *Energy Procedia*, 114, 3496–3506, <https://doi.org/10.1016/j.egypro.2017.03.1479>, 2017.
- Nicolas, A.: *The Mid-Oceanic Ridges*, Springer Berlin Heidelberg, Berlin, Heidelberg, <https://doi.org/10.1007/978-3-662-03136-0>, 1995.
- North American Commission on Stratigraphic Nomenclature: NORTH AMERICAN STRATIGRAPHIC CODE, strat, 18, 153–204, <https://doi.org/10.29041/strat.18.3.01>, 2021.
- Piaz, G. V. D., Bistacchi, A., and Massironi, M.: Geological outline of the Alps, *Episodes Journal of International Geoscience*, 26, 175–180, <https://doi.org/10.18814/epiugs/2003/v26i3/004>, 2003.
- Pizzella, L., Alais, R., Lopez, S., Freulon, X., and Rivoirard, J.: Taking Better Advantage of Fold Axis Data to Characterize Anisotropy of Complex Folded Structures in the Implicit Modeling Framework, *Math Geosci*, 54, 95–130, <https://doi.org/10.1007/s11004-021-09950-0>, 2022.
- Power, M. R., Hill, K. C., Hoffman, N., Bernecker, T., and Norvick, M.: The structural and tectonic evolution of the Gippsland Basin: Results from 2D section balancing and 3D structural modelling, in: *Eastern Australasian Basins Symposium 2001: A Refocused Energy Perspective for the Future*, edited by: Hill, K. C. and Bernecker, T., Petroleum Exploration Society of Australia, 373–384, ISBN 978-0-207-16928-1, 2001.
- Reddy, S. M., Wheeler, J., Butler, R. W. H., Cliff, R. A., Freeman, S., Inger, S., Pickles, C., and Kelley, S. P.: Kinematic reworking and exhumation within the convergent Alpine Orogen, *Tectonophysics*, 365, 77–102, [https://doi.org/10.1016/S0040-1951\(03\)00017-9](https://doi.org/10.1016/S0040-1951(03)00017-9), 2003.



- Rubatto, D., Gebauer, D., and Fanning, M.: Jurassic formation and Eocene subduction of the Zermatt–Saas-Fee ophiolites: implications for the geodynamic evolution of the Central and Western Alps, *Contrib Mineral Petrol*, 132, 269–287, <https://doi.org/10.1007/s004100050421>, 1998.
- 685 Ruiz, M., Schaltegger, U., Gaynor, S. P., Chiaradia, M., Abrecht, J., Gisler, C., Giovanoli, F., and Wiederkehr, M.: Reassessing the intrusive tempo and magma genesis of the late Variscan Aar batholith: U–Pb geochronology, trace element and initial Hf isotope composition of zircon, *Swiss J Geosci*, 115, 20, <https://doi.org/10.1186/s00015-022-00420-1>, 2022.
- Salvador, A. (Ed.): *International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure*, 2nd ed., International Union of Geological Sciences and Geological Society of America, Boulder, Colorado, 214 pp., ISBN 0-8137-7401-2, 1994..
- 690 Schaltegger, U. and Corfu, F.: The age and source of late Hercynian magmatism in the central Alps: evidence from precise U–Pb ages and initial Hf isotopes, *Contr. Mineral. and Petrol.*, 111, 329–344, <https://doi.org/10.1007/BF00311195>, 1992.
- Schneeberger, R., de La Varga, M., Egli, D., Berger, A., Kober, F., Wellmann, F., and Herwegh, M.: Methods and uncertainty estimations of 3-D structural modelling in crystalline rocks: a case study, *Solid Earth*, 8, 987–1002, <https://doi.org/10.5194/se-8-987-2017>, 2017.
- 695 Schneeberger, R., Egli, D., Lanyon, G. W., Mäder, U. K., Berger, A., Kober, F., and Herwegh, M.: Structural-permeability favorability in crystalline rocks and implications for groundwater flow paths: a case study from the Aar Massif (central Switzerland), *Hydrogeol J*, 26, 2725–2738, <https://doi.org/10.1007/s10040-018-1826-y>, 2018.
- Sides, E. J.: Geological modelling of mineral deposits for prediction in mining, *Geologische Rundschau*, 86, 342–353, <https://doi.org/10.1007/s005310050145>, 1997.
- 700 Simonetti, M., Pieruccioni, D., Carosi, R., Montomoli, C., Iaccarino, S., and Zucchi, M.: A review of criteria, methods, and standards for mapping crystalline terrains: integrating field geology and analytical data, *Italian Journal of Geosciences*, 143, 426–454, <https://doi.org/10.3301/IJG.2024.22>, 2024.
- Tertois, A.-L.: *Création et modification de modèles géologiques par champs de potentiel. Application au modèle GeoChron*, PhD thesis, Institut National Polytechnique de Lorraine, Nancy, 173 pp., NNT 2007INPL032N, <https://theses.fr/2007INPL032N>, 2007.
- 705 Tierny, J., Favelier, G., Levine, J. A., Gueunet, C., and Michaux, M.: The Topology ToolKit, *IEEE Trans. Visual. Comput. Graphics*, 24, 832–842, <https://doi.org/10.1109/TVCG.2017.2743938>, 2018.
- de la Varga, M., Schaaf, A., and Wellmann, F.: GemPy 1.0: open-source stochastic geological modeling and inversion, *Geoscientific Model Development*, 12, 1–32, <https://doi.org/10.5194/gmd-12-1-2019>, 2019.
- 710 Vo Thanh, H., Sugai, Y., Nguete, R., and Sasaki, K.: Integrated workflow in 3D geological model construction for evaluation of CO₂ storage capacity of a fractured basement reservoir in Cuu Long Basin, Vietnam, *International Journal of Greenhouse Gas Control*, 90, 102826, <https://doi.org/10.1016/j.ijggc.2019.102826>, 2019.
- Vollgger, S. A., Cruden, A. R., Ailleres, L., and Cowan, E. J.: Regional dome evolution and its control on ore-grade distribution: Insights from 3D implicit modelling of the Navachab gold deposit, Namibia, *Ore Geology Reviews*, 69, 268–284, <https://doi.org/10.1016/j.oregeorev.2015.02.020>, 2015.
- 715 Wang, J., Zhao, H., Bi, L., and Wang, L.: Implicit 3D Modeling of Ore Body from Geological Boreholes Data Using Hermite Radial Basis Functions, *Minerals*, 8, 443, <https://doi.org/10.3390/min8100443>, 2018.



- Wang, Z., Qu, H., Wu, Z., Yang, H., and Du, Q.: Formal representation of 3D structural geological models, *Computers & Geosciences*, 90, 10–23, <https://doi.org/10.1016/j.cageo.2016.02.007>, 2016.
- 720 Wehrens, P., Baumberger, R., Berger, A., and Herwegh, M.: How is strain localized in a meta-granitoid, mid-crustal basement section? Spatial distribution of deformation in the central Aar massif (Switzerland), *Journal of Structural Geology*, 94, 47–67, <https://doi.org/10.1016/j.jsg.2016.11.004>, 2017.
- Wellmann, J. F. and Regenauer-Lieb, K.: Uncertainties have a meaning: Information entropy as a quality measure for 3-D geological models, *Tectonophysics*, 526–529, 207–216, <https://doi.org/10.1016/j.tecto.2011.05.001>, 2012.
- 725 Wellmann, J. F., Horowitz, F. G., Schill, E., and Regenauer-Lieb, K.: Towards incorporating uncertainty of structural data in 3D geological inversion, *Tectonophysics*, 490, 141–151, <https://doi.org/10.1016/j.tecto.2010.04.022>, 2010.
- Williams, P. F.: Multiply deformed terrains—problems of correlation, *Journal of Structural Geology*, 7, 269–280, [https://doi.org/10.1016/0191-8141\(85\)90035-5](https://doi.org/10.1016/0191-8141(85)90035-5), 1985.
- Witter, J. B. and Phillips, N.: Integrated 3D geophysical inversion and geological modelling for improved geothermal exploration and drillhole targeting, *Geothermal Resources Council Transactions*, 36, 831–834, <https://publications.mygeoenergynow.org/grc/1030325.pdf>, 2012.
- 730 Xiong, Z., Guo, J., Xia, Y., Lu, H., Wang, M., and Shi, S.: A 3D Multi-scale geology modeling method for tunnel engineering risk assessment, *Tunnelling and Underground Space Technology*, 73, 71–81, <https://doi.org/10.1016/j.tust.2017.12.003>, 2018.
- Zlatanova, S., Rahman, A. A., and Shi, W.: Topological models and frameworks for 3D spatial objects, *Computers & Geosciences*, 30, 419–428, <https://doi.org/10.1016/j.cageo.2003.06.004>, 2004.
- 735