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Interpretation and representation in geomodels: the POKIMON ontology for formalizing geomodelling knowledge

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Abstract. With the rapid growth of the development and use of three-dimensional (3D) geological models, understanding their interpretative and representational aspects has become increasingly important. Such understanding will not only clarify key premises, inferences, and conclusions, but also enable more informed applications. Yet the epistemic foundations are often opaque. Critical information about assumptions, conceptual structures, reasoning steps, and uncertainties often remains tacit in the mind of the geomodeller, and this lack of transparency hampers explainability, reproducibility, and broader utility. Current practices therefore limit trust, knowledge transfer, and automation in geomodelling workflows. To address these limitations, we develop the POKIMON ontology, designed to make explicit the expert knowledge underlying 3D geological models. POKIMON provides a formalized framework to represent how geological and geomodelling concepts are applied during model construction. Motivating use-cases, the ontological structure, and application to the use-cases are presented to demonstrate utility and to advance automated knowledge-driven 3D geomodelling.

1 Introduction

Three-dimensional (3D) geological models (Mallet et al., 1989; Terrington et al., 2008) are digital representations of portions of the subsurface geological architecture. They are produced using a geomodelling workflow involving a series of operations typically carried out by multiple geoscientific experts (Perrin and Rainaud, 2013; Wellmann and Caumon, 2018). The experts iteratively interpret inputs and configure algorithms to generate numerical 3D representations (Caumon et al., 2004, 2009; Mao et al., 2012; Wellmann and Caumon, 2018). Critical interpretive decisions are made throughout the process, such as selecting data and specific knowledge, standardizing inputs, adjusting algorithmic parameters, proposing geological entities to explain the data and knowledge, and omitting extraneous or anomalous elements (Bond, 2015; Bond et al., 2012, 2015; Bourgine et al., 2008; Diepolder et al., 2019; Frodeman, 1995; Laouici et al., 2024; Zhang, 2008). These decisions are shaped by the modelers' expertise, prior experience, and general knowledge, which may be incomplete or specifically focused (Bond et al., 2007; Brodaric et al., 2004; Raab and Frodeman, 2002). Subjectivity and bias are thus unavoidably introduced into the interpretive process, causing the final geomodel to be a particular expert-influenced simplification of geological reality.

Most significantly, these interpretative aspects are typically absent in a final geomodel, though tacitly remain in the mind of the expert (Guillen et al., 2008; Kessler et al., 2009; Laouici et al., 2024; Zhivodkov et al., 2016). This leads to a loss of modelling history that limits the explicability, reproducibility, and general usability of the geomodel. It also points to the need to explicitly represent such knowledge not only to address these limitations, but also to aid geomodel construction: once prior knowledge, inferences, and decisions are explicitly available they can help guide the direc-

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tion of a geomodel and enable a form of knowledge-driven 3D geomodelling.

Ontologies are a powerful and recent means of formally and explicitly specifying a knowledge domain (Brodaric et al., 2008; Gruber, 1995; Guarino et al., 2020; Guarino and Giaretta, 1995; Guizzardi, 2005, 2007). Beyond their growing adoption, ontologies are methodologically useful to geoscience modelling and information management because they provide:

- *Explicit representation and formal logic*: concepts, relationships, and constraints can be encoded formally, making assumptions and rules explicit. This enables logical consistency checking, computable validation, and transparent interpretation of geological representations.
- *Semantic interoperability and data integration*: Geoscience data and information often exist in heterogeneous forms, with differing structures, terminologies and associated concepts. Ontologies provide a shared conceptual framework, enabling integration, interoperability across software platforms, and reuse in multidisciplinary teams.
- *Traceability and reproducibility*: By formalizing modelling workflows, including interpretation choices, constraint definitions, and provenance, ontologies can ensure that every step of model construction is documented. This addresses the "black box" nature of many 3D models and facilitates reproducible and explainable research.

In practice, ontologies can be implemented as semantic layers associated with geomodel objects, integrated into modelling software, or structured as knowledge graphs supporting reasoning, validation, and workflow guidance.

Although geoscience ontologies are prevalent (Babaie et al., 2006; Brodaric and Richard, 2020; Cox and Richard, 2015; Garcia et al., 2020; Zhong et al., 2009), they focus on descriptions of geological objects and, to date, do not exhaustively address the knowledge used in model construction. To fill this gap, we develop POKIMON (Processes, Observations, Knowledge, Information, and Modelling ONtology), which represents the nature of a geomodel itself, its manifestation as a digital or material artifact, as well as the processes, inferences, decisions, data and knowledge enacted during its construction.

After presenting a short review of related work on geoscience ontologies (Sect. 2), this paper introduces motivating use-cases and establishes the requirements for POKIMON (Sect. 3). The method of construction, including a recap of reused ontologies, is presented in Sect. 4, while Sect. 5 details key POKIMON components and their application to the use-cases. Section 6 then evaluates and discusses the results.

2 Related work

The use of formal languages and ontologies is growing in the geosciences, with numerous standards and knowledge models developed (Fauziati and Watanabe, 2010; Hwang et al., 2012; Lombardo et al., 2018; Ma et al., 2012; Mantovani et al., 2020; Qu et al., 2023; Simons et al., 2006; Wang et al., 2018). These ontologies are actively used in a range of contexts, including the construction of knowledge graphs, the integration of heterogeneous geoscientific datasets, and the formalization of domain knowledge for specific applications such as petroleum reservoir characterization tools and subsurface modelling software services. They also underpin standardization efforts and vocabularies to support consistent data exchange and interoperability. Among these diverse efforts, we distinguish two categories of ontologies: (1) general ontologies describing basic geological entities, and (2) specific ontologies designed for particular geoscience applications.

Ontologies belonging to the former category either focus on a specific subset of geological entities such as structures, faults, and the geological timescale (Babaie et al., 2006; Cox and Richard, 2015; Qu et al., 2023; Zhong et al., 2009), more broadly provide a framework for any geological entity (Brodaric and Richard, 2020; Garcia et al., 2020; Raskin and Pan, 2005), or focus on general geological knowledge and norms, such as geological and natural laws, principles, and classification systems (Brodaric et al., 2008). Ontologies belonging to the latter category are developed for describing 3D modelling input metadata (Mastella et al., 2009), geomodelling services (Belaid, 2011; Belaid et al., 2009), topological and geometric properties (Wang et al., 2016; Zhan et al., 2022), and geological constraints for model construction (Perrin et al., 2005).

A shortcoming of many of these application ontologies is their lack of reuse of general ontologies, despite such reuse being identified as good practice for developing interoperable tools (Fernández-López and Gómez-Pérez, 2002; Gruber, 1995; Katsumi and Grüninger, 2016). Very few geological ontologies also align with top-level ontologies, hindering convergence with other domains. Important conceptual considerations are made to distinguish between a model, its representation, and its visualization (Perrin and Rainaud, 2013), thus laying the foundation for an ontological framework for geological image classification, e.g., illustrations, maps, and seismic profiles (Abel et al., 2019). However, relations between these elements and the represented geological entities remain unaddressed in a robust ontological framework.

Existing ontologies also do not represent the interpretive tasks (Frodeman, 1995) and related processes used by experts during the construction of 3D models. Although previous work on the process of 3D geological interpretation (Laouici et al., 2024) develops a minimal ontology, the ontology is geared to a specific application and is too incomplete for general use. The RESQML standard (Morandini et al., 2011, 2017), widely used by petroleum companies, does address the interpretation aspect partially by tagging geological entities proposed during 3D modelling as interpretations, but it is not expressed as a formal ontology and does not distinguish geological entities in reality, which are not interpretations, from geological entities in models, which are interpretative constructs. Data standards, controlled vocabularies, and conceptual schemas developed in e.g., the Unified Modeling Language, primarily support the structural description of domain entities (e.g., geoscience classes, attributes, and associations), but remain limited in their ability to formally encode and enforce complex constraints. For instance, a schema may specify that a Fault entity is associated with a Stratigraphic Unit through an offset relation, yet such a specification does not guarantee that all fault instances actually participate in this relation, nor does it enable automated consistency checking across datasets without ad hoc procedural validation. Similarly, domain rules such as "if a unit truncates another, then it is younger than it" cannot be expressed in a machine-interpretable and inferable manner with these standards. In contrast, formal ontologies expressed in OWL (Antoniou and Harmelen, 2009), grounded in Description Logic (Baader and Nutt, 2003), enable the explicit specification of such constraints as logical axioms (e.g., Fault $\sqsubseteq \exists$offsets StratigraphicUnit or truncates $\sqsubseteq$ youngerThan), which can be automatically evaluated by a reasoner. This allows a more expressive formalization of experts' knowledge in addition to offering possible automated consistency checking (e.g., detecting incompatible stratigraphic relationships) and inference of implicit knowledge (e.g., deducing relative ages from stratigraphic ordering). This distinction is increasingly reflected in geoscience standardization efforts. GeoSciML and GroundWaterML2, for example, are based on conceptual models intended to function as ontologies and are progressively being translated from UML representations into formal ontology languages to enable semantic interoperability and reasoning.

Finally, although the IAEG guidelines (Baynes and Parry, 2022) for geomodel construction provide a template for the interpretation process, including several important conceptual distinctions, neither the template nor distinctions are represented in a formal ontology environment. The ontological representation of interpretation in 3D geomodelling remains a challenge, as does the ontological representation of the entire process of model construction.

3 Use-cases

Seven use-cases are developed to help specify POKIMON requirements (Laouici, 2024). These use-cases clarify what the ontology must represent, how it should behave, and why it is being built, thus guiding the structure, scope, and level of detail of the ontology. In this paper we focus on the three most significant cases that illustrate what models are, how they are built, and their main characteristics. Although not exhaustive, these three use-cases represent common geomodelling scenarios and their analysis helps identify key ontology contents. The geology addressed in the examples is situated in a rock quarry in western France, within the Central Armorican Domain (CAD) in Brittany, France. The CAD is part of the Armorican Massif and is primarily composed of Paleozoic rocks, intensely deformed during the Hercynian Orogeny. This compressional event led to the formation of folded layers and complex structural patterns. The Grès de Chatellier Formation, addressed in the use-cases, is a 100 m-thick Ordovician layer and consists of sandstone, siltstone, and quartzite beds. These beds are slightly metamorphosed and lack clear lithological separation (Vernhet et al., 2010), thus their further delineation is purely synthetic and included for demonstration purposes.

Ontology requirements drawn from the use- cases are referenced by a capital R indexed by a Roman numeral (e.g., R_{XX}) and summarized at the end of this section. The three selected use-cases are:

- Use-Case 1: Fig. 1 depicts different representations for selected geological units in the quarry: a photographic image as one particular representation of the unit boundaries (Fig. 1A); a digital rendition of a *geomodel* (Fig. 1B); and an alternative textual representation of the same geomodel (Fig. 1C), illustrating model representations are founded on distinct *representation systems and properties* (Liben et al., 2010) that need to be formally structured in the POKIMON ontology (R_{I}).
- Use-Case 2: Fig. 2 shows a simplified overview of the construction of a geomodel from field measurements with emphasis on inputs, the geomodelling processes and resulting outputs. Figure 2A illustrates a series of observations grouped into three situations using principles of spatial proximity and lateral continuity, with each situation requiring distinct interpretation. Figure 2B shows a coarse model (stratigraphic column) that can be conceptualized based on the observation data, which is used to guide the computation of the 3D geomodel with its spatial and temporal properties. Numerous iterations over situations generate new information (e.g., distinct geomodel parts) (Fig. 2B) resulting in a final interpretation and model (Fig. 2C). These results conform to established geological norms and constraints, avoid conflicts with the observations, are assessed for geological plausibility in an evaluation process, and accepted (Fig. 2C) or rejected (Fig. 2D) during a decision process. The final geomodel contains information with various origins (e.g., initially observed, or progressively interpreted). Ontological requirements then include: the *geological entities* (R_{II}) to be contained by a *geomodel* (R_{III}); *situations* and their links to initial observations (R_{IV}); *geomodelling* and *interpretation processes* (R_{V}) used to infer and assess the ge-

omodel parts documented in interpretations; final geomodelling outputs (resulting in various *types of geomodels*) (R_{VI}); associated *geological norms* and *constraints* (R_{VII}) and the *origins* (R_{VIII}) of represented geological entities.

- Use-Case 3: Fig. 3 shows geomodels are inherently simplifications of reality (Oreskes et al., 1994; Reinecke et al., 2024), as no model can represent all real details, and simplification can vary by modelling purpose: Fig. 3A shows a photograph of geological units fractured by several faults; Fig. 3B depicts a geomodel containing the faults, e.g., for reservoir and fluid modelling; Fig. 3C shows the geomodel with the faults removed, e.g., for macroscopic tectonic modelling; and Fig. 3D shows a further simplification where the seven units are grouped in three larger units. A key requirement then is retention of *detailed* and *simplified models*, and the *relations* between them (R_{IX}). Simplification might also involve the introduction of new entities, e.g. merged units, or the modification of properties, e.g. simpler geometries, further emphasizing the previous requirement of capturing the origin of the represented geological entities (R_{VIII}).

In summary, the key requirements for the POKIMON ontology include:

- R_{I}: Representation. The ontology must account for the fact that the same geological information can be expressed in different ways (e.g., diagram, 3D models, text), each with its own structure and characteristics. It should therefore distinguish what is represented from how it is represented.
- R_{II}: Geological models as central objects. Geological models must be explicitly represented as structured collections of information about the subsurface, serving as the main objects produced and manipulated throughout the modelling workflow.
- R_{III}: Geological entities within models. The ontology must include the geological features that make up these models (e.g., layers, faults, units), along with their properties and relationships.
- R_{IV}: Situations requiring interpretation. Incomplete or ambiguous sets of observations that need to be interpreted should be represented as "situations" forming the starting point of geomodelling and guiding the interpretation process.
- R_{V}: Geomodelling and interpretation processes. The ontology must describe how models are built, including the different processes involved (e.g., interpreting data, estimating properties, evaluating results, making decisions), as well as intermediate steps and iterations.
- R_{VI}: Resulting models and their types. Different kinds of outputs should be distinguished (e.g., intermediate vs final models, conceptual vs. spatial models) and their roles captured in the modelling workflow.
- R_{VII}: Geological rules and constraints. The ontology must be equipped to include the knowledge used to assess models, including geological principles and modelling constraints that guide, validate, or reject interpretations.
- R_{VIII}: Empirical nature of model contents. The origin of information should be tracked – whether it is directly observed, inferred through interpretation, or introduced as an assumption – since this affects its reliability and further use.
- R_{IX}: Simplification aspects. Finally, the ontology must capture how models simplify reality, including relationships between detailed and more general versions of the same geological setting, and how entities may be grouped, omitted, or transformed.

4 Ontology Design Method

As highlighted from the use-cases, POKIMON must represent aspects of two related domains: (1) the geomodelling domain, consisting of entities involved in developing interpretations and related entities and (2) the geological domain, consisting of basic geological entities. To achieve this, POKIMON adapts selected components from several ontologies (Fig. 4).

For the geomodelling domain, it draws on the Basic Formal Ontology (BFO) (Otte et al., 2022), the Information Artifact Ontology (IAO) (Ceusters and Smith, 2015), and the Information Ontology Foundry Core Ontology (IOF) (Drobnjakovic et al., 2022; Karray et al., 2020). For the geological domain, it draws on the Geoscience Ontology (GSO) (Brodaric and Richard, 2020), though POKIMON is not restricted to GSO and is designed to be compatible with other geological ontologies.

POKIMON follows an extraction and extension approach, as per Katsumi and Grüninger (2016), in which only certain axioms are extracted from the original ontologies and any new axioms preserve the intent of the original components. As many of these original ontologies are quite large and diverse as well as conceptually misaligned in areas generally not significant to POKIMON, this approach simplifies ontology construction and avoids conceptual and logical conflicts, thus facilitating the attainment of logical consistency. In essence, POKIMON requires only a few components from the selected ontologies, so their full import is unnecessary. This enables POKIMON to remain compact, internally consistent, and readily debugged.

BFO: The Continuant and Occurrent classes are key BFO distinctions. Continuants are fully present at any timepoint,

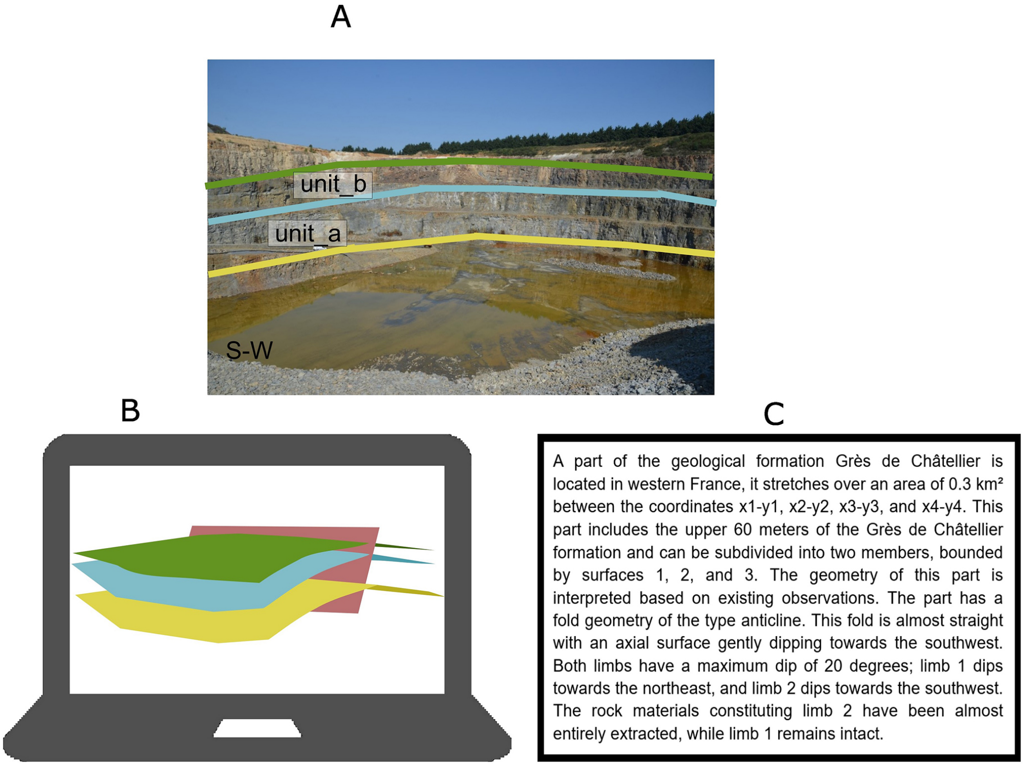

Figure 1. Use-Case 1 – representation of the study area **(A)**. Three-dimensional geomodel of the study area is shown in **(B)**, and the same geomodel is described as text in **(C)** illustrating model representations are founded on distinct representation systems and properties but can share similar abstract semantic content.

thus persisting in time (e.g., a rock). They may appear and disappear (e.g. ephemeral lakes), but when present they have all their essential parts. On the contrary, occurrents unfold over time as an ongoing development (e.g., an earthquake) and they are never fully present at any timepoint, missing some essential parts at each timepoint (e.g., the start of an earthquake is not present in the middle of its activity nor at its end).

Continuants are further delineated by their external dependence on entities that are not its parts: (1) a Specifically Dependent Continuant (SDC) exists only if another specific external entity exists, e.g., the color of a lump of mineral exists only if the specific mineral lump exists, with the color inhering in the lump and the color and lump are not a part of each other; (2) a Generically Dependent Continuant (GDC) exists only if some instance of a type exists, e.g., the content of a mineralogy book exists only if written on some unspecific hardcopy or hard-drive, with the content possibly written in multiple copies; and (3) an Independent Continuant (IC) is existentially unbound to any external entity, e.g., an amount of mineral is not dependent for its existence on any external entity, such as a geological unit, as the mineral exists even if detached from the unit. Other key entities extracted from BFO include qualities, such as color, shape, or size, and their values, such as green, round, or big, as well as dispositions, such as the capacity to host fluid flow. These entities are SDCs that inhere-in some IC, such as in a geological unit or fold.

IAO: Relevant IAO extensions of BFO include components for representation. Significantly, IAO delineates the information present in a representation from the bearer of the information, so the information can be borne by multiple representations, e.g. a book, a hard-drive, the toy bricks on a desk, or the mind of a geomodeller can all bear the same geomodel. The information is an Information Content Entity (ICE), which is immaterial. It is made concrete (concretized) in a quality, an Information Quality Entity (IQE), that inheres-in a material bearer, the Information Artifact (IA). "Inheres" then denotes a relation between certain dependent properties such as a quality (e.g. size, thickness, colour) and the entity that bears it. For example, as shown in Fig. 5, the information in a book consists of immaterial abstract symbols (ICE) and these are concretized by the specific pattern (IQE) that inheres-in the ink spots borne by a book, the bits in a file on a hard-drive, or the neurons of a mind (IA).

The ICE also is about something, such as the information about a real geological situation. Whereas the ICE generically depends on the bearer, as the information must be represented in some unspecific material thing, the IQE specifi-

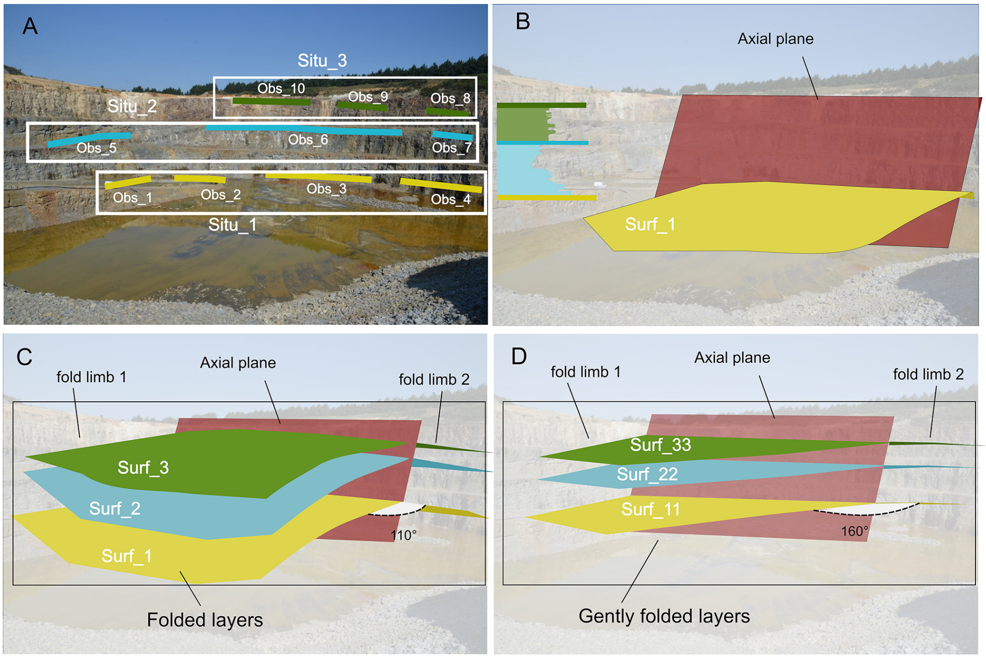

Figure 2. Use-Case 2 – representation of the study area and steps in the construction of a geomodel. From the literature it is known that folding structures have a maximum inter-limb angle of about 150°, thus such information can be used to constrain the model and validate it. Panel **(A)** shows the different observations grouped into three interpretation situations. Panel **(B)** shows a stratigraphic column (a conceptual model). Panel **(B)** also shows the first modelling iteration over situation 1 resulting in a folded yellow surface continuous over the space and the fold's axial plane in red. Panel **(C)** shows the final model after various iterations resulting in three folded surfaces and the fold. Panel **(D)** shows an alternate geomodel from an interpretation that is rejected due to its contradiction of the inter-limb angle constraint (over 150°).

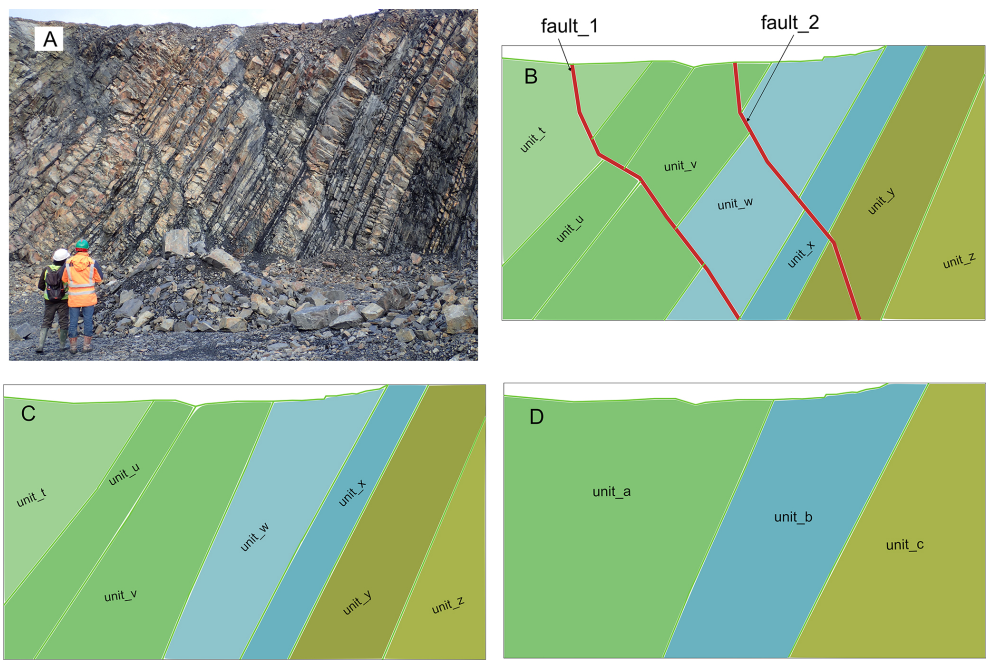

Figure 3. Use-Case 3 – the outcrop area **(A)** and different simplifications **(B, C, D)** made during its modelling. The outcrop and its geological layers can be modelled as distinct units with faults **(B)**, as distinct units without faults **(C)**, and as three lumped units **(D)**.

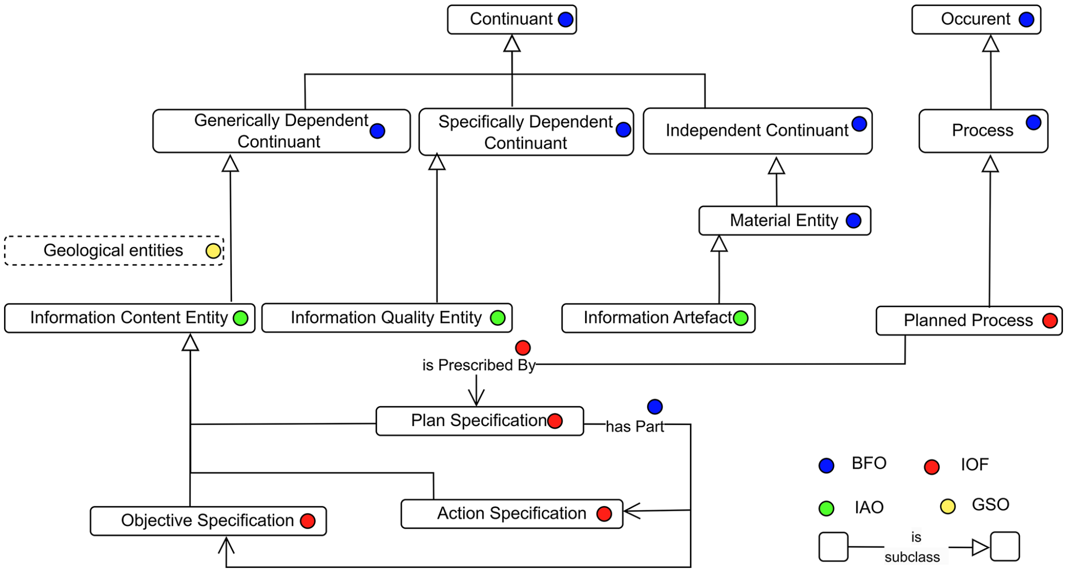

Figure 4. Components reused from BFO, IOA, IOF, and GSO. dashed lines denote multiple geological entities from GSO (not shown).

cally depends on its bearer, i.e. the inherent patterns can only belong to a specific book, hard drive, or mind, and not some other.

IOF: This ontology extends both BFO and IAO, and is a core ontology for data, processes, and information interoperability in manufacturing. Planned Process is of particular interest. It is an occurrent that runs over time following the steps laid out in some abstract Plan Specification, its ICE, as concretized in an IQE and manifest in an IA such as a hardcopy operations manual or digital software code. The plan specification has two ICEs as parts, an Action Specification and an Objective Specification, which respectively describe the steps to be run and the purpose of the plan. In a variation of the aboutness relation, a planned process is prescribed by the plan specification. This is highly relevant to POKIMON, inasmuch geosciences modelling and interpretation are planned processes.

GSO: GSO contains three layers. Its top layer includes general classes applicable to any discipline, adapting elements from top level ontologies such as BFO, DOLCE (Borgo et al., 2022), and UFO (Guizzardi and Wagner, 2010). The second layer contains geoscience classes and is meant to cover the range of entities in geology, such as geological objects, materials, structures, qualities, geologic time, and geologic relations. The third layer extends the general geoscience layer into specific geologic subdomains, for example for geologic units or structures, drawing on aspects of data exchange standards such as GeoSciML (Simons et al., 2006). GSO is a comprehensive ontology including over 8000 entities, but POKIMON utilizes only a few GSO classes, most notably Fold, Fault, and Geological Unit. These classes are further integrated with BFO: GSO geological units are independent continuants, and GSO geological structures are specifically dependent continuants that depend on some host, e.g., both folds and faults are hosted by specific geological units. Note that although POKIMON draws on GSO, other geo-ontology frameworks could be substituted, such as GeoCore (Garcia et al., 2020).

5 The POKIMON Ontology

In its current version, POKIMON consists of 178 classes and 57 relations, including entities borrowed from other ontologies. To convey POKIMON more effectively, we present both its theoretical foundations and its practical application to the use cases. This section is structured into four parts: (Sect. 5.1) a theoretical framework for the formalization of geomodels, (Sect. 5.2) the inputs to geomodelling, (Sect. 5.3) the processes involved in building geomodels, and (Sect. 5.4) the resulting outputs and their characteristics.

5.1 Information and Models in POKIMON

POKIMON fundamentally distinguishes a collection of objects and relations in the real world from their analogues in representations, such that each represented entity is about something in reality or that hypothetically could exist in reality. POKIMON adapts and extends the Information Artifact Ontology to successfully model this as an Information Content Entity that is about some real or hypothetical thing that can be multiply concretized, but this does not explicitly account for the same informational content being expressed through different representation paradigms. In other words, while copyability is captured, the nature of the representational system remains implicit. Therefore, POKIMON introduces an explicit separation between semantic and de-

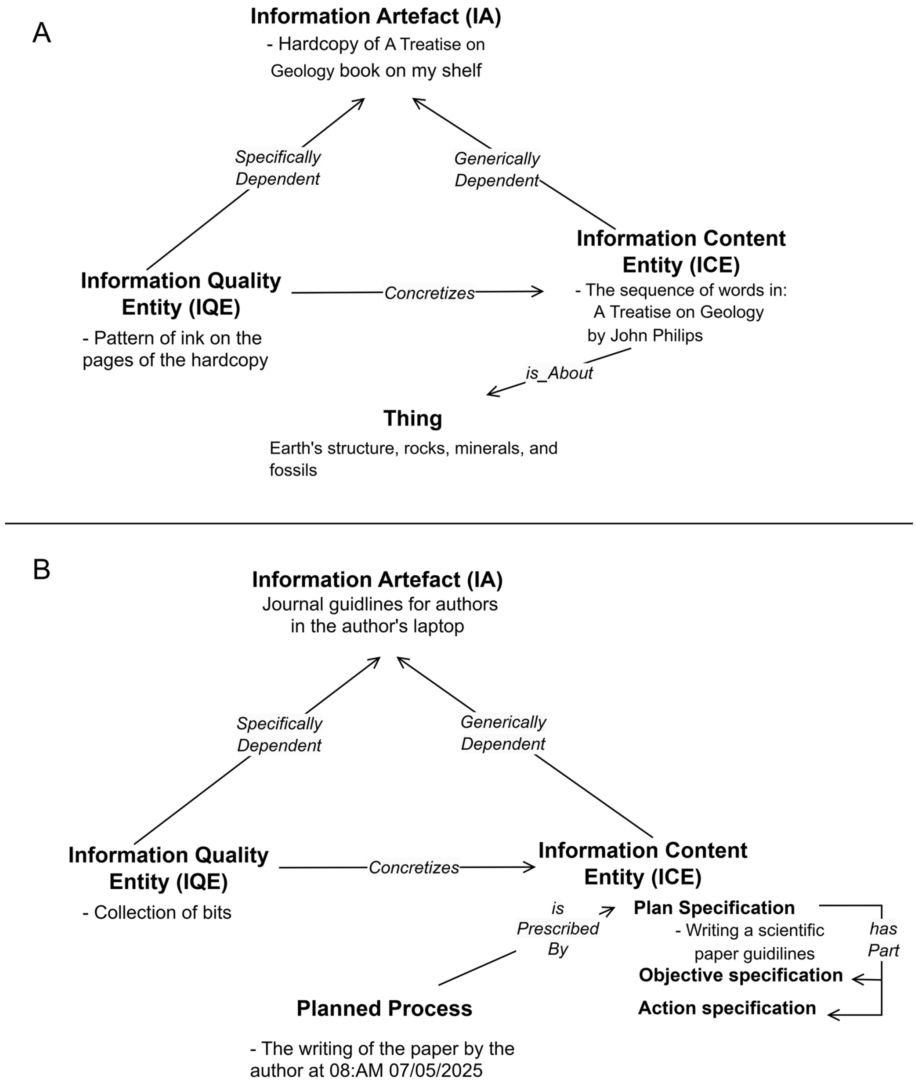

Figure 5. Main IAO/IOF components: representations of objects **(A)** and plan specifications **(B)**.

pictional components of informational content. A Semantic Content Entity captures the ontological and epistemic aspects of a representation. Ontologically, it links to geological entities, such as instances of faults or stratigraphic units. Epistemic aspects such as uncertainty, provenance (e.g., interpreted vs observed), and relation to (hypothetical) reality are then further associated with an SCE. Both ontologic and epistemic aspects are independent of their representation. A Depiction Content Entity (DCE) then specifies how the semantic content is structured and expressed in a representation paradigm. This distinction enables multiple heterogeneous representations to share the same semantic content while differing in their depictional form.

Such distinction applies to any geological entity, either simple such as the value of the dip of a surface derived from an observational data, or complex such as a model constructed via a geomodelling process. Accordingly, a model in POKIMON is a collection of SCEs, and it is a geomodel if its semantic content is about geological entities in (hypothetical) reality. Each geomodel contains one or more SCEs that link to geological entities and have epistemic aspects (Fig. 6), as well as a single depictional component. To achieve this, POKIMON further extends IAO:

– *Geomodel*: is an ICE that links to real geological entities via the aboutness relation. Each geomodel has Semantic Content Entities (SCE) and a Depiction Content Entity (DCE) as essential parts. The geomodel is internally specifically dependent on the SCEs and on the DCE. The dependence is internal because the SCEs and DCE are parts of the geomodel, which excludes the geomodel from specifically depending on the SCE in the BFO sense.

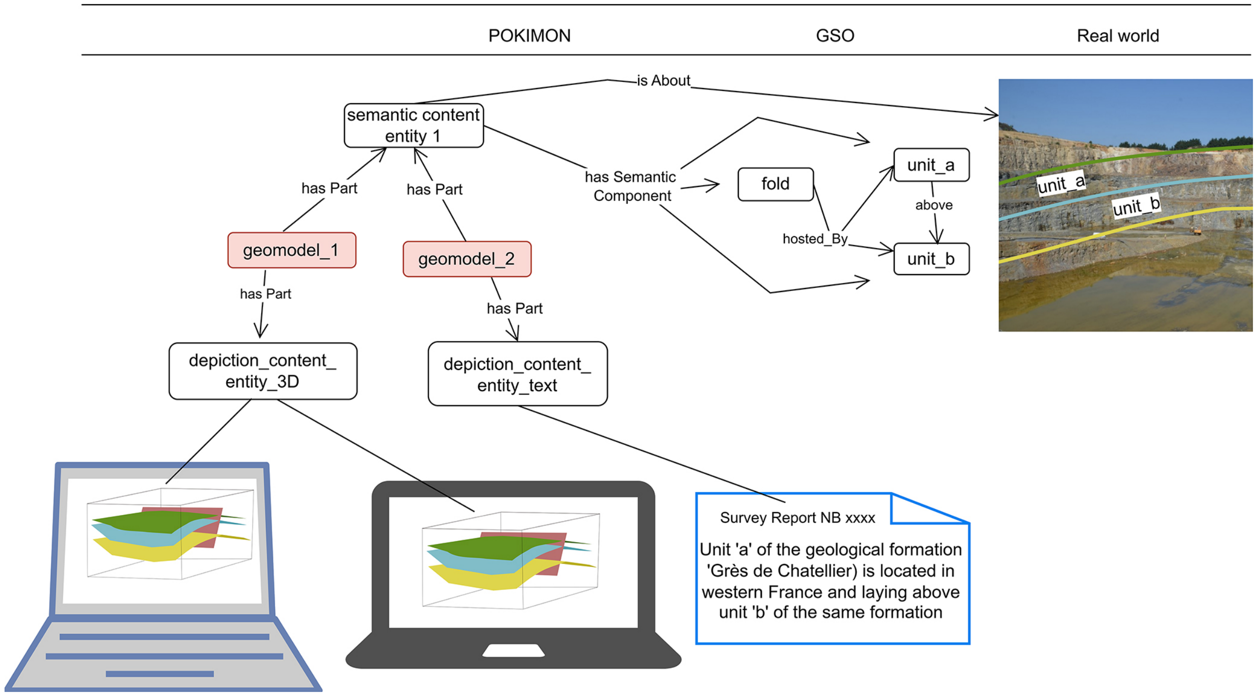

Figure 6. Semantic Content Entity (SCE) and Depiction Content Entity (DCE).

- *Semantic Content Entity* (SCE): is an ICE that links to a geologic entity, such as a geological unit, and possesses interpretative aspects, such as a record of the process of its interpretation, related uncertainty, and origin (e.g., observed). As with any ICE, the SCE is about something in (hypothetical) reality – some portion of reality that its contents are about.

- *Depiction Content Entity* (DCE): is an ICE specifying a paradigm for representation, such as a text report, a 2D map or 3D model, and specifies representational components, such as a particular font, specific image size or resolution, or a specific block size and shape. The DCE is about the same thing that is the subject of its geomodel. Furthermore, a geomodel and its SCEs and DCE are concretized by the same IQE. Four types of DCE are distinguished (after types of signs; Sowa, 2015):

  - *Figurative Content Entity*: the geomodel is represented using a figure. The figure can be volumetric, such as a 3D geometric model using explicit or implicit surfaces (Wellmann and Caumon, 2018), or planar, such as a sketch, image, section, or transect.
  - *Proposition Content Entity*: the geomodel is represented using a sequence of terms from a language (having a syntax and grammar) for artifacts such as reports, papers, and map sidebars.
  - *Connectionist Content Entity*: the geomodel is represented through a connectionist pattern such as a machine-learning model or the configuration of neurons in a mind (for mental representations).
  - *Material Content Entity*: the geomodel is represented as a configuration of material entities, e.g. plastic blocks or wooden sticks.

- *has_Semantic_Component*: a relation that holds between an SCE and a geological entity involved in interpretation.

- *has_Depiction_Component*: a relation that holds between a DCE and its representational components, e.g. size or scale.

5.2 Geomodelling Inputs

Observational data (e.g., field measurements, seismic lines) provide the empirical basis for constraining geomodelling workflows. These data are captured as Semantic Content Entities (SCEs). Geomodelling in a practical sense then begins with the placement of some SCEs into an Interpretation Situation (IS), which typically exhibits incompleteness (e.g., missing attributes) or inconsistency (e.g., deviation from expected geological configurations), so the situation bears a disposition of being interpretable. This disposition motivates the application of interpretative processes to complete, reconcile, or explain the situation. POKIMON then defines:

An *Interpretation Situation* (IS) is an Independent Continuant that is collection of SCEs that are selected to be interpreted. Once the collection is selected, if their geological entities lack attributes or deviate from established norms, then the situation acquires a disposition of being interpretable, e.g., some isolated parts of a geological surface that were observed, a fold that is interpreted without location and amplitude, or a normal fault exhibiting reverse displacement.

Figure 7 shows the POKIMON implementation of the three interpretation situations from the second use-case.

5.3 Geomodelling Processes

Geomodelling is a process that takes a collection of SCEs as input and produces one or more geomodels. In practice, it generates multiple intermediate (sub-)geomodels, many of which are revised or discarded, leading to one or several accepted final models. It is thus a complex, iterative process composed of interrelated subprocesses, shaped by the use case, the geomodeller, the tools employed, and the study area. At this stage, POKIMON provides an ontological backbone for formalizing knowledge about geomodelling processes, without imposing a single rigid framework. To illustrate how this backbone can be applied, we adopt the generic framework for geomodelling and interpretation proposed in Laouici et al. (2024), which describes a semi-automated, knowledge-based approach. Within this framework, geomodelling processes include, but are not limited to, interpretation, estimation, evaluation, and decision processes.

These processes are intentional processes in the sense of BFO/IOF: they are carried out by agents (human or systems) according to a plan that specifies how a given objective is to be achieved. Accordingly, each geomodelling process instance is a planned process that realizes a corresponding plan specification.

To adequately represent such processes, POKIMON extends the IOF process framework with two main contributions: (i) a refined characterization of planned processes, and (ii) the introduction of algorithms as a distinct subclass of plan specifications.

5.3.1 Planned processes

In POKIMON, a plan specification – used to prescribe a planned process – is specifically internally dependent on its action specification and objective specification parts, such that (1) any two plans with these same parts are identical and (2) replacing these parts results in a different plan. Conversely, an action specification can apply to zero or one plan, meaning it can exist without a plan, but if connected to a plan it is unique to the plan; whereas the objective specification can apply to multiple plans and be shared among them. For example, multiple experts working on separate geomodels for a region may share the same objective (i.e., to produce a consistent model for the region), but their individual plans may differ in terms of data preparation, interpretation, interpolation, and representation. Each planned process individual is prescribed by a single plan specification, but a planned process type is prescribed by possibly multiple plan specifications. An application then can query process types for appropriate plans to possibly execute, or query plan objectives to obtain plan actions and related process types.

Accordingly, the proposed geomodelling processes described in Laouici et al. (2024) are formalized in POKIMON as follows:

- *Interpretation Process*: inputs are situations, and the output is a geomodel. An interpretation process is typically composed of several sub-processes, which are appended as parts during the creation of a geomodel: e.g. selecting, adding, modifying, deleting, evaluating or deciding on SCEs and their components.
- *Estimation Process*: estimates values of qualities of geological entities, e.g. through mathematical operations such as interpolation to propose characteristics for entities in a geomodel, such as shape or thickness. Inputs are qualities and outputs are values attached to the qualities.
- *Evaluation Process*: assesses a geomodel for its satisfaction of various information entities such as norms, constraints, and other geomodels. The input is a geomodel and the output is an evaluation quality attached to the geomodel with values listing the degree of conformance.
- *Decision Process*: assesses whether a geomodel should be kept or abandoned. Inputs are the geomodel and its evaluation, and the output is a decision entity (which is an Information Entity) such that the decision is about the model.
- *Representation Process*: takes a geomodel having a SCE as input and outputs a DCE and information artifact such as a text report, a 3D digital file on hard-drive, toy bricks configuration, or mental state.

5.3.2 Algorithms

A central objective of POKIMON is to formalize geomodelling knowledge in a machine-readable manner and to enable computational systems to understand and possibly execute geomodelling processes. It is then crucial to specify the algorithms that prescribe how such processes are carried out. POKIMON defines Algorithm as a subtype of plan specification, one that is a finite, ordered set of unambiguous instructions for solving a problem or performing a computation that, when executed, produces a result. An algorithm uniquely determines the actions of a planned process to achieve its goal, and while its objective may be shared across multiple algorithms, the specific sequence of steps – the action specification – is unique to each algorithm. Algorithms in geomodelling are associated with one of these key action specifications:

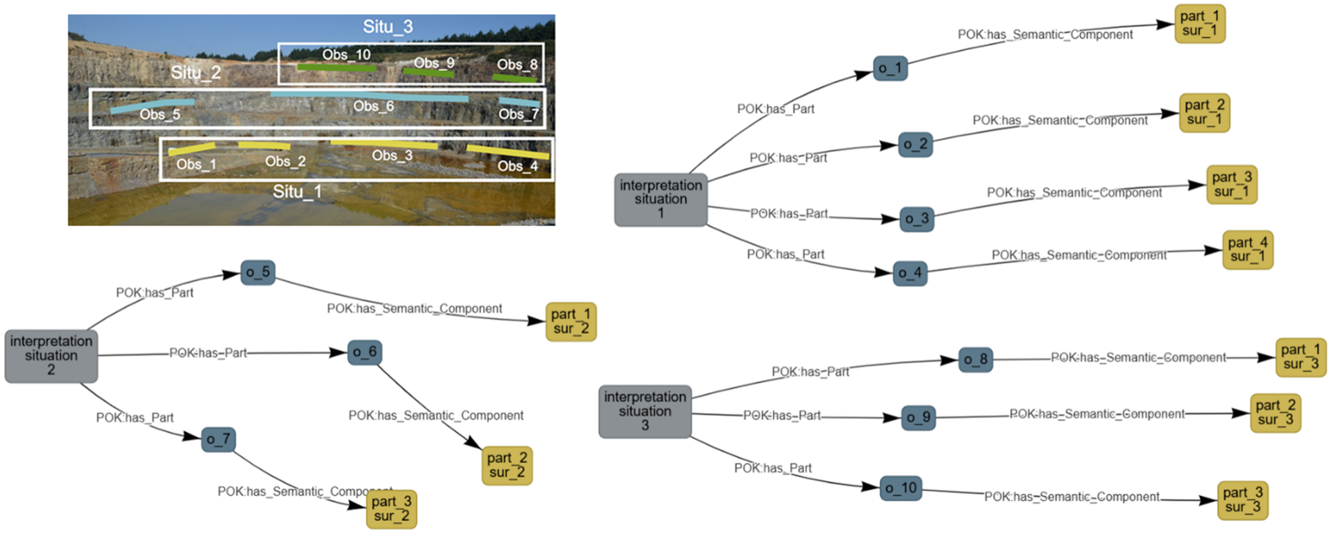

Figure 7. Example of the three interpretation situations and their relations to observations from use-case 2. Each interpretation situation has a collection of SCEs as its parts (steel blue boxes). These SCEs link in their turn to the geological entities (modeled as parts of the boundaries of a geological unit) (yellow boxes).

- *Deterministic action specification*: specifies step-by-step actions with precise instructions in a specific order, with no randomness for conditional operations. An example is kriging – a mathematical method to estimate unknown values of a given quality across space (Oliver and Webster, 1990). Different kriging variants (e.g., ordinary, simple, co-kriging) are implemented in geomodelling tools. In POKIMON, each kriging variant is represented as a distinct action specification, detailing the step-by-step procedure specific to the method. These action specifications are associated with individual algorithm instances (e.g., Algorithm: Ordinary_Kriging, Algorithm: Simple_Kriging). Despite their procedural differences, all these algorithms share a common objective specification: computing unknown spatial values.

- *User-based action specification*: relies on inputs and decisions based on user preferences. For example, during model validation, a geologist may choose among alternative interpretations of a seismic horizon based on their domain knowledge (Di and Gao, 2016).

- *Conditional action specification*: outlines actions that are dependent on specific conditions, allowing for more flexible responses to changing circumstances. For instance, in geomodelling workflows, fault modelling follows different procedures depending on the intersection with stratigraphic surfaces (Caumon et al., 2009).

- *Random action specification*: specifies actions chosen randomly from a list of possible actions, introducing an element of unpredictability. An example from geomodelling is Monte Carlo Uncertainty Estimation (MCUE), where multiple plausible geological models are generated by randomly sampling disturbance in observations (Pakyuz-Charrier et al., 2018a, b). In POKIMON, this is modelled as a random action specification.

- *Probabilistic action specification*: specifies actions that have ranges of possible outcomes and are executed based on probabilities. E.g., in structural geomodelling, Bayesian inference is used to estimate the posterior probability distribution of fold parameters (Grose et al., 2018).

- *Machine learning action specification*: outlines actions determined by models that learn and adapt from data over time and have a black-box component. One example is the use of geometric deep learning with graph neural networks (GNNs) to construct the geometries of structural surfaces in models (Hillier et al., 2021).

Figure 8 shows selected geomodelling processes in the second use-case and their implementation in POKIMON framework.

5.3.3 Unplanned processes

Another important category of processes addressed in POKIMON are *geological processes*. These are not geomodelling processes per se, but they are fundamental for understanding the geometry and spatial organization of geological entities represented in a geomodel. Although geological processes are typically not explicitly encoded within current geomodelling systems, they are often described in associated resources such as scientific reports and publications. As POKIMON aims to provide a comprehensive ontological backbone

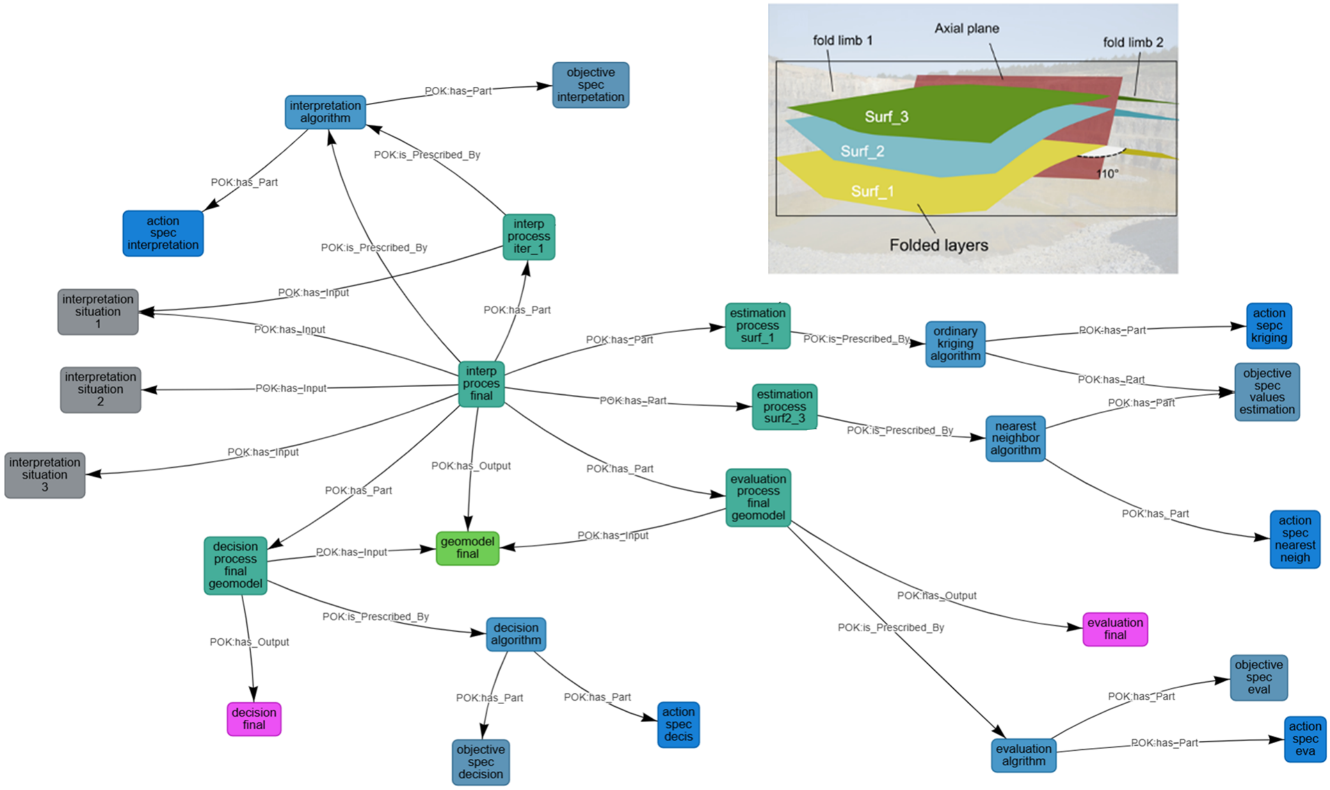

Figure 8. Representation in POKIMON of the geomodelling processes described in use-case 2. It includes the overall interpretation process and subprocesses that generated an initial and the final geomodel of use-case 2 (shown in the top right corner); nodes representing processes are shown in spring green. Algorithms prescribing these processes, their objectives and action specifications are shown in blue boxes. The interpretation process "final" has five subprocesses, including estimation of the surface_1, estimation of surfaces 2&3 together, an evaluation and decision processes. The overall interpretation process has inputs (grey boxes) consisting of the three interpretation situations described in the previous example (Fig. 7). The two interpretation processes share the same interpretation algorithm. The two estimation subprocesses of the geological surfaces have different algorithms of interpolation, but both algorithms share the same objective while diverging in the action specifications. The evaluation and decision subprocesses have the same input (the generated geomodel), the former has an evaluation entity for output and the latter a decision entity (both in pink boxes).

for geomodelling knowledge, it is necessary to account for these processes, even when they are not directly operationalized, e.g., by identifying a particular originating process type or instance.

To this end, POKIMON extends the IOF framework by explicitly incorporating the notion of *unplanned processes*. In alignment with IOF, unplanned processes correspond to natural processes that are not prescribed by a plan specification, such as erosion, folding, or faulting. These processes unfold according to physical and geological norms rather than intentional action specifications. Within POKIMON, unplanned processes can be components of *Semantic Content Entities (SCEs)* – for example, an SCE may capture the sequence of depositional and intrusive events responsible for a given stratigraphic arrangement. As per BFO, processes only have parts that are processes, thus either planned or unplanned. For example, consider a person throwing a rock from a cliff: the launching part is planned with an objective and predefined action, the falling part is unplanned and governed by gravity. All processes involve participants as inputs or outputs, and all continuants in POKIMON can participate in processes, though some processes are restricted to certain participant types. E.g. unplanned geological processes have some geological entities as inputs and outputs. All geomodelling processes are considered planned processes and have restricted participants.

5.4 Geomodelling Outputs

The primary outputs of a geomodelling process are one or more geomodels deemed valid by geomodellers with respect to a given objective specification and background knowledge. In addition, the inherently iterative nature of geomodelling leads to the production of multiple intermediate geomodels (or sub-geomodels), many of which are subsequently revised, refined, or discarded. POKIMON provides a unified characterization of both intermediate and final outputs as instances of geomodels, differing in their role within the process and their degree of acceptance.

To better account for the characteristics of geomodelling outputs and related validation, POKIMON first distinguishes two types of geomodels, conceptual and space-time, and introduces two essential ontological relations: satisfies and contradicts.

5.4.1 Types of geomodels

A Conceptual Geomodel (Fig. 9) is essential and relational: it specifies the essential properties and relations for a geological object, but not exact geospatial location. Examples include stratigraphic columns, geological map legends, and cartoon maps or Lego models. Non-essential properties and relative positioning are optionally included, such as located in southern France, beside a certain unit, or older than a certain unit. In contrast, the objects in a Space-Time Geomodel are fully located in geospace and time, such as those in a geological map or an interpolated 3D geomodel.

This distinction is ontological rather than epistemic: a conceptual geomodel is not necessarily a validated, causal, or expert-held interpretation, but a coarse abstraction that may precede, guide, or result from data acquisition and processing. In practice, geologists often collect data guided by an existing conceptual geomodel, which may function as an interpretative framework and influences how observations are acquired and interpreted. However, this is not a requirement. Conceptual geomodels may also be constructed after data acquisition, iteratively refined, or generated computationally, or entirely derived from a space-time geomodel (e.g., defining a conceptual geomodel from a stochastic forward model). As a result, conceptual and space-time geomodels may converge during the modelling process, but they remain distinct: one defines a coarse understanding of possible geological configurations, while the other is a specific configuration with an explicit spatial and temporal character.

Critically, to be valid, a space-time geomodel satisfies some conceptual model, and each SCE in the space-time model satisfies one or more SCEs in the conceptual model. The geological entities in a conceptual geomodel thus are reflected without contradiction by a space-time geomodel. E.g. the entities in a geological map legend or stratigraphic column (conceptual geomodel) are reflected without contradiction by the contents of any associated geological map or 3D model (space-time geomodel), thus the geological map satisfies the map legend.

Satisfies and *Contradicts* are relations that indicate respectively whether an entity, or pair of entities, conforms to, or contravenes, a governing entity, such as a geomodel, norm, or constraint (see next section). These relations hold between: (1) geomodels; (2) geomodels or SCEs and a norm or constraint; and (3) SCEs in different geomodels.

A conceptual model can be satisfied by multiple space-time models, reflecting the various interpretations possible in the geological mapping or modelling process, including the possibly different algorithms used to obtain the same model. An SCE in a conceptual model also can be satisfied by multiple SCEs in a single space-time model. E.g. if a stratigraphic unit is comprised of several disconnected spatial fragments, then each fragment satisfies the compositional and topological criteria set out for the unit in the conceptual model. In addition, a geological entity can belong to multiple geomodels with a distinct interpretation in each geomodel, e.g. the same fold could be interpreted with various uncertainties and different algorithms in different space-time models. Note that a space-time geomodel (and its contents) not only satisfies a conceptual model (and its contents), but also likely contradicts other conceptual models and their contents. Conceptual models also can satisfy other more general conceptual models, to account for model generalization, or contradict other conceptual models or space-time models.

Figure 10 shows how these foundations are applied to address use-cases 1 and 2.

5.4.2 Validation of geomodels

For a geomodel to be valid, it ought to satisfy norms, and constraints which are often described as prior knowledge. In POKIMON, a norm or a constraint is an Information Entity that manifests in reality, but does not need to be represented to exist:

- *Norm*: is an information entity that governs the behavior of other entities. This includes geological laws, principles, and theories that govern the behavior of natural entities, such as Walter's law (López, 2015), superposition principle (De Freitas, 2009), and plate tectonics (Falvey, 1974), respectively.

- *Constraint*: An information entity that imposes limits on aspects of geological entities within a geomodel but is not part of the initial inputs used to generate the model (e.g., in the interpolation process). Constraints may define fixed bounds (e.g., minimum/maximum length, thickness, or wavelength), spatial conditions (e.g., location of a geological surface), or structural requirements (e.g., number of elements). They can be formally expressed through ontology-based restrictions (e.g., a fold has exactly two limbs) and referenced in POKIMON if needed. Constraints help document why certain geomodels are rejected (Laouici et al., 2024). Importantly, geological data (e.g., bedding measurements, contact points) are not constraints themselves but observations of geological entities. Constraints are derived from such data and specify how they guide modelling – for example, requiring a surface to pass through a location or conform to an orientation range. In this sense, data describes reality, while constraints define how such reality guides or restricts geomodel construction.

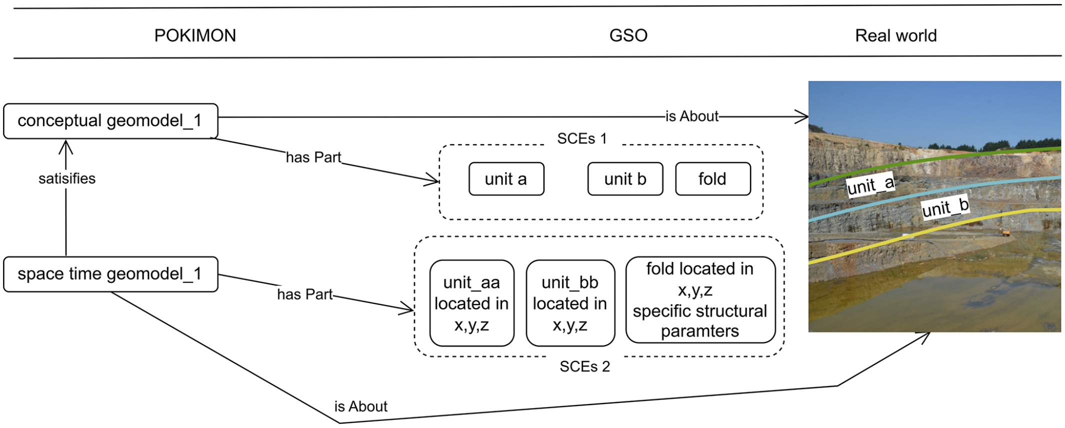

Figure 9. Conceptual and Space-Time geomodels (dashed lines denote a has Part relation to a distinct SCE).

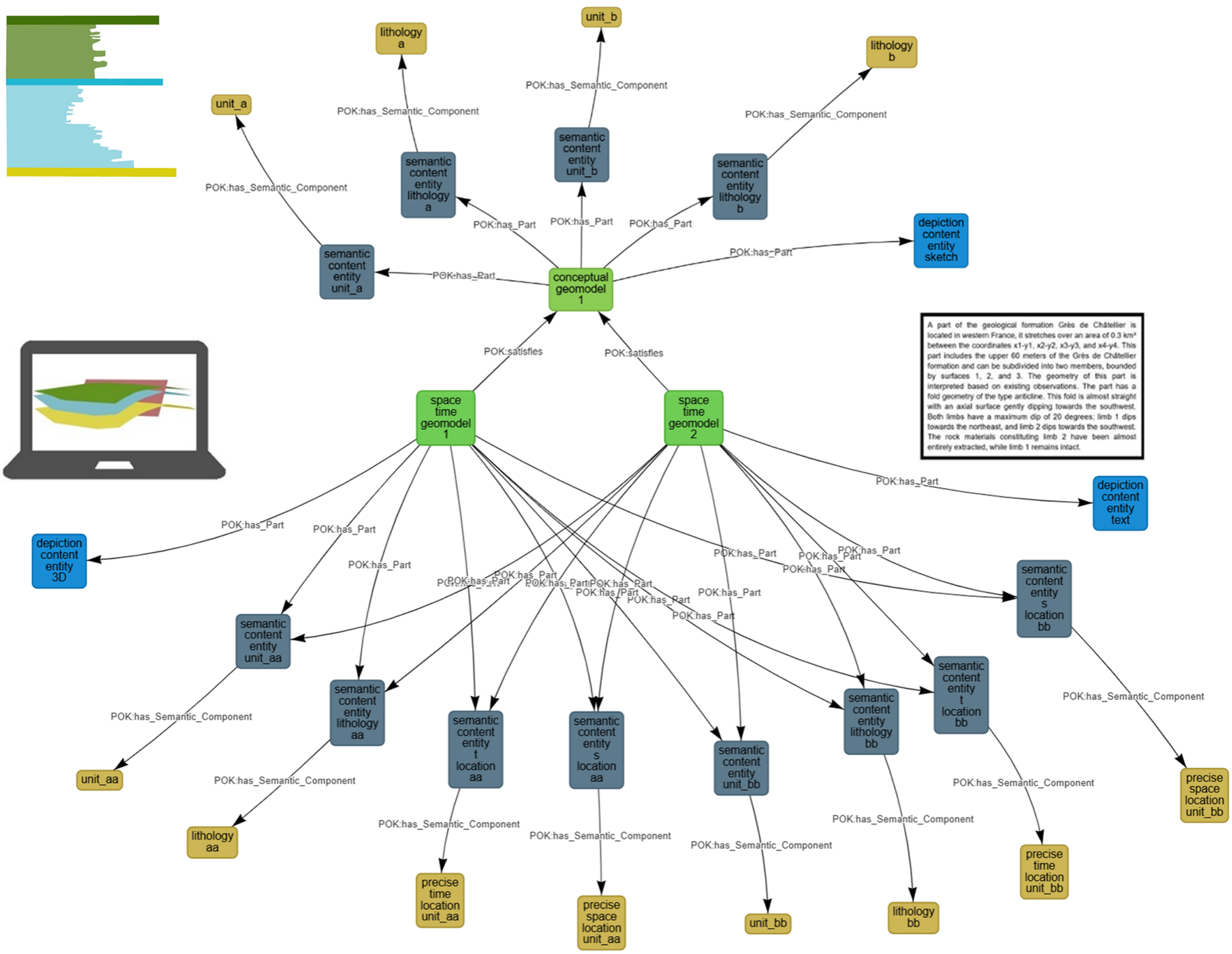

Figure 10. Example of two space-time geomodels representing the same semantic content entities with different depictional components (3D and text; from use case 1). The geomodels are shown in green and the depiction content entities are shown in blue. SCEs are shown in steel blue while geological entities are shown in yellow. These two geomodels satisfy the same conceptual geomodel (the stratigraphic column left upper corner) from use-case 2.

Each SCE, its associated geological entity, and the geomodel itself can satisfy or contradict a norm or constraint as shown in Fig. 11.

Because geomodel construction is iterative, validation occurs progressively: intermediate geomodels and their components are evaluated during the construction process. This may lead to refinement of existing SCE properties or the creation of new entities (Laouici et al., 2024). If a geomodel successfully accounts for a situation without violating relevant norms, constraints, or conceptual models, an explains relation is established.

- *Explains*: A relation between a geomodel and a situation, where the geomodel explains the situation by satisfying (and not contradicting) relevant norms, constraints, and conceptual models. Due to the iterative nature of geomodelling, this relation may temporarily hold for intermediate geomodels before all the prior knowledge is fully verified.

Finally, POKIMON does not explicitly include an "interpretation" continuant: any geomodel that explains a situation is, by definition, a valid interpretation. Conversely, invalid geomodels fail to explain the situations for which they are proposed. Figure 11 illustrates the explanation of the previous three situations throughout interpretation iterations.

5.4.3 Simplification of geomodels

A geomodel is a selective representation of geological reality at a given granularity, which determines which constraints apply and how they are enforced. Features below a defined scale may be omitted, and constraints may vary with resolution; thus, a model may satisfy all constraints at one level while violating them at another. Within POKIMON, the outcomes of such activity are captured via the simplifies/details relations, which provides a formal mechanism to relate models across levels of detail. In addition, the simplification process itself can be modeled as a planned processes; the term simplification is preferred over abstraction to avoid overloading the latter, which in Ontology Engineering typically denotes ontology-internal conceptual operations (Cima et al., 2023; Ginzburg, 2005). Important aspects include:

- *Geological Resolution:* A BFO quality inhering in an information content entity (e.g., a geomodel) that determines the granularity of geological entities it can represent, and thereby conditions which entities are included or omitted, as well as which constraints are applicable.
- *Simplifies:* A relation between two geomodels where one reduces the complexity of another by representing fewer geological entities, or the same entities at a lower level of detail.
- *Details:* The inverse of *simplifies*. It holds when one geomodel increases the complexity of another by representing additional entities or finer detail.

A canonical example of simplification addressed by POKIMON is found in geological mapping platforms: zooming in reveals finer subdivisions of units with further structural detail; these units appear as larger blocks at lower resolution. Thus, when two geomodels represent the same situation at different resolutions, they can be compared through simplification relations, which operate exclusively between geomodels

Simplification (and its inverse, detailing) operates through two main mechanisms. First, aggregation, where multiple entities are grouped (lumped) into a higher-order entity (e.g., several fault segments represented as a single structure, or formations grouped into a geological group). Second, omission, where entities are excluded because they fall below the model's resolution (e.g., small faults deemed insignificant). For two geomodels to stand in a simplifies/details relation, they must be of the same type (e.g., both conceptual or both space-time models) and differ in resolution. By contrast, geomodels of similar resolution that represent partially overlapping but non-identical sets of entities are not simplifications of one another. Instead, the following relations apply:

- *Overlaps:* A relation between geomodels of the same type and similar resolution that describe (partially) the same geological entities.
- *Ignores:* A relation holding between a geomodel and the geological entities represented in a comparable geomodel (of similar resolution) but absent from the former.

Figure 12 illustrates how the described simplification aspects are implemented concretely in POKIMON.

5.4.4 Origins

The final characteristic is the origin of components. POKIMON characterizes the epistemic status of SCEs based on the degree of certainty about the geological entities being modelled. It distinguishes three origins and models them as BFO qualities:

- Observed origin: A quality assigned to an SCE when the information is certain, as in cases where it is directly recorded from real-world phenomena and for which there is no dispute regarding their existence (e.g., an outcropping layer or a visible fault plane). The agreement concerns their presence, even if interpretations may later differ, or certainty about some of its value i.e., measurement uncertainty).
- Interpreted origin: A quality applied when entities whose existence is argued for based on indirect evidence, reasoning, or background geological knowledge. Their presence (or absence) can be debated among geologists, and they result from interpretative inference.

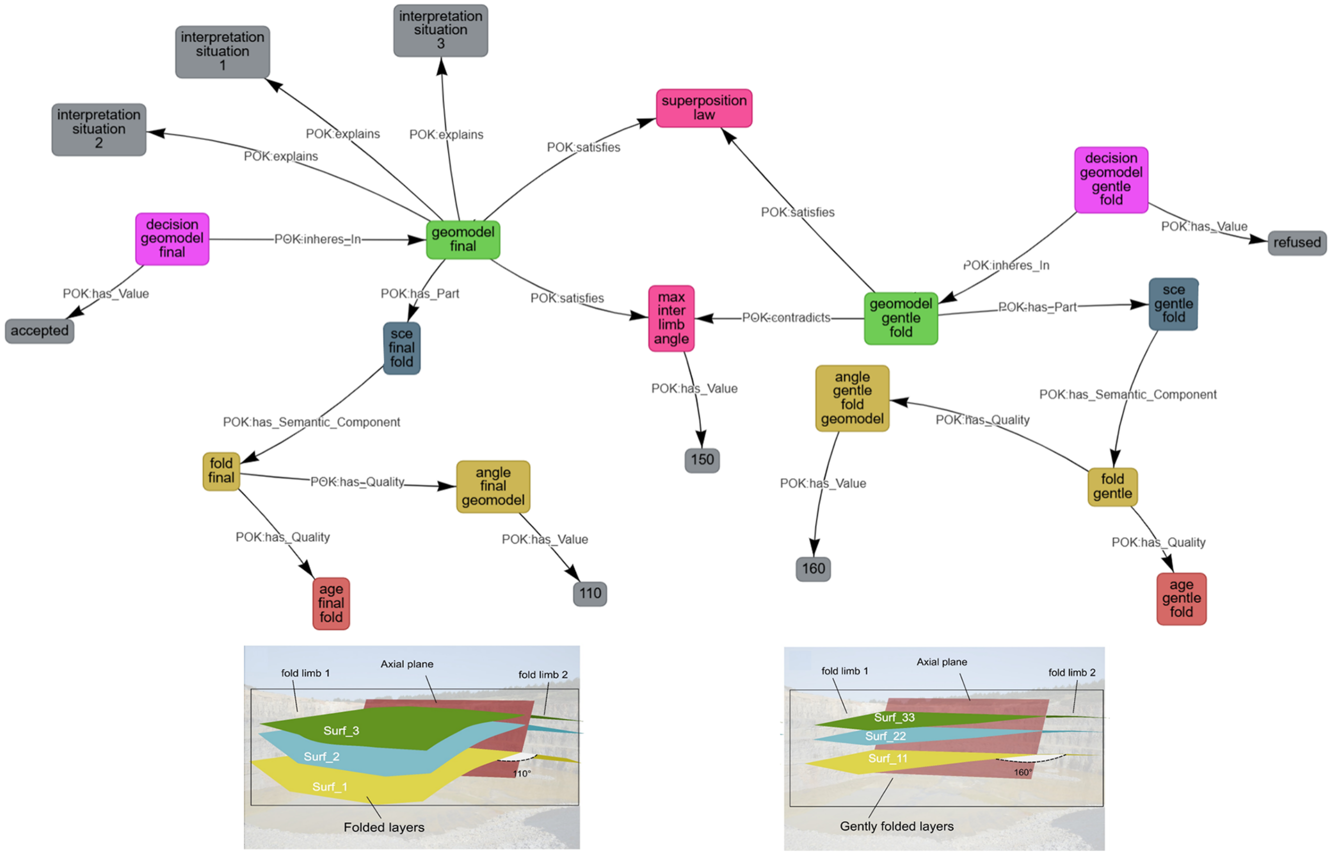

Figure 11. An example from use case 2 with an accepted and rejected geomodel with their SCEs and linked geological entities (yellow boxes; selected for aspects of folds). Geomodel nodes are in green, the decision entities in pink. Both geomodels satisfy the superposition law (pink box) but only the "final" accepted geomodel satisfies the constraint of 150° for the inter-limb angle. The other geomodel contradicts this constraint and is therefore rejected. Accordingly, an explains relation is asserted between the accepted geomodel and the interpretation situations (grey boxes).

– Assumed origin: A quality indicating the SCE is created purely for modelling purposes involving entities that knowingly do not exist in reality, but their (non)existence relies primarily on background theory. Assumed entities are hypothetical constructs introduced for explanatory, pedagogical, or simplification purposes. For example, a teacher might ask students to imagine a specific geological configuration beneath the university campus and construct a model of it, despite being aware that such a configuration does not actually exist.

Figure 13 shows the origins of SCEs in the final geomodel of use case 2.

6 Evaluation and discussion

6.1 Evaluation

POKIMON is implemented in the ontology web language OWL (Antoniou and Harmelen, 2009; Breitman et al., 2007) using Protégé (Noy et al., 2003), and can be found at this link (POKIMON, https://doi.org/10.5281/zenodo.17375904, Laouici and Brodaric, 2025). Axioms adapted from other ontologies are migrated into the POKIMON namespace and prefixed with "pok" in the OWL implementation, to distinguish them from the original. The adaptations are meant to retain the essence of the original.

Reasoning and queries over the use-cases instances are executed without delay for this small application run on a desktop PC with moderate capacity (10th Gen Intel i5 CPU). SPARQL queries used to generate the presented graph-based outputs above are shown in Figs. A1–A8 (Appendix), demonstrating how POKIMON enables structured querying of modelling results, including interpretations. Additional applications illustrating the full capabilities of POKIMON's components are provided in Laouici (2024).

Through application, POKIMON demonstrates meeting the conceptual content requirements identified in the Use Cases (Sect. 3):

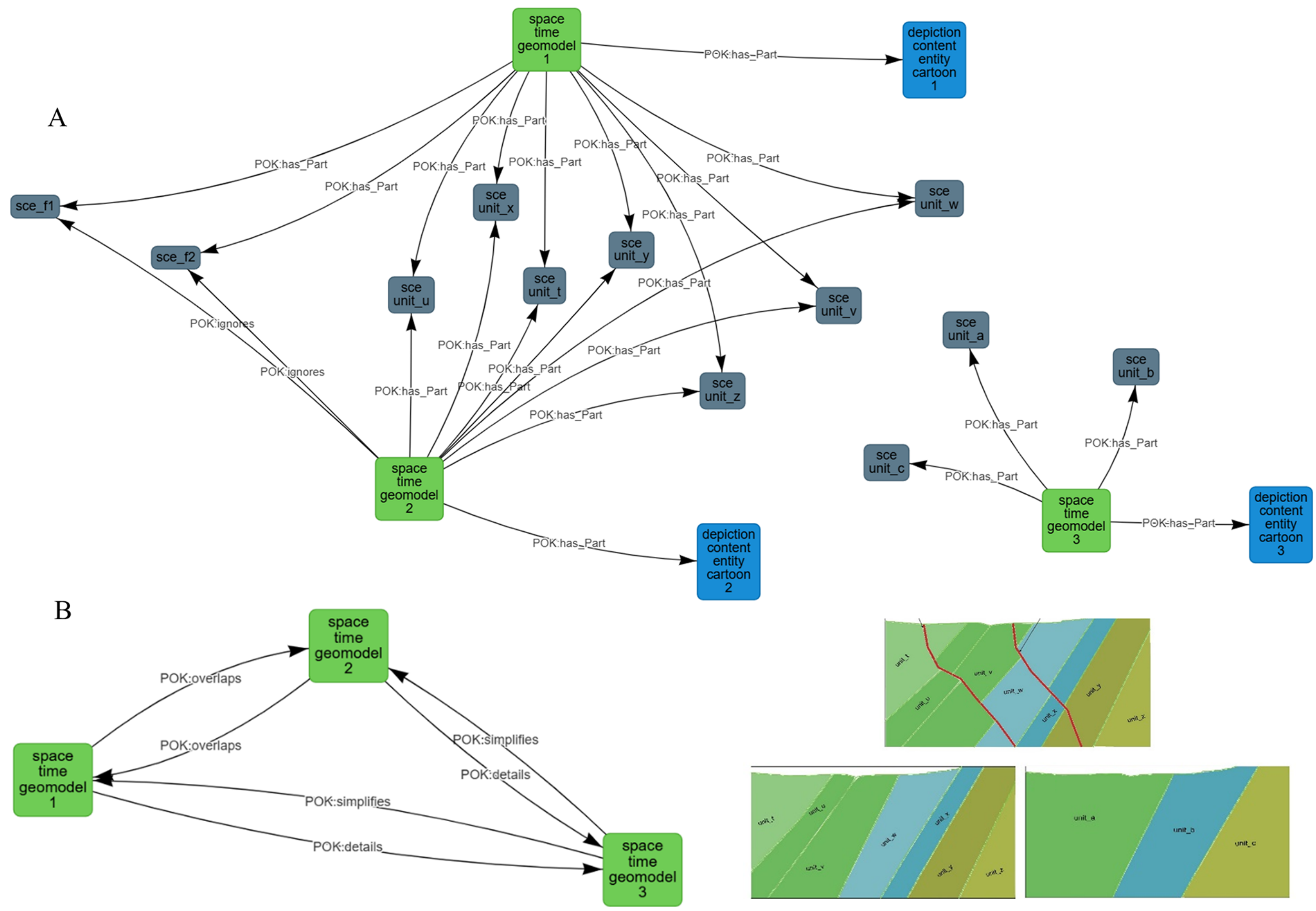

Figure 12. Three space–time geomodels from Use Case 3: geomodel 1 (upper model in the lower-left inset) includes all entities and faults; geomodel 2 (lower-left) ignores faults; and geomodel 3 (bottom-right) represents the most simplified case, with three lumped units. **(A)** Illustrates the semantic components and omitted entities of each model, and **(B)** shows the resulting simplification and overlap relations.

- Application to Use-Case 1: demonstrates satisfaction of requirements (R_{I}): ontological formalization of the abstract content of information and relation to the representation paradigms.
- Application to Use-Case 2: demonstrates satisfaction of requirements ($R_{\mathrm{II–VIII}}$): the geological models and their types) (R_{II}, R_{VI}), involved geological entities (R_{III}), situations (R_{IV}), geomodelling and interpretation processes (R_{V}), norms and constraints (R_{VII}), and the empirical nature of model components (R_{VIII}).
- Application to Use-Case 3: demonstrates satisfaction of requirement (R_{IX}): model simplification.

These major POKIMON components are illustrated in Figs. 14 and 15. Furthermore, their application has been informally reviewed by geological and geomodelling experts, with the results found to be reasonable and the related knowledge and interpretative processes to be adequately represented. Logical consistency is verified by the Hermit (Glimm et al., 2014) and Pellet (Sirin et al., 2007) reasoners in Protégé, not only for the ontology itself, but also for its application to the use-cases.

6.2 Discussion

3D geomodels are often described as a combination of inputs and outputs, including relevant concepts, interpolation algorithms, and 3D artifacts (Calcagno et al., 2008; Loiselet et al., 2016). While this pragmatically enables adequate storage and query of geomodels, it views geomodels from a functional rather than an ontological perspective and overlooks key distinctions, such as the conceptual and space-time model behind every geomodel. The conceptual framework behind a geomodel therefore is incomplete in such a functional perspective, and this can hinder downstream usage such as fully informed decision-making that considers the history of interpretation, including the underlying theoretical and conceptual basis. These gaps align with several challenges posed by Whitehead and Gahegan (2012) about the epistemic and uncertain aspects of geoscientific information often not addressed by geological ontologies. POKI-

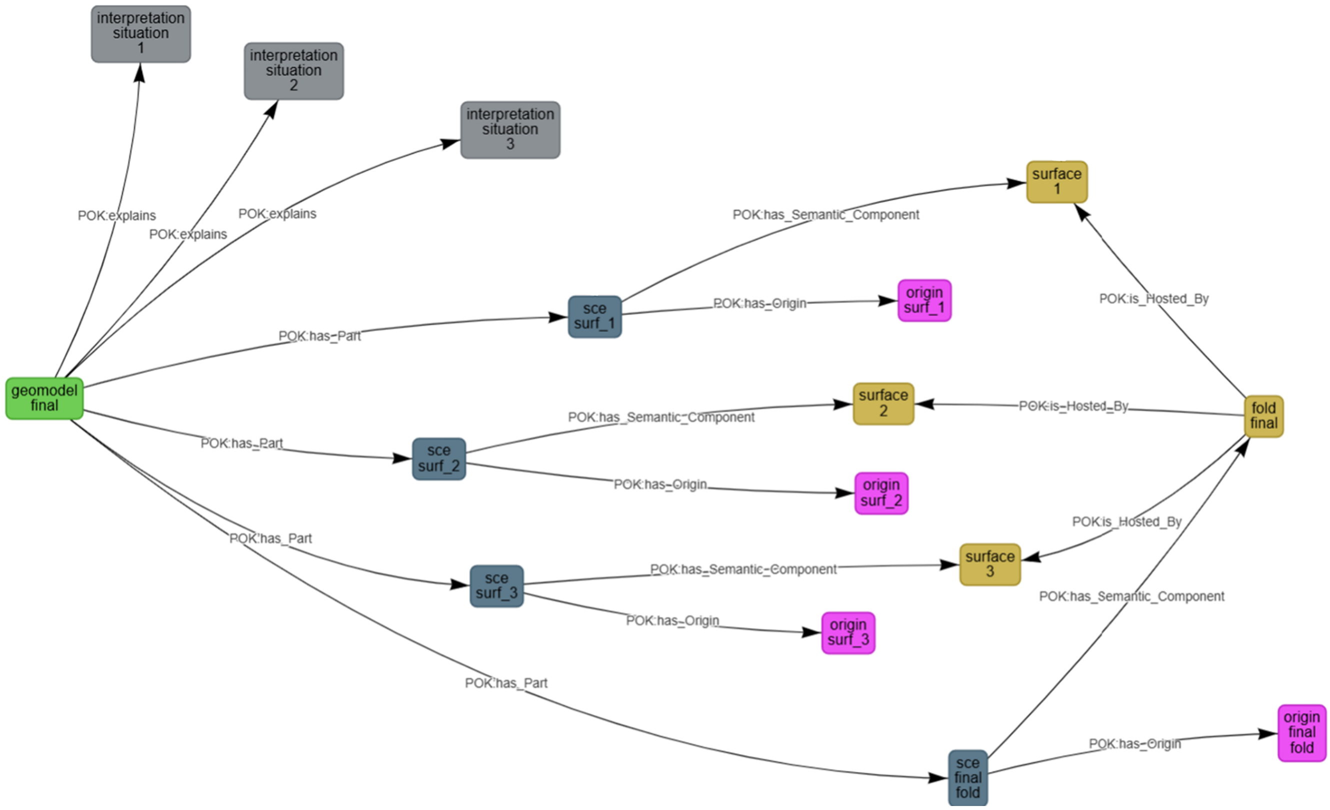

Figure 13. Origin of the semantic content entities from the final geomodel of use-case 2. The final geomodel is shown in the green box, its SCEs in steel blue, interpretation situations in grey, modeled geological entities in yellow, and origin of the SCEs nodes are shown in pink boxes.

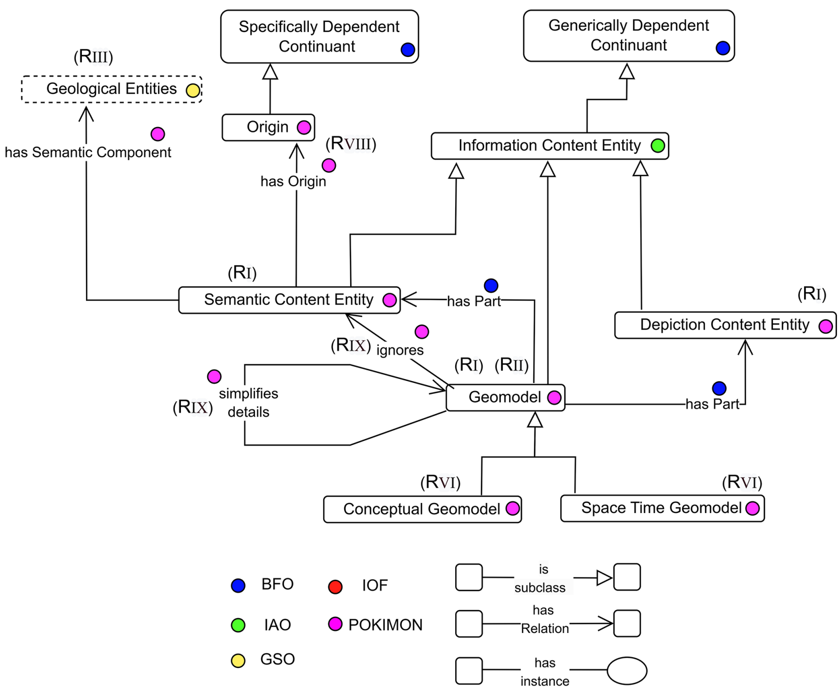

Figure 14. Main POKIMON geomodel-related entities; dashed box denotes multiple classes from POKIMON.

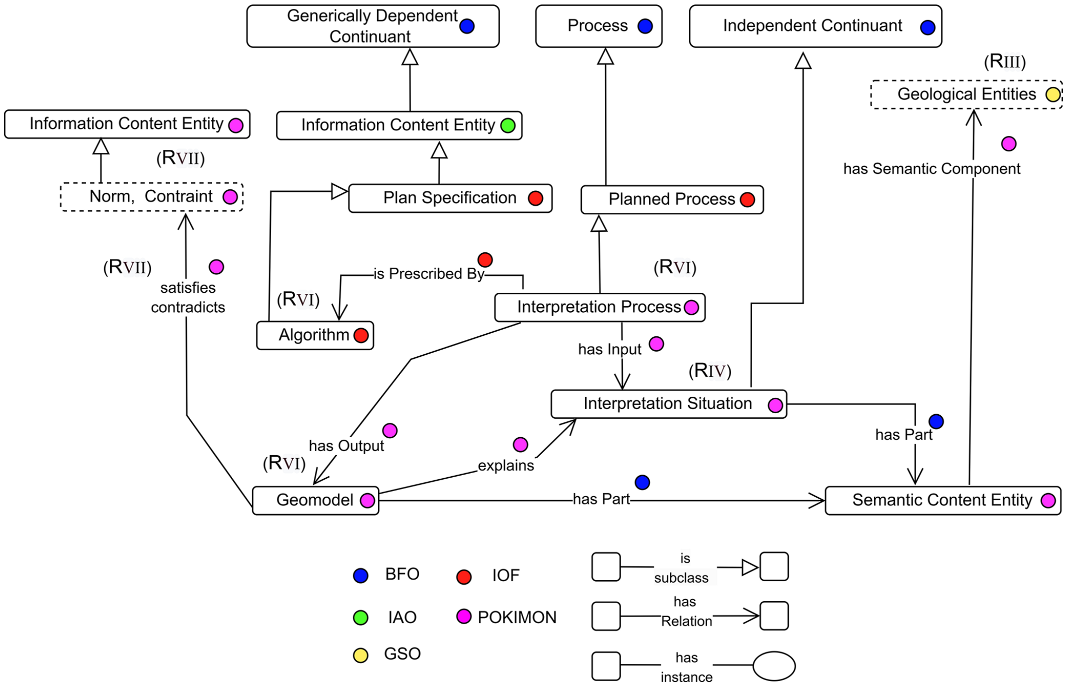

Figure 15. Main POKIMON interpretation-related entities; dashed box denotes multiple classes.

MON begins to address these gaps by enabling representation of many of these aspects.

An outstanding question concerns comparison of geological conceptual models, as described herein, and informational conceptual models, as described by the applied ontology and knowledge engineering communities. Apart from building on BFO, IAO, and IOF, POKIMON's geological conceptual model also builds on the contributions of Perrin and Rainaud (2013), which delineate models, representations, and visualizations, and Abel et al. (2019), who categorize and formalize visual content in petroleum engineering. Altogether, these foundations further align with Guizzardi (2005) and Guarino et al. (2020), who describe conceptual models as a group of abstract constructs filtered by mental representations (mental models) and expressed using a modelling language (e.g., UML, FOL) in some specification (e.g., a file on hard-drive).

POKIMON's alignment with this approach is shown in Fig. 16: a collection of SCEs is akin to a conceptualization, a DCE encompasses modelling languages, and an information artifact is a specified model. However, there also exist some differences:

- Conceptual model: is the resultant artifact in Guarino et al. (2020), whereas in POKIMON it is the abstract structure consisting of the non-depictional components (SCEs). In this sense, POKIMON's conceptual model is akin to a conceptualization in Guizzardi (2005) and Guarino et al. (2020). This preserves a common understanding in the geosciences in which a conceptual model is a generalized and abstract description of a geological configuration (Chambefort et al., 2016; Miller et al., 2010; Silva-Fragoso et al., 2021; Wolf, 1976; Zhang, 2008).
- Mental model: unlike Guarino et al. (2020), a mental model does not have a privileged position in POKIMON, it is simply another artifact – another representation of an underlying abstract structure (the conceptualization) that need not be mental.
- Artifact: following IAO, a model must be represented in POKIMON – there must be an artifact – but this dependency is not explicit in the other approaches, though might be implicit.
- Interpretation: as any representation is a construction, POKIMON explicitly represents the construction process, whereas it is implicit in these other approaches.

A ramification of the proposed approach concerns the metaphysical nature of geomodel contents. Whereas a geological entity in the real world is an actual entity – one that can be touched and sampled – entities in conceptual or space-time geomodels are hypothetical (or possible) geological entities that are about an actual entity. Then each represented entity is associated with three entities (actual, conceptual, space-time), and each of these is an individual instantiating a geological class, e.g., each actual fold and each hypothetical fold in a conceptual or space-time geomodel is an individual instantiating the class Fold class. Furthermore, real and hypothetical entities might have different but compatible essential

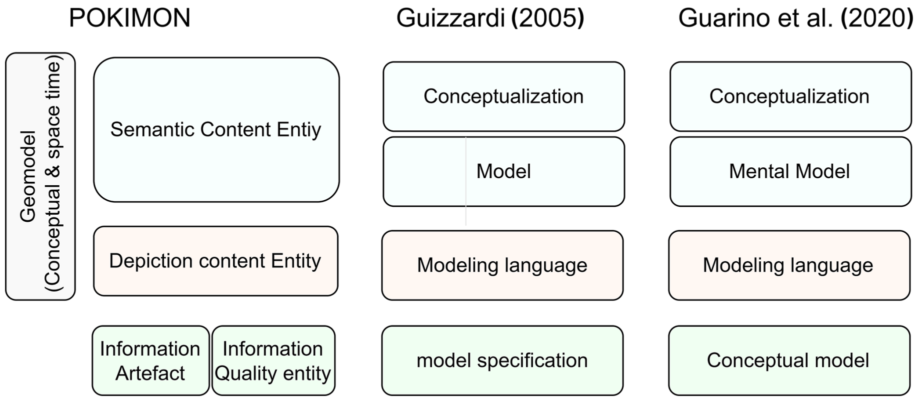

Figure 16. Comparison with related definitions of conceptual models.

properties: although both follow the essential properties for instances set out in the class, hypothetical entities might add essential properties. E.g. it might be essential for a fold in a conceptual model to have some unspecified amplitude or wavelength, and it might be essential for a fold in a space-time model to have a specific amplitude or wavelength.

Then any change of these characteristics leads to a different fold instance with a distinct SCE, with the SCE thus reflecting the reason and processes involved in the change. This does, however, lead to a further question about the metaphysical nature of things in a conceptual geomodel. It is tempting to understand them as classes rather than individuals, because they are a structural and content pattern repeated in possibly multiple objects in a space-time model. However, POKIMON's treatment of them as individuals has practical as well as theoretical value. Practically, ontology design and reasoning is simplified as it avoids adding conceptual model contents, e.g., Unit_X, to the geology ontology class hierarchy. On the theoretical side, BFO's notion of an ICE repeating in some bearers is extended such that an ICE can also repeat within an ICE, e.g. a conceptual model repeats in some space-time models (via satisfies), which further repeat in some bearers (via concretizes and inheres-in).

POKIMON provides a flexible framework to represent multiple facets of expert knowledge during 3D geomodel construction. Its deployment in existing modeling environments has begun, for example in a knowledge-driven 3D modeling system (Laouici et al., 2024), where the ontology supports interpretation, though only a precursor ontology (MOGI) has been implemented to date. Understanding the geological interpretation process in depth remains important; POKIMON is neutral regarding the content populating its structure, so comprehensive surveys of tools, practices, and expert preferences are needed to guide knowledge-driven geomodelling.

In practice, POKIMON can be integrated into routine 3D geomodelling workflows as a semantic layer associated with existing modelling environments, without requiring modification of the logic of the underlying software. During model construction, key steps – such as data selection, interpretation, interpolation method choice, constraint definition, and simplification decisions – can be captured as structured semantic entities and processes. Rather than only storing the final geometrical outputs (e.g., surfaces or volumes), the modelling workflow itself becomes explicitly documented, including which observations support certain interpretations, which assumptions are introduced, and which computational methods are applied.

This explicit representation enables several practical uses. First, it supports traceability and reproducibility by preserving the sequence of modelling decisions, allowing alternative models to be compared based on their underlying assumptions and constraints rather than only their geometrical outputs. Second, it facilitates collaborative modelling by making implicit reasoning explicit and shareable across experts and teams. Third, it enables systematic comparison of scenarios, for example by identifying how different parameter choices, datasets, or conceptual assumptions lead to divergent model realizations.

With respect to uncertainty, POKIMON does not directly quantify uncertainty but provides a framework to localize and characterize its sources. Uncertainty may arise from sparse or uncertain observations, interpretative choices, simplifications, or algorithmic parameters. By explicitly representing these components and their relationships, POKIMON enables a structured analysis of epistemic uncertainty, making it possible to trace how such uncertainty propagates through the modelling workflow and influences the final geomodel.

While this paper focuses on 3D geological models, the ontology is sufficiently flexible to accommodate geodynamic, hydrodynamic, or other simulation-based models (e.g., weather simulation models), provided that the relevant domain geosciences ontology describes the natural processes to be simulated. Then the simulated natural processes can be modelled as planned processes, which are about the real or hypothetical natural processes modelled as geological entities linked to SCEs, e.g. as sedimentation processes from GSO.

7 Conclusion

This paper presents POKIMON, an ontology designed to capture the knowledge aspects in 3D geosciences modelling. By integrating foundational concepts from established ontologies such as the Basic Formal Ontology (BFO), the Information Artifact Ontology (IAO), the Industrial Ontologies Foundry (IOF), and some geology ontology (e.g., GSO), POKIMON provides a robust basis to represent both geomodel objects and interpretation processes. Through detailed examples and use cases, the efficacy of POKIMON is demonstrated, including its capacity to encapsulate complex geological interpretations during modelling. As such, POKIMON contributes to the advancement of knowledge-driven 3D geosciences modelling.

Appendix A

```
PREFIX poki: <http://www.POKIMON#POK:>
SELECT DISTINCT ?subject ?predicate ?object
WHERE { ?subject rdf:type ?Interpretation_Situation .
  { ?subject poki:has_Part ?object .
    BIND(poki:has_Part AS ?predicate)}
  UNION
  {?subject poki:has_Semantic_Component ?object .
    BIND(poki:has_Semantic_Component AS ?predicate)}}
```

Figure A1. SPARQL query to retrieve the graph-based output in Fig. 7, including the interpretation situations of use-case 2, their SCE parts, and their semantic components (“o_”).

```
PREFIX poki: <http://www.POKIMON#POK:>
SELECT DISTINCT ?subject ?predicate ?object
 WHERE {{ VALUES ?targetClass { poki:Interpretation_Process
 poki:Estimation_Process poki:Evaluation_Process
 poki:Decision_Process }
     ?subject rdf:type ?targetClass .
     ?subject poki:has_Part ?object .
     BIND(poki:has_Part AS ?predicate)}
   UNION
   { VALUES ?targetClass { poki:Interpretation_Process
 poki:Estimation_Process poki:Evaluation_Process
 poki:Decision_Process }
     ?subject rdf:type ?targetClass .
     ?subject poki:is_Prescribed_By ?object .
     BIND(poki:is_Prescribed_By AS ?predicate)}
    UNION
   { VALUES ?targetClass { poki:Interpretation_Process
 poki:Estimation_Process poki:Evaluation_Process
 poki:Decision_Process }
     ?subject rdf:type ?targetClass .
     ?subject poki:has_Input ?object .
     BIND(poki:has_Input AS ?predicate)}
    UNION
   { VALUES ?targetClass { poki:Interpretation_Process
 poki:Estimation_Process poki:Evaluation_Process
 poki:Decision_Process }
     ?subject rdf:type ?targetClass .
     ?subject poki:has_Output ?object .
     BIND(poki:has_Output AS ?predicate)}
   UNION
   { ?subject rdf:type poki:Algorithm .
     ?subject poki:has_Part ?object .
     BIND(poki:has_Part AS ?predicate)}}
```

Figure A2. SPARQL query to retrieve the graph-based output in Fig. 8, including the interpretative processes in use-case 2, their parts as sub-processes, their inputs and outputs, the prescribing algorithms of these processes, and the objective and action specifications of related algorithms.

```
PREFIX poki: <http://www.POKIMON#POK:>
SELECT DISTINCT ?subject ?predicate ?object
WHERE {{ VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:has_Part ?object .
    BIND(poki:has_Part AS ?predicate)}
  UNION
{ VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:satisfies ?object .
    BIND(poki:satisfies AS ?predicate)  }
  UNION
  { ?subject rdf:type poki:Semantic_Content_Entity .
    ?subject poki:has_Semantic_Component ?object .
    BIND(poki:has_Semantic_Component AS ?predicate)}}
```

Figure A3. SPARQL query to retrieve the graph-based output in Fig. 10, including the geomodels, their parts, the semantic components, and the relation of satisfaction.

```
PREFIX poki: <http://www.POKIMON#POK:>
SELECT DISTINCT ?subject ?predicate ?object
WHERE {{ VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:has_Part ?object .
    BIND(poki:has_Part AS ?predicate)}
  UNION
  { VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:satisfies ?object .
    BIND(poki:satisfies AS ?predicate)}
   UNION
  { VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:contradicts ?object .
    BIND(poki:contradicts AS ?predicate)}
  UNION
  { VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:explains ?object .
    BIND(poki:explains AS ?predicate)}
  UNION
  { VALUES ?targetClass { poki:Evaluation poki:Decision }
    ?subject rdf:type ?targetClass .
    ?subject poki:inheres_In ?object .
    BIND(poki:inheres_In AS ?predicate)}
 UNION
 { ?subject rdf:type poki:Semantic_Content_Entity .
   ?subject poki:has_Semantic_Component ?object .
   BIND(poki:has_Semantic_Component AS ?predicate)}
  UNION
 { ?subject rdf:type poki:Fold .
   ?subject poki:has_Quality ?object .
   BIND(poki:has_Quality AS ?predicate)}
 UNION
 { ?subject poki:has_Value ?object .
   BIND(poki:has_Value AS ?predicate)}}
```

Figure A4. SPARQL query to retrieve the graph-based output in Fig. 11, which includes the accepted final geomodel and the refused geomodel generated during interpretation in use-case 2. It also displays the satisfaction and contradictions of norms as well as the resulting qualities and their values.

```
PREFIX poki: <http://www.POKIMON#POK:>
SELECT DISTINCT ?subject ?predicate ?object
WHERE {{  VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:has_Part ?object .
    BIND(poki:has_Part AS ?predicate)}
  UNION
  {  VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:ignores ?object .
    BIND(poki:ignores AS ?predicate)}}
```

Figure A5. SPARQL query to retrieve the graph-based output in Fig. 12, including the geomodels of use-case 3, their parts, and relationships to ignored entities.

```
PREFIX poki: <http://www.POKIMON#POK:>
SELECT DISTINCT ?subject ?predicate ?object
WHERE {{ VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:simplifies ?object .
    BIND(poki:simplifies AS ?predicate) }
  UNION
{  VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:details ?object .
    BIND(poki:details AS ?predicate)}
    UNION
 {  VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:overlaps ?object .
    BIND(poki:overlaps AS ?predicate)}}
```

Figure A6. SPARQL query to retrieve the graph-based output in Fig. 12, including relations of simplification, detailing, and overlap between geomodels of use-case 3.

```
PREFIX poki: <http://www.POKIMON#POK:>
SELECT DISTINCT ?subject ?predicate ?object
WHERE {{ VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:has_Part ?object .
    BIND(poki:has_Part AS ?predicate)}
  UNION
  { VALUES ?targetClass { poki:Conceptual_Geological_Model
poki:Space_Time_Geological_Model }
    ?subject rdf:type ?targetClass .
    ?subject poki:explains ?object .
    BIND(poki:explains AS ?predicate)}
  UNION
  { ?subject rdf:type poki:Semantic_Content_Entity .
    ?subject poki:has_Semantic_Component ?object .
    BIND(poki:has_Semantic_Component AS ?predicate)}
  UNION
  { ?subject poki:is_Hosted_By ?object .
    BIND(poki:is_Hosted_By AS ?predicate)}
    UNION
   { ?subject rdf:type poki:Semantic_Content_Entity .
     ?subject poki:has_Origin ?object .
     BIND(poki:has_Origin AS ?predicate)}}
```

Figure A7. SPARQL query to retrieve the graph-based output in Fig. 13, including the final geomodel, its semantic components, and their origins (use-case 2).

Code and data availability. The ontology and data generated during the current study are publicly available in the Zenodo repository at https://doi.org/10.5281/zenodo.17375904 and can be cited as Laouici and Brodaric (2025).

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