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INTERPETATION AND REPRESENTATION IN GEOMODELS: the POKIMON ontology for formalizing geomodelling knowledge

Imadeddine Laouici[1-3], Boyan Brodaric[2], Christelle Loiselet[3*], Gautier Laurent[1]

[1]ISTO, UMR 7327, Université d'Orléans, CNRS, BRGM, OSUC, F-45071 Orléans, France
[2]Geological Survey of Canada, Natural Resources Canada, 601 Booth Street, Ottawa, ON K1A 0E8, Canada
[3]BRGM, Orléans, F-45060, France
[*] Now at Institut de Recherche de la Construction, ESTP, 28 Avenue du Président Wilson, F-94230, Cachan, France

Correspondence to: Imadeddine Laouici (i.laouici@brgm.fr)

Abstract. With their growing volumes and uses, it is increasingly important to understand the interpretative and representational aspects of three-dimensional (3D) geosciences models. 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, reasoning steps, and uncertainties typically remains tacit in the mind of the geomodeller. 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, interpretative choices, and conceptual structures underlying 3D geosciences models. POKIMON provides a formalized framework to represent how geological and geomdelling concepts are applied during model construction. Motivating use cases, the ontological structure, and its 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

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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 direction 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). 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 the description of the 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 (Section 2), this paper introduces motivating use-cases and establishes the requirements for POKIMON (Section 3). The method of construction, including a recap of reused ontologies are presented in Section 4, while Section 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). 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).

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A shortcoming of the latter is the lack of reuse of domain geology ontologies, while such reuse is 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. Furthermore, important conceptual considerations are made to distinguish between a model, its representation, and its visualization (Perrin and Rainaud, 2013), 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~~. any of these previous ontologies.

Existing ontologies also do not represent the interpretive tasks 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 interpretations. 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.

If we can define workable standards without an ontology underlying it – why do we need ontologies at all?? (I do think ontologies are important – but this needs to be explained to the reader in this section).

3 Use-cases

Seven use-cases are developed to help specify POKIMON requirements and guide its design (Laouici, 2024), but this paper will focus on the three most significant cases that illustrate what are models, how they are built, and their main characteristics. Although not exhaustive, these 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-meter-thick Ordovician layer and consists of sandstone, siltstone, and quartzite beds. These beds are slightly metamorphosed and lack clear lithological separation (Verhnet, 2010), thus their further delineation is purely synthetic and included for demonstration purposes.

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

- Use-Case 1: Figure 1 depicts different representations and geomodels for selected geological units in the quarry: (Fig. 1A) a photographic image as one particular representation of the units; (Fig. 1B) stratigraphic columns illustrating a

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geological conceptual model (R_{I}) containing some relations and properties of the units, but without exactly locating them in space and time; (Fig. 1C) a digital rendition of a *geological space-time model* (R_{II}) locating the units in space and time; and (Fig. 1D) an alternative textual representation of the same space-time model, illustrating model representations are founded on distinct *representation systems and properties* (R_{III}) (Liben et al., 2010).

- Use-Case 2: Figure 2 shows the construction of a geomodel with emphasis on the interpretation process. (Fig. 2A) illustrates a series of observations grouped into three situations using principles of spatial proximity and lateral continuity, with each situation requiring distinct interpretation. Numerous iterations over situations generate 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. Ontological requirements then include: the *geological entities* (R_{IV}) to be contained by a geomodel; *situations* (R_{V}) and their links to initial observations; *interpretations* (R_{VI}) documenting how geomodel parts are derived; *interpretation processes* (R_{VII}) used to infer and assess the geomodel parts documented in interpretations; the *origins* (R_{VIII}) of represented geological entities, such as observed, assumed, or interpreted; and associated *geological norms* and *constraints* (R_{IX}).
- Use-Case 3: Figure 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_{X}). 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}).

↳ Consider adding a few paragraphs on simplification, why it is necessary, and how it is typically achieved to the previous section. Formalization of this simplification process is one of the most valuable applications that I see for POKEMON. (Gotta catch 'em all? No - just enough to get the job done!)

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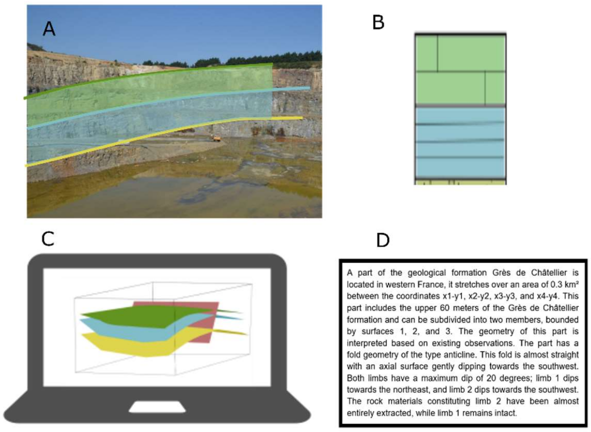

Figure 1: Use-Case 1 -representation of the study area (A) and different types of models. The conceptual model for this area is shown in B as a stratigraphic column, and a fully spatio-temporally described model is shown as a digital 3D model in C, and as text in D

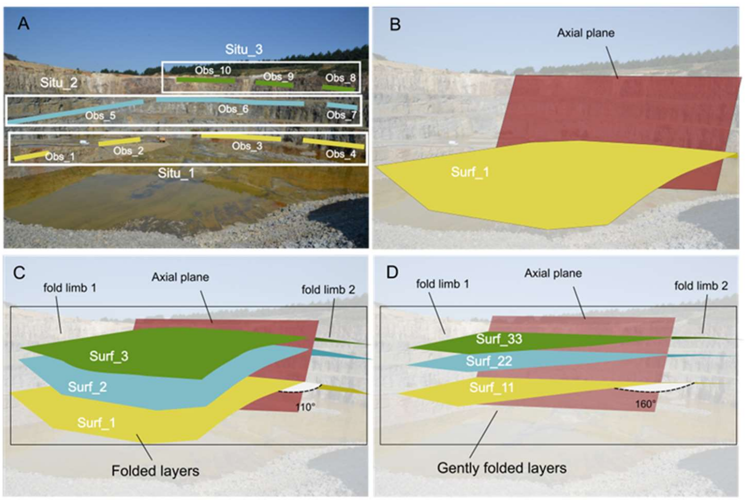

Figure 2: Use-Case 2 - representation of the study area and steps in the construction of a geomodel. A maximum inter-limb angle is set to 150° as a modelling constraint. (A) shows the different observations grouped into three interpretation situations. (B) is a first modelling iteration over situation_1 resulting in a folded yellow surface continuous over the space and the fold's axial plane in red. (C) shows the final model after various iterations resulting in three folded surfaces and the fold. (D) shows an alternate geomodel from an interpretation that is rejected due to its contradiction of the inter-limb angle constraint.

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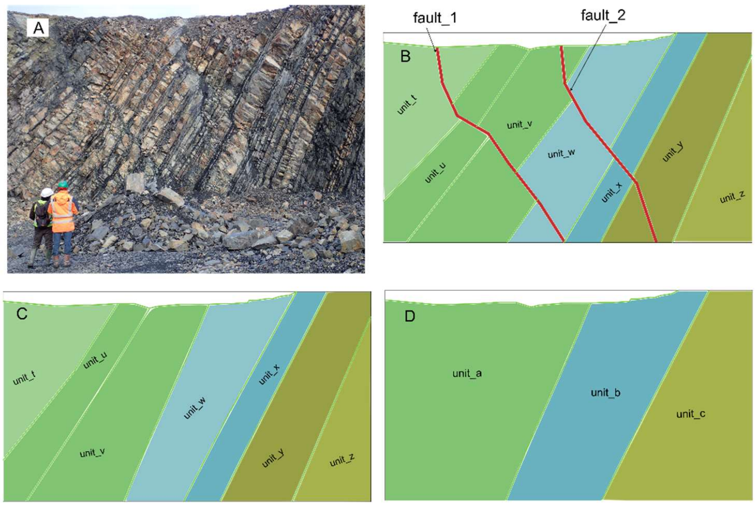

Figure 3: Use-Case 3 - the outcrop area (A) and different simplifications (B, C, D) made during its modelling. The outcrop and its geological layers can be modelled as distinct units with faults (B), as distinct units without faults (C), and as three lumped units (D).

In summary, the key content requirements for POKIMON include:

- (R_{I}) Geological conceptual model;
- (R_{II}) Geological space-time model;
- (R_{III}) Representation systems and properties;
- (R_{IV}) Geological entities;
- (R_{V}) Situations to be interpreted;
- (R_{VI}) Interpretations of situations;
- (R_{VII}) Interpretation processes;
- (R_{VIII}) Empirical nature of model contents: e.g., observed, interpreted, assumed;
- (R_{IX}) Geological norms and constraints;
- (R_{X}) Simplification aspects.

⟹ it would be useful to include a short definition (in a table?) for each of these aspects, as they are not self-explanatory.

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 (Figure 4).

→ These guiding "use-case" examples are all at quite a small scale (compared to many geomodels). Might larger models (e.g. of the Permian Basin, or of "Switzerland", have different ontological requirements? Please justify why all three examples are so similar (quarry scale, lightly deformed sedimentary rocks).

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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., 2021). 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, persisting in time (e.g., a rock). They may appear and disappear, but when present they have all their essential parts. On the contrary, occurrents are never fully present at any timepoint, missing essential parts at a timepoint, as they unfold over time as an ongoing process (e.g., an earthquake).

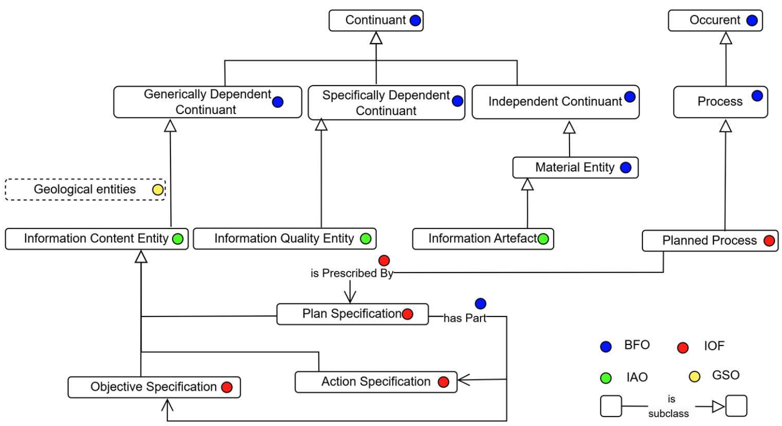

Figure 4: components reused from BFO, IOA, IOF, and GSO. dashed lines denote multiple geological entities to be borrowed from GSO that are not hierarchized in this preview).

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, while the color and lump are not a part of the 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)

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an Independent Continuant (IC) is existentially unbound to any external entity, e.g., a Material Entity, such as 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 that will be 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 abstract thus immaterial. It is made concrete (concretized) in a quality, an Information Quality Entity (IQE), that inheres-in a material bearer, the Information Artifact (IA). For example, as shown in Figure 2, the information in a book consists of 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 specifically depends on its bearer, e.g. 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. Of particular interest is Planned Process which 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 can be 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).

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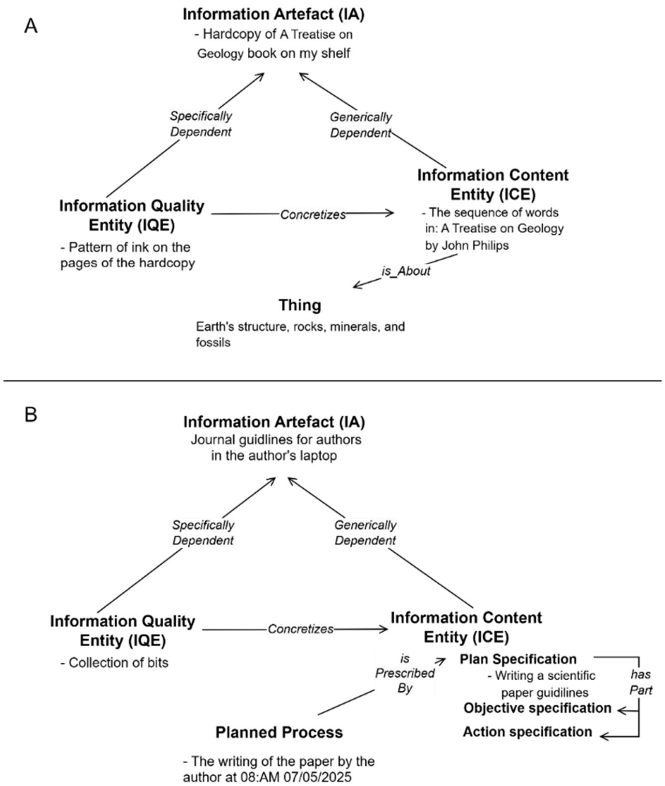

Figure 5: main IAO/IOF components: representations of objects (A) and plan specifications (B).

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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. Following the use-case sequence —which address what models are, how they can be built, how they relate to one another, and their main characteristics—the section is organized into three parts: Models (use-cases 1-2), Processes (use-case 2), and Characteristics of Models (use-cases 2-3).

5.1 Models

POKIMON fundamentally distinguishes a collection of objects and relations in the real world from their analogues in representations, such that each represented entity and its information content is about something in reality. A collection of represented entities is a model in POKIMON, and it is a geomodel if its information content is about geological entities. Each geomodel further contains one or more semantic components that point to geological entities (Figure 6) as well as a single depictional component.

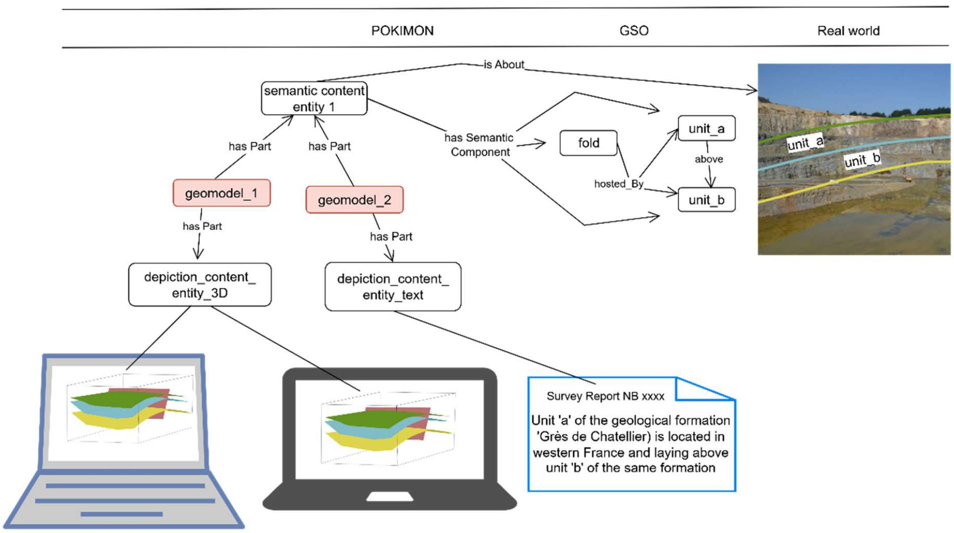

Figure 6: Semantic Content Entity (SCE) and Depiction Content Entity (DCE).

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Accordingly, POKIMON extends IAO in the following ways:

- Geomodel: is an ICE that points to real geological entities via the aboutness relation. Each geomodel has Semantic Content Entities (SCE) and a Description 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).
- Semantic Content Entity (SCE): is an ICE that possesses interpretative information for a geological entity, 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 reality - some portion of reality that its geomodel is about.
- Depiction Content Entity (DCE): is an ICE specifying a paradigm for representation, such as a text report, a 2D map or 3D model, having a particular font, specific image size or resolution, or a specific block size and shape, The DCE is about something in reality that its geomodel is about. 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)):

Is font really important? ..I guess you mean structure (in the information sense)

    - 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 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.

5.1.1 Types of geomodels

POKIMON further distinguishes two types of geomodels: Conceptual and Space-Time (Figure 7). A Conceptual Geomodel 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 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 model.

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Critically, each 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). 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.

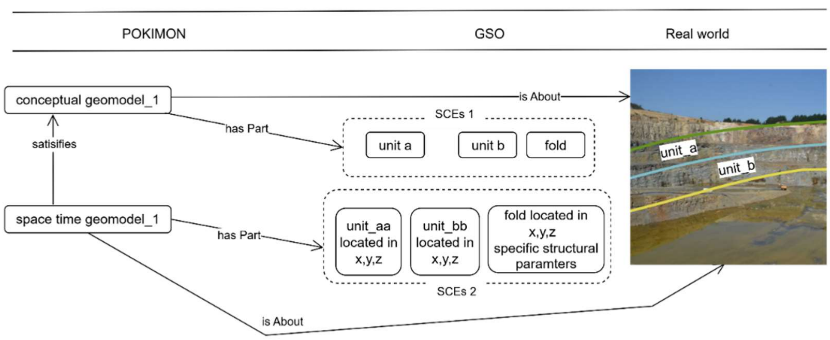

Figure 7: Conceptual and Space-Time geomodels (dashed lines denote a has Part relation to a distinct SCE for each geological entity).

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 uncertainty 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.

Figure 8 shows how these theoretical foundations are applied to address the requirements of the first use-case. This includes a conceptual geomodel satisfied by two space-time models, with these about two geological units having some lithological and spatial properties (Figure 8). The conceptual model is depicted via a DCE as a cartoon figure, and space-time models are depicted via distinct DCEs, one textually and the other 3D digitally. The space-time models share the same SCEs, that satisfy SCEs in the conceptual model: e.g. the unit in the space-time model satisfies the corresponding unit in the conceptual model (not shown in Figure 8 for visualization purposes).

- 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 section 5.3.2). These relations hold between: (1) geomodels; (2) geomodels or SCEs and a norm or constraint; and (3) SCEs in different geomodels.

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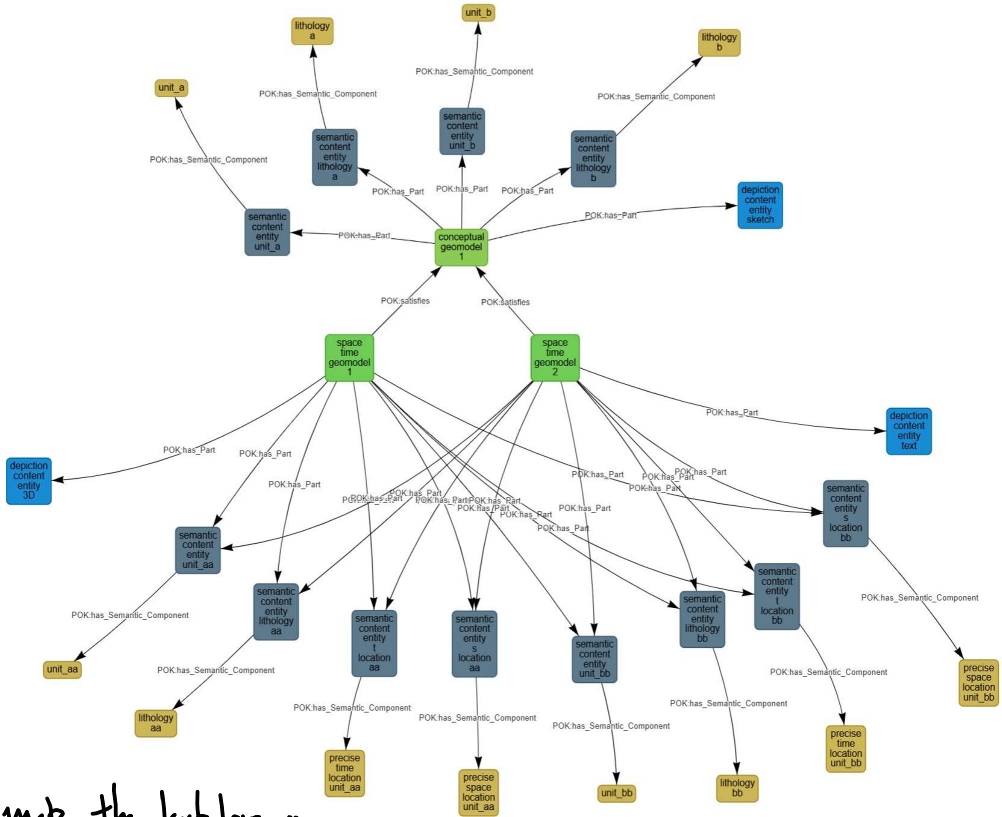

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Figure 8: conceptual and space-time geomodels (green) in use-case 1, their semantic (grey) and depictions contents (yellow).

5.1.2 Situations

A finalized geomodel is typically constructed iteratively, with each iteration introducing additions or modifications through a process of interpretation. Each iteration begins by selecting specific situations for interpretation.

- An Interpretation Situation (IS) is an Independent Continuant that is collection of SCEs that are selected to be interpreted. Once the collections of SCEs 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 9 shows the implementation of the three interpretation situations from the second use-case. These situations have SCEs as parts with each SCE associated with a part of a surface bounding the modelled geological units.

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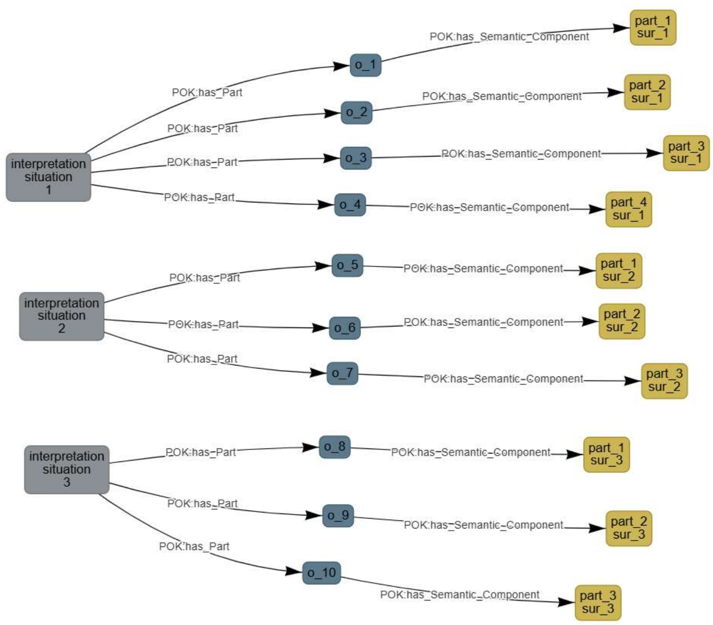

please add a geological sketch outlining the interpretation situations you are trying to represent here??

Figure 9: example of the three interpretation situations and their relations to observations from use-case 2.

During an iteration of the interpretation process (Laouici et al., 2024), the qualities of SCEs selected in the IS may be modified and new geological entities might be created. Significantly, if a geomodel succeeds in explaining a given situation, such that norms and constraints (see section 5.3.2) and relevant conceptual geomodels are not violated, then an explains relation is asserted between the geomodel and the situation.

- Explains: holds between a geomodel and a situation, such that the geomodel explains the situation by satisfying and not contradicting relevant norms, constraints, and conceptual models.

Note that POKIMON does not explicitly contain an Interpretation continuant, because any geomodel explaining a situation is a valid interpretation of the situation, i.e. explained geomodels are interpretations. Figure 10 illustrates the explanation of the previous three situations throughout some interpretation iterations. Only the first and the final iterations and their outcomes are modelled. An initial geomodel, resulting from a first interpretation iteration, explains the first situation and contains a fold hosted by a single surface (Figure 10A). The final geomodel explains all three situations and contains three geological unit surfaces and a fold (Figure 10B).

Surely I can also make invalid interpretations?

(Just state that all geomodels are interpretations)

Why is there a bullet point outside of a list??

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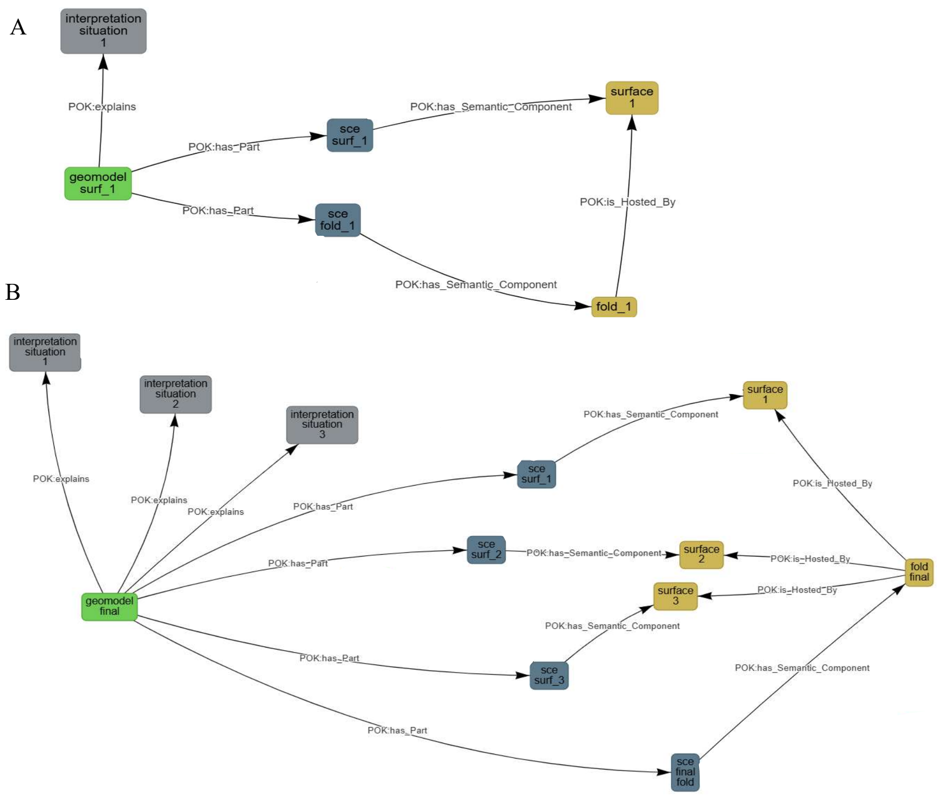

Figure 10: modelling of the first and final iterations resulting in geomodels that explain the three interpretation situations of use-case 2.

Ditto – please add geological sketches.

5.2 Processes

POKIMON extends the IOF framework for processes with four important contributions: a more precise characterization of planned processes (5.2.1), the introduction of algorithms as a distinct subclass of planned processes (5.2.2), the inclusion of unplanned processes (5.2.3), and the definition of key processes for interpretation and model construction (5.2.4).

5.2.1 Planned processes

In POKIMON, a plan specification – used to prescribe a planned process – is specifically internally dependent on its action specification and objective sepcification 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

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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.

5.2.2 Algorithms

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:

- 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) .

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- 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).

↳ How/why is this different to a Deterministic action (e.g. Kriging)??

5.2.3 Unplanned processes

POKIMON introduces unplanned processes to address natural processes, particularly those in geology such as erosion, folding, and faulting. These processes are governed by various norms that determine their progression over time. In POKIMON, unplanned processes can be targets of a Semantic Content Entity that models a natural configuration, such as the processes involved in the deposition of two units and the intrusion of another. It is important to note that, although POKIMON is not intended to support simulation engines, digitally simulated geological processes can be modeled as planned processes with explicit plan specifications. In such cases, these processes are merely analogous to and about their natural counterparts and are represented through specific algorithmic implementations rather than natural occurrences.
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.

5.2.4 Geomodelling processes

Apart from core processes that add, delete, and modify instances of POKIMON classes, key geomodelling planned processes include:

- 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 semantic 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. Inputs are the geomodel and the information entities, 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.

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- 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.

Figure 11 shows selected geomodelling processes in the second use-case. It includes the overall interpretation process that generated the previously described final geomodel (Figure 9); this process is prescribed by an algorithm of interpretation and has some key subprocesses like estimation of qualities' values, evaluation of geomodels, decisions about them, and their prescribing algorithms.

5.3 Characteristics of geomodels and their contents

POKIMON captures key characteristics of geomodels during their creation and evolution. This includes the origin of geological entities in the models, the norms and constraints to which the models conform or deviate, and critically, the relationships between geomodels, particularly when they are constructed with detailed or simplified contents.

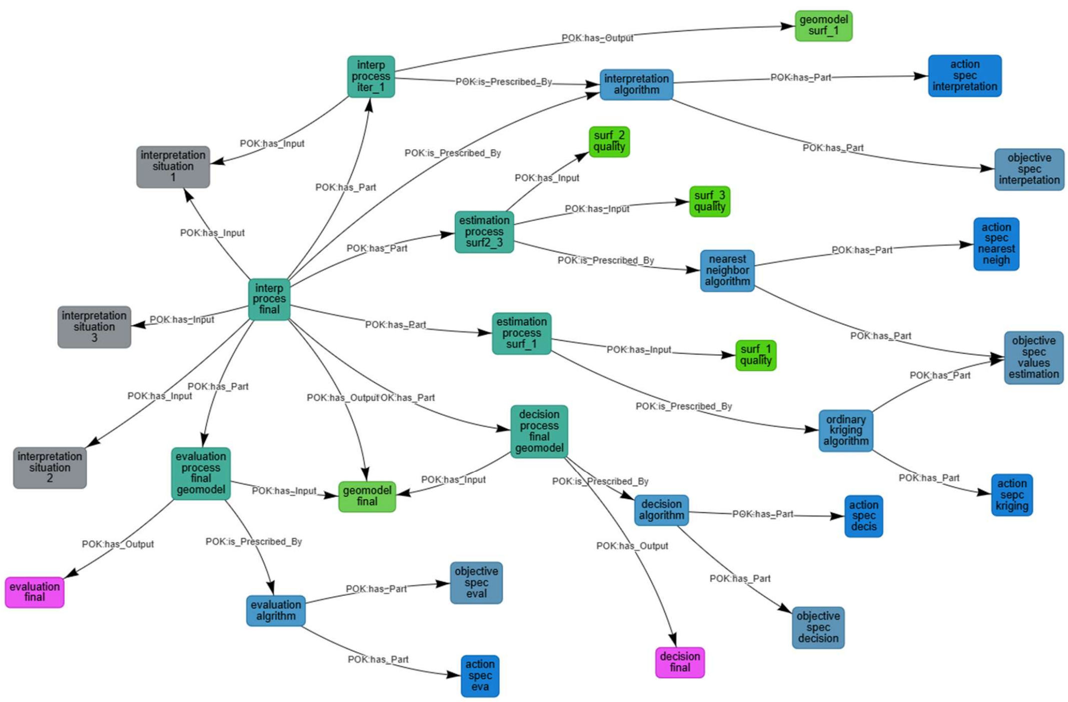

Figure 11: modelling of interpretation processes for the final geomodel of use-case 2.

↳ Include subfigures showing the representation process and final DCE?

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5.3.1 Origins

The semantic description of a geological entity (an SCE) can emerge through direct observation of natural objects, interpretative processes, or assumptions made for representational or other purposes. Accordingly, POKIMON classifies the origins of geological entities into three types — observed, interpreted, and assumed — and models them as qualities. These origin qualities are differentiated by the degree of certainty about the geological entities being modelled:

- 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. One could argue that things considered as observations in a model often bear a level of interpretation and uncertainty (e.g., a rock being considered as belonging to a given lithology based on its petrophysical properties). This apparent limitation can be overcome by specifying what matters to the observed origin quality is that the SCE is *considered* to be certain in the model. In other words, observed SCEs are those that are not going to be questioned by the modelling process.
- Assumed origin: A quality indicating the SCE is created purely for modelling purposes involving entities that are knowingly hypothetical and do not exist in reality, but their (non)existence relies primarily on background theory. 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.
- Interpreted origin: A quality applied when entities exist within a probabilistic framework supported by observed data, so their existence is moderately uncertain and subject to validation or refutation, e.g., the location of geological boundaries interpolated from seen points.

In the previous example, where a final geomodel is built to explain the three situations through a series of iterations, each semantic component is assigned an origin as per Figure 12.

> Would common modelling assumptions fit here? E.g. the assumption that a fault has dip-slip (rather than oblique) displacement. Please clarify how such an assumption would be represented.

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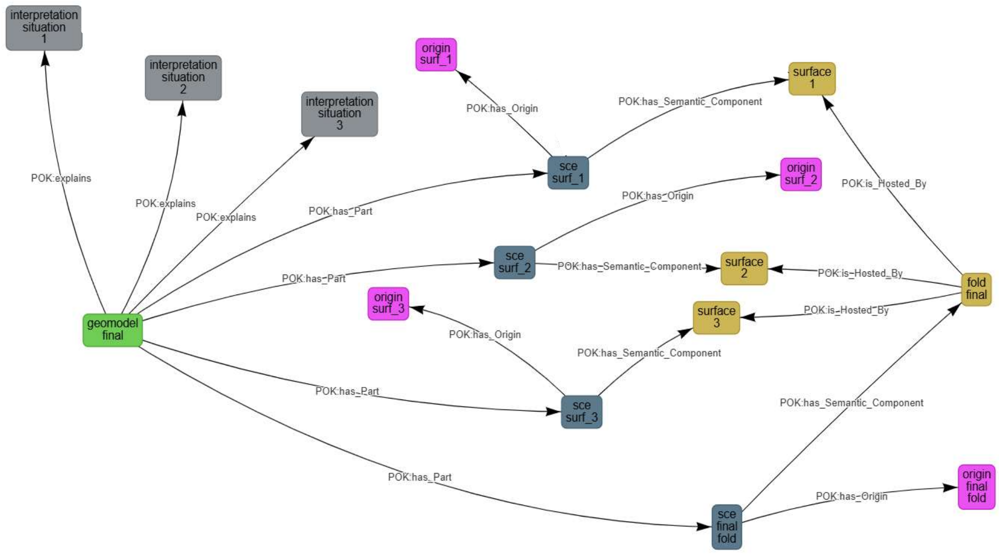

Figure 12: origin of the semantic content entities from the final geomodel of use-case 2.

5.3.2 Norms and constraints

→ Are "data" (e.g. bedding measurements) considered to be constraints in this framework? Please clarify.

Interpretation of a situation includes the satisfaction of norms and constraints, which include prior geological knowledge. A norm or constraint is an Information Entity that is manifest in the world, 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: is an information entity that sets limits on certain aspects of geological entities within a geomodel. Constraints may serve depictional purposes or reflect static values for entities—for example, specifying maximum and minimum values for properties such as length, thickness, or wavelength. Constraints are formally defined through existential restrictions within the geology ontology and can be subsequently referenced in POKIMON if needed. Constraints also enable models to capture the rationale behind the rejection of certain geomodels, e.g., violating a constraint (Laouici et al., 2024).

Please expand this section to explain how POKIMON can be used to capture the reasoning/choices behind geological constraints — as this seems crucial?

E.G. Observations at location A lead me to interpret lithology X at this location. Observations at nearby location B lead me to interpret lithology Y, which should not contact X given the current stratigraphy. Hence, I have inferred a fault between A & B.

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Relevant norms and constraints are often identified by experts at the beginning of the modelling process. Each SCE, its associated geological entity, and the geomodel itself can satisfy or contradict a norm or constraint. For example, if use-case 2 has a constraint in which the proposed folds' inter-limb angles cannot exceed 150 degrees to be accepted. In the course of obtaining the final geomodel, an intermediary geomodel is rejected for violating such constraints even if it satisfies relevant norms and the conceptual model (Figure 13).

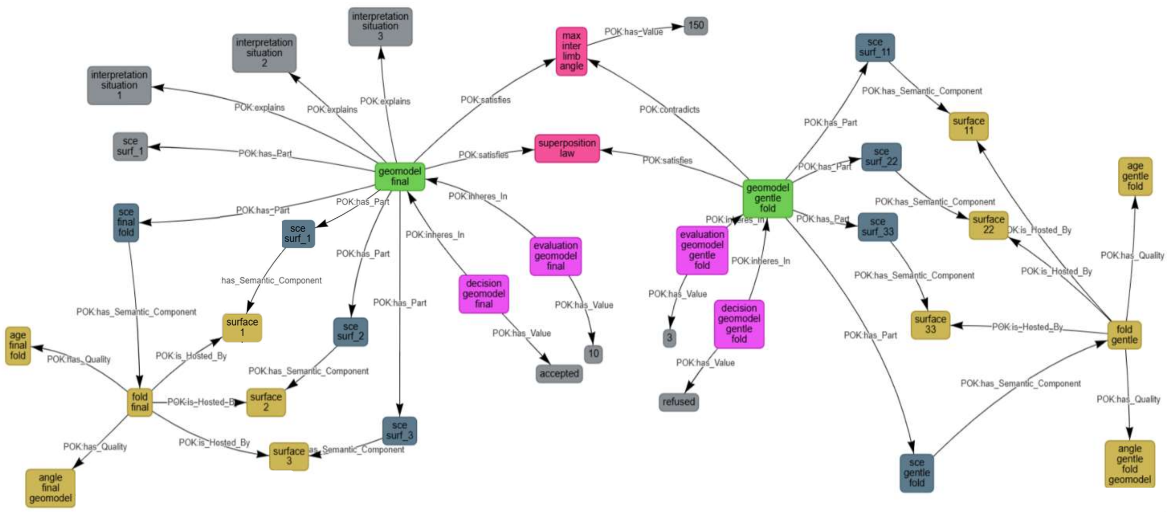

Figure 13: use-case 2 final geomodel and rejected geomodel; relations between situations (grey) and their geological entity components (yellow) not shown.

5.3.2 Simplification

When a model is built with a selected subset of entities, it inherently focuses on certain aspects of reality with a certain level of detail according to a certain resolution. If a second model is created that includes more or less detail, then models can be related via simplification and compared side by side. Simplification operates exclusively between geomodels. Therefore, POKIMON defines the following relations:

- Geological Resolution: A quality that inheres in an information content entity (such as a geomodel) and determines the granularity of entities that can be represented within that model. For example, in geological mapping platforms, zooming in reveals finer subdivisions of units with further structural detail; these units appear as larger blocks at lower resolution.
- Simplifies: holds between two geomodels when one reduces the complexity of another, by describing fewer geological entities, or the same geological entities with less detail.
- Details: the inverse of simplifies, it holds between two geomodels, when one increases the complexity of another by describing additional geological entities, or the same entities but with additional detail.

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Two simplification aspects are covered by simplifies/details; first, when some geological entities of a geomodel are aggregated into a larger geological entity in another geomodel (e.g., some fault segments into one larger segment, some geological units of a lower order, e.g. formation, grouped into a unit with a higher order, e.g. group); and second, when some geological entities are neglected and not modeled, for example, a fault is too small for the resolution and thus has insignificant impact. . For two geomodels to simplify / detail each other, they should be of the same type (i.e., either conceptual, or space-time) and have different resolutions. Models having the same resolution as well as overlapping but not identical geological entities then do not simplify / detail each other, they merely overlap each other; also entities in one model but not in another are ignored by the latter model:

Commonly called "lumping"?

- Overlaps: a relation between two geomodels of the same type and with similar resolutions describing mutually the same geological entities.
- Ignores: relations that holds between a geomodel and the semantic entities not shared by the other compared geomodel with similar resolution.

The proposed relations are used to model the elements of the use-case 3 (Fig.14). Figure 14.A displays the three space-time geomodels with their semantic parts and ignored entities; then in Figure 14.B with the emerging simplification, detailing and overlapping relations.

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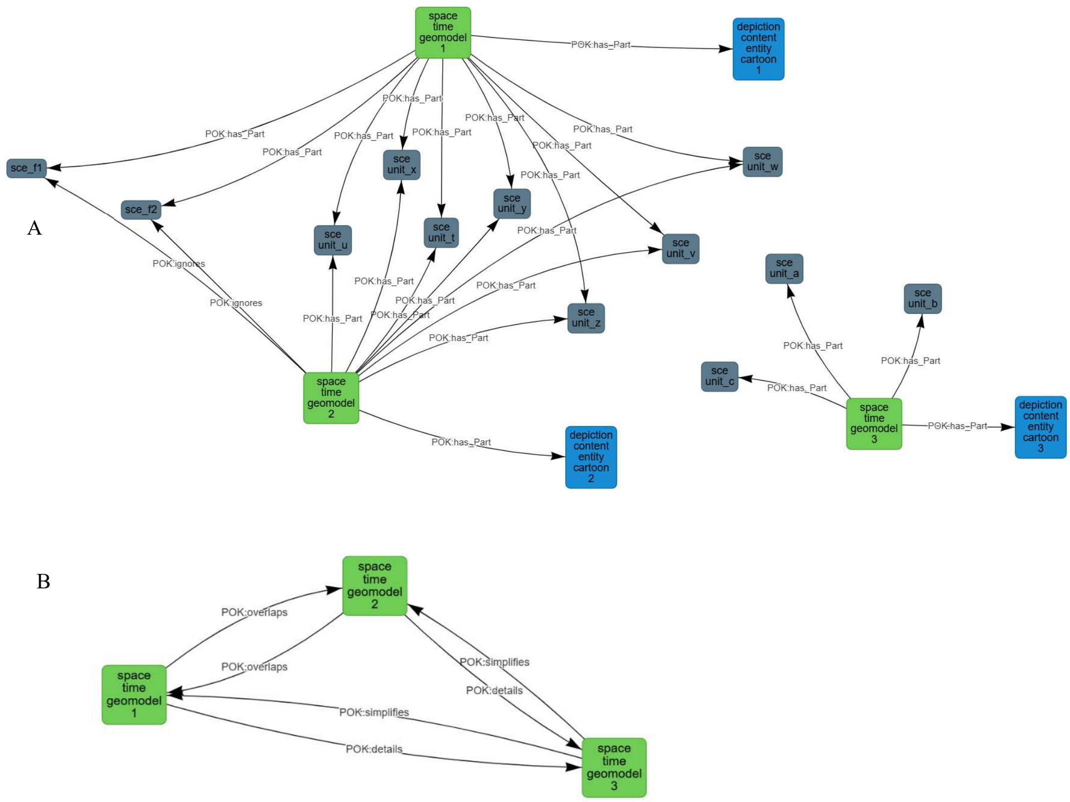

Figure 14: three space time geomodels of use-case 3, (A) their semantic parts and ignored entities, and (B) the resulting relations of simplification and overlap.

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). 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.

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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 Figures 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 (Section 3):

- Application to Use-Case 1: demonstrates satisfaction of requirements R_{I-III}: ontological representation of conceptual (R_I) and space-time models (R_{II}), and various representations of each (R_{III}).
- Application to Use-Case 2: demonstrates satisfaction of requirements R_{IV-IX}: the involved geological entities (R_{IV}), situations (R_V), interpretations in the form of geomodels that explain situations (R_{VI}), the interpretation processes leading to such geomodels (R_{VII}), the origins of model components (R_{VIII}), and norms and constraints (R_{IX}).
- Application to Use-Case 3: demonstrates satisfaction of requirement R_X: model simplification.

These major POKIMON components are illustrated in Figures 15 and 16. Furthermore, the application has been informally reviewed by geological and geomodelling experts, with 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.

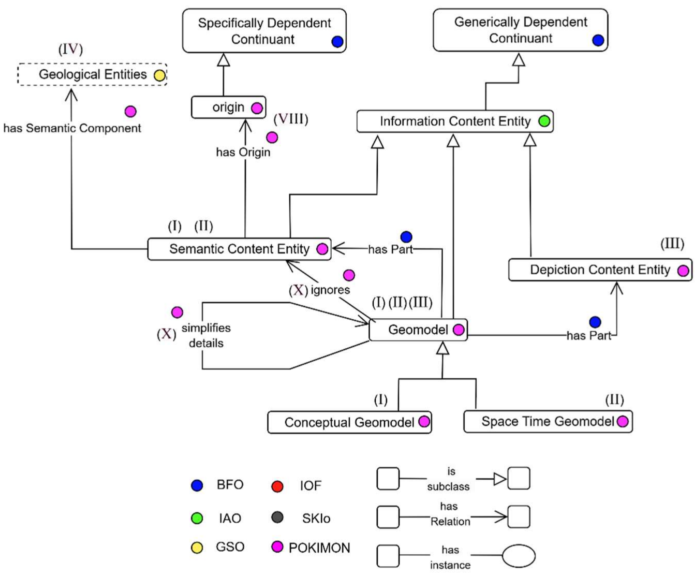

Figure 15 Main POKIMON geomodel-related entities; dashed box denotes multiple classes from POKIMON.

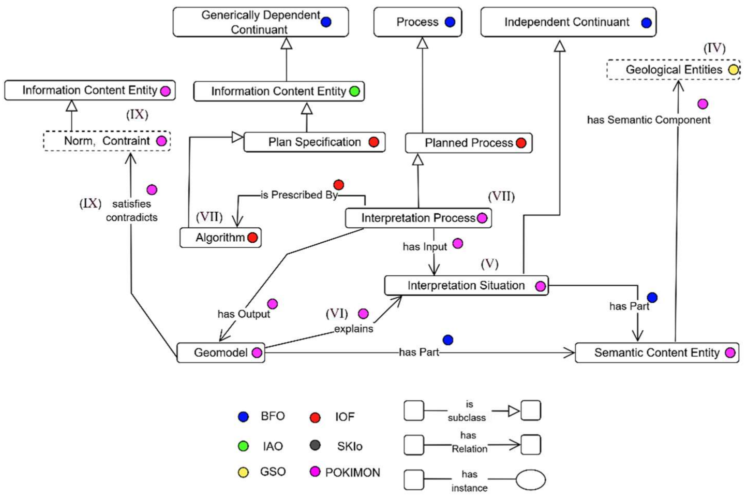

Figure 16: Main POKIMON interpretation-related entities; dashed box denotes multiple classes.

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., 2018). 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. POKIMON 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 categorizes and formalizes 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 Figure 17: 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; Heather R. Miller and Herbert, 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.

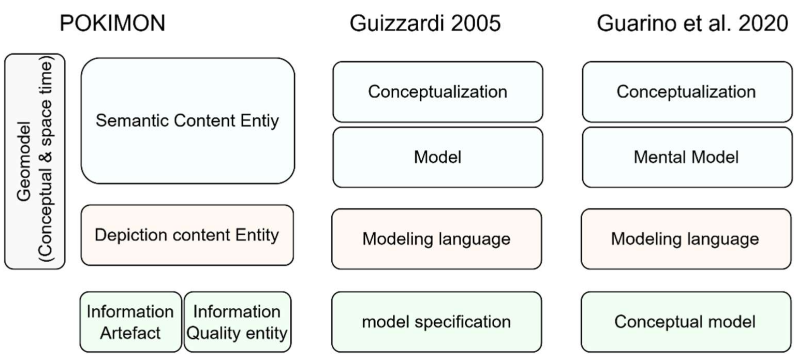

Figure 17: comparison with Guizzardi and Guarino definition of models.

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 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

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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).

As illustrated by its application, POKIMON offers a flexible and generic approach to represent different facets of expert knowledge during 3D geomodel construction. A natural concern is the manner and ease of its deployment in existing modelling environments. Some initial steps have been undertaken to test this, via the building of a knowledge-driven 3D modelling system (Laouici et al., 2024), in which the ontology provides a framework for interpretation. However, only a precursor to POKIMON has this far been deployed in this system (MOGI).

In a related issue, a greater understanding of the geological interpretation process is required. Although POKIMON offers a general and flexible structure, it is neutral about the content populating this structure. Comprehensive surveys on geomodelling tools, practices, and expert preferences are needed to establish interpretation patterns that might guide knowledge-driven geomodelling tools.

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), and 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.

7 Data and Code Availability

The current version of POKIMON is archived and publicly available on Zenodo at https://zenodo.org/records/17375904 under the DOI https://doi.org/10.5281/zenodo.17375904 (POKIMON, 2025). Example datasets and plots are included in the same repository. The scripts to generate the diagrams are not part of the results, just part of their illustration, so it is not essential for reviewers to access them.

7 Author Contributions

Imadeddine Laouici and Boyan Brodaric conceptualized, developed the methodology, and designed the proposed approach. Christelle Loiselet and Gautier Laurent supervised and managed the project, providing critical insights into the methodology and validating the results. Imadeddine Laouici and Boyan Brodaric prepared and wrote the manuscript, with all co-authors contributing to validation, rewording, and revision.

7 Competing Interests

The authors declare that they have no conflict of interest.

8 Acknowledgements

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Appendix

```
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 A1: SPARQL query to retrieve the graph-based output in figure 8, 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 { ?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 A2: SPARQL query to retrieve the graph-based output in figure 9, 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: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)}}
```

Figure A3: SPARQL query to retrieve the graph-based output in figure 10, including the geomodels of the iterations in use-case 2, their semantic parts, and the semantic components.

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```
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 A4: SPARQL query to retrieve the graph-based output in figure 11, 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.

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```
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 A5: SPARQL query to retrieve the graph-based output in figure 12, including the final geomodel, its semantic components, and their origins (use-case 2).

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```
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 A6: SPARQL query to retrieve the graph-based output in figure 13, 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 A7: SPARQL query to retrieve the graph-based output in figure 14, including the geomodels of use-case 3, their parts, and relationships to ignored entities.

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```
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 A8: SPARQL query to retrieve the graph-based output in figure 14,including relations of simplification, detailing, and overlap between geomodels of use-case 3.

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