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GeoFault: A well-founded fault ontology for interoperability in geological modeling

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ABSTRACT

Geological modeling currently uses various computer-based applications. Data harmonization at the semantic level using ontologies is essential to make these applications interoperable. Since geo-modeling is part of several multidisciplinary projects, interoperability requires semantic harmonization to exchange information between geological applications and integrate other domain knowledge at a general level. Therefore, domain ontologies that describe geological knowledge must be based on a sound ontological background to ensure this knowledge is integrable. Faults are essential for understanding and solving structural problems but are complex to model because the concept of fault includes a group of geological entities with a distinct ontological nature. A fault can correspond to thin, deformed rock volumes or spatial arrangements resulting from the displacement of geological blocks, but at a broader scale, geologists describe faults as surfaces or components of complex fault arrays. Our work intends to harmonize these views by presenting a domain ontology, GeoFault, resting on the Basic Formal Ontology (BFO) and the GeoCore ontology. GeoCore and GeoFault support the parametric description of geological sites as a preliminary step for quantitative and qualitative analysis. We have proposed GeoFault after systematically revising the literature and several knowledge-acquisition sessions with expert structural geologists. The ontology formalizes a vocabulary for fault "sensu stricto," excluding ductile shear deformations. It covers the regional to outcrop scales, excluding structures at the microscopic, orogenic, and tectonics scales, and it avoids interpretive language associated with geological processes as far as possible. Extending the BFO and GeoCore ontologies allows the fault concept to be related to formal ontological classes in a consistent semantic-rich framework. The ontology artifact is implemented in OWL 2, validated by competency questions with two use cases, and tested using an in-house ontology-driven data entry application. The GeoFault ontology is publicly available and provides a solid framework for clarifying fault knowledge and a foundation for many applications.

1. Introduction: research context

Computer-based applications are essential: they assist geologists in data collection, interpretation, modeling, and simulation tasks. Usually, these applications embed the knowledge of the domain in the computer code or have it represented explicitly in knowledge models. The diversity of the views over the domain associated with the variety of possible representations of the entities and their properties lead to difficulties in the data exchange in these applications – the interoperability problem. The theory of Ontology (Guarino 1998) brings some light to this scenario by providing a formal, explicit representation of the meaning of the vocabulary, which software applications can use as a reference for interoperability or new functionality development. In this project, we apply the theory of Ontology to build an ontology in the domain of Structural Geology to formalize the terminology for describing geological faults and their characterization.

A geological fault is a fundamental deformation structure closely connected to aspects of human activities, and its comprehension has an important economic impact on the evaluation of ore and petroleum reserves. A good understanding of faults is required in fields such as petroleum geology (Ogilvie et al., 2020), hydrogeology (Goldscheider et al., 2010), mining (Donnelly, 2009), CO_2 capture and storage (Skurtveit et al., 2021), earthquake hazard studies (Manighetti et al., 2007), and civil engineering (Li et al., 2010). GeoFault work

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complements previous research on geological ontologies that specializes in the Basic Formal Ontology (BFO) (Arp et al., 2015) in a network of domain ontologies that aim to cover the terminology required through the petroleum exploration chain. The GeoCore ontology proposed by (Garcia et al., 2017, 2020) plays a fundamental role in structuring this network by offering a set of high-level, general concepts of entities and fundamental geological relations with the purpose of generalizing every concept of the several subdomains in Geology to support applications in industry. The network of ontologies covers the deep-water reservoir architecture (Cicconeto et al., 2022), geological spatial relations (Cicconeto et al., 2020), weathering (Vieira et al., 2020), risk analysis (Silva et al., 2021), and now, tectonic characterization through the GeoFault ontology described in this paper.

Over the last two decades, various research institutes and national geological surveys have collaborated to produce a significant spectrum of geoscience knowledge representations like the NADM conceptual model (NADM Steering Committee, 2004; Richard and Sinha, 2006), SWEET (Raskin and Pan, 2005), and GeoSciML (IUGS/CGI, 2013). SWEET is a loosely structured model that outlines some general structural geology concepts with no core ontology to extend geological concepts into details. GeoSciML is a highly structured markup language presently considered an unofficial standard for exchanging geological map data. GeoSciML defines *geologic structure* with the sub-categories *shear displacement structure, fold, and foliation*, making GeoSciML a reference for modeling structural geology. However, this model only considers faults as immaterial entities, which is not adequate to model three dimensional entities like fault zones for example, which are important for reservoir exploitation. GeoSciML also fails to specialize a top-level ontology that would help further integration with other modeling artifacts. These limitations also exist in the data exchange standard RESQML (Morandini et al., 2017), derived from GeoSciML and widely used by petroleum geologists. Brodaric and Probst (2008) adopted a tentative approach for linking SWEET and GeoSciML under the DOLCE top-ontology. This model focuses on representing rocks and geological units and does not have further discussion on geological structures such as fold, foliation, and fault.

Following these initial developments, the geological community has produced several structural geology models (Babaie et al., 2006; Zhong et al., 2009), plate tectonics and volcanology (Sinha et al., 2007), facies description (Garcia et al., 2017), geochronology (Cox and Richard, 2005, 2015; Perrin et al., 2011; Ma and Fox, 2013; Wang et al., 2022), geological mapping (Boyd, 2016; Lombardo et al., 2018; Mantovani et al., 2020), geomodeling (Morandini et al., 2017), and hydrogeology (Tripathi and Babaie, 2008). Recently, some ontologies have described particular geological processes (Babaie and Davarpanah, 2018; Le Bouteiller et al., 2019) and interpreted structural geological event sequences (Zhan et al., 2021).

There are currently two domain ontologies specifically focused on structural geology. The first is the Structural Geology Ontology developed by Babaie et al. (2006), which is a Unified Modeling Language (UML) conceptual model organized in taxonomies. It records many essential terms related to fractures, foliation, and folds; however, the authors have not ontologically defined the terms with the requested axioms and logical definitions. Therefore, software methods cannot process the model in the course of data exchange between applications, requested to guarantee interoperability. The second is the Ontology of Fractures developed by Zhong et al. (2009). It has good coverage of vocabulary related to fracture but lacks an ontological formal characterization.

Various other works have proposed standardizing geological vocabulary. From a cognitive science perspective, Shipton et al. (2020) highlight the importance of the mental model and potential biases for representing structural geology knowledge. The RESQML model now integrates the Open Group OSDU Forum catalog, which aims to offer a standardized solution to break data silos and support energy industry digitalization. Hintersberger et al. (2018) designed a new database and an online thesaurus for structuring regional geodynamic knowledge. Funded by the European Union's Horizon 2020, the European Fault Database describes the fault domain knowledge (van Gessel et al., 2021). These attempts are solid and valuable works but satisfy specific needs and do not address ontological formalism. There has been no deep ontological analysis and evaluation of faults based on a proper framework. The GeoFault ontology addresses this issue. Our project associates four geologists, including two experienced structural geologists, and two logic and conceptual modeling experts to collect the knowledge from human and legacy sources and organize it in a formal model. Currently, our model supports several distinct geological software applications and keeps evolving.

We organize this paper as follows. Section 2 offers a background on Ontology and knowledge models that will help the reader go through this paper. Section 2 also introduces the BFO top-level ontology (Arp et al., 2015) and the GeoCore core ontology (Garcia et al., 2020), which defines the conceptual framework for GeoFault ontology. Section 3 describes the geological components of single faults and fault systems and their properties and relationships. Section 4 presents the knowledge and ontological models currently available for describing geological faults; it details the GeoFault domain ontology, discusses our ontological perspective, and justifies our modeling strategy. Section 5 presents a validation of our ontology by considering two use cases. Finally, Section 6 concludes the study. The entire ontology and documentation are publicly available; the link is in the code availability section.

2. Background in ontology and knowledge models

Although knowledge models and ontologies share the goal of representing the knowledge of the world, ontologies differ when they aim to capture the *knowledge's intensional nature* (Guarino et al., 2009) in a subject-independent and modal way. In other words, ontologies represent what an entity is in its *essence*, in all possible existences in all possible worlds, without considering the observer, the application, or even the real existence of the entity instances. On the other hand, knowledge models try to capture the *extensional* nature of the domains: the generalization of the instances in the way they occur in the particular domain. The modelers create knowledge models intending to represent the necessary knowledge to perform a task or solve a problem. Otherwise, ontology engineers develop ontology artifacts for many uses, such as to serve as a reference for knowledge models, for documentation, or even to support non-ambiguous communication.

Well-founded ontologies act as standards for terminology use. However, they also enhance how thesauri and industrial standards support interoperability by incorporating axiomatic restrictions of entity existence in a logical language based on a more abstract system of categories (in our case, the BFO top ontology and, in the medium-level GeoCore ontology, further detailed in this paper). This capability allows the software applications (not only humans) to detect data exchange inconsistencies and match the vocabulary through data and knowledge models, which ameliorate the achievements of previous standards such as RESQML[1] and GeoSciML[2] that relay named-based definitions, instead of logical axioms and restrictions. Ontologies are multi-purpose models that derive several applications and are important artifacts to support interoperability. Well-founded ontologies also follow strict rules for evolution and reuse (Vita et al., 2018), leading to an ecosystem of potentially interoperable artifacts.

A typical example of the capability of ontologies is the project OBO Foundry portal,[3] where the Biological and Biomedical community collectively builds and formalizes the technical terminology for documentation and software applications in Medicine and Biomedical

[1] https://www.energistics.org/resqml-current-standards/.
[2] http://www.geosciml.org/.
[3] http://obofoundry.org/.

Sciences. The community develops OBO Foundry under strict rules of vocabulary adoption and terminological definition as described in (Smith et al., 2007). Similarly, the ONTOUML[4] community organizes the artifacts developed under the Unified Foundation Ontology – UFO (Guizzardi et al., 2018) and provides automatic verification of the model consistency. Although the petroleum industry is still far from the ontology development of the medical domain, some relevant efforts created a path following the initial proposal of the GeoSciML reference model to facilitate long-term interoperability between models and knowledge-based applications. Recent contributions, like the GeoCore ontology and the O3PO (ontology for petroleum plant production equipment and installation) (Santos et al., 2022), follow good practices for ontology development and FAIR principles (Vita et al., 2018) and have derived several knowledge-based models and associated software applications, such as (Silva et al., 2021).

In recent years, the scientific community has recognized ontologies as unique tools for disentangling conceptual ambiguities and building specialized domain vocabulary. Ontologies help reduce data collection and management biases, facilitate database integration and storage, and define classes that optimize data analytics.

2.1. Types of ontologies

There are different types of ontologies based on their level of generality. ***Top-level ontologies*** provide broad frameworks for describing knowledge across domains with classes and properties and classifying concepts in a unified way (Guarino, 1998; Arp et al., 2015). Three top-level ontologies support geological applications: Descriptive Ontology For Linguistic and Cognitive Engineering (DOLCE) (Gangemi et al., 2002), Unified Foundational Ontology -UFO (Guizzardi, 2005), and Basic Formal Ontology – BFO (Arp et al., 2015). We have adopted BFO as a top-level ontology for two reasons: (1) BFO was conceived to model material entities in natural domains, initially the Biomedical domain that shows similar challenges in modeling to Geology; (2) BFO allows primitive extensions, which let us define constructs to model homeomerous non-maximally connected entities to represent rocks and sediments.

Domain ontologies cover a specific discipline vocabulary. A broad scientific field split into many subfields, like Geology, can be the subject of many domain ontologies. Since these specialized ontologies are likely to be developed independently, integrating them is often challenging. A ***core ontology*** (Oberle, 2006) can help with this difficulty. A core ontology defines a few general concepts in a field, constituting the foundations on which models can anchor terms (Scherp et al., 2011). Furthermore, knowledge engineers do not develop domain ontologies from scratch but often integrate, embed, or link existing ontologies (Suárez-Figueroa et al., 2015). A standard reference to a top-level ontology and core ontology may facilitate this.

Knowledge models represent the entities and instances of a portion of the domain under a particular view of the modeler. They focus on the role of ontological entities in the domain and the relationships that support the problem-solving method needed to solve a particular task, such as geological environment interpretation, identification of adequate structure to trap oil, and classification of a seismic horizon as a stratigraphic surface or a fault. Knowledge models can benefit from a domain ontology terminological definition since the ontology axioms prevent the construction of unintended or incomplete geological knowledge models.

2.2. The BFO and GeoCore ontologies

We selected BFO (Arp & al., 2015) as our reference top-level ontology for building the GeoFault ontology. BFO has the advantage of being a small and compact top-level ontology, which is well-documented and used in many fields. ISO standard (ISO/IEC 21838–2) and the Industrial Ontology Foundry,[5] created by the National Institute of Standard Technologies to develop digital twins in the energy industry (D'Amico et al., 2022) have adopted BFO as the top-level ontology. Above all, BFO is particularly useful for modeling scientific knowledge because it rests on the principle of realism. This philosophical position assumes that reality and its constituents exist independently of our representations. It separates the material entities that constitute reality and the abstract concepts used to describe it. In this view, a fault exists whether we consider it a material entity or a particular organization of earth matter.

Another major reference for our ontology is the core ontology GeoCore[6] (Garcia et al., 2020). GeoCore specializes the BFO entities (Fig. 1) into the following general geological entities:

- A *geological object* is an entity that configures a whole, and it is maximally connected
- *Earth material* is the uncountable, homeomerous entity that models both rock and earth fluid;
- A *geological structure* is a BFO: generically dependent continuant of a geological object or part, which describes the internal arrangement of a material entity;
- A *geological process* and a *geological time interval* are BFO: occurrent;
- A *geological object* bears the relation GeoCore: *generated_by* a geological process.

In addition, Cicconeto et al. (2020) proposed a spatial relation ontology (SpatialRelations) to describe the position and connection of depositional units, such as *Externally_Connected_With*: a symmetric sub-relation between two independent continuants (BFO) with adjacent external boundaries. Compared to BFO: *adjacent_to* and BFO: *located_in*, this ontology allows geologists to describe more complex spatial relationships. We extracted the relations from this ontology to complement the BFO/GeoCore framework and describe the spatial relationships between the fault entities.

3. The fault concept in geology

Analyzing relevant knowledge is a prerequisite for building a domain ontology. Faults are brittle shear deformation structures that form in rigid rocks in the upper 10–15 km of the Earth's crust in response to the stress configuration (Fossen, 2016). Faults are major structures and so are essential in any geological modeling. Alongside stratigraphic layers, they define the compartmentalization of rock volume and influence fluid migration as a barrier or conduit (Perrin and Rainaud, 2013). From a formal ontological analysis perspective, this work outlines the terminology to describe faults and their characteristics, considering them as material entities that we analyse at the regional, outcrop, or hand sample scales (excluding microscopic and tectonic scales). We focus our modeling activity on the *continuants* (entities that exist as a whole in a single snapshot of time). The processes that produce faults (or the *occurrents*, entities that happen and extend over time) are not the primary concern of our work in this stage because we intend to provide a conceptual tool to capture descriptions of faults for further automatic reasoning and data analysis.

A fault is a shear fracture along which two bodies of rock move with respect to each other. In most cases, rocks and a fault core are associated with a fault zone bounded by a damage zone (Caine et al., 1996). For this reason, alongside being a "structure" that modifies the spatial organization of the crustal rocks, a fault is generally considered a material object. At the basin or smaller regional scale, geologists describe a fault

[4] https://ontouml.org/.

[5] https://www.industrialontologies.org/.

[6] https://github.com/BDI-UFRGS/GeoCoreOntology.

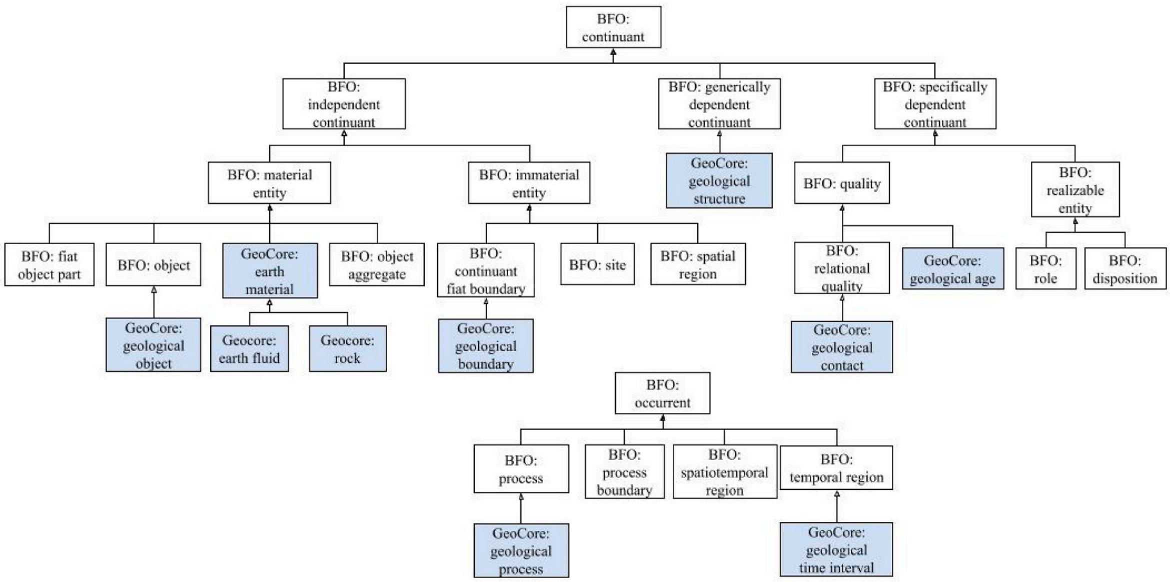


Fig. 1. The BFO and GeoCore ontologies. The blue boxes correspond to the GeoCore Ontology, and the white boxes correspond to the BFO categories to which they are related (Modified from Garcia et al. (2020)).

as a surface that splits apart geological layers. Depending on the context, a fault is thus considered as a deformed volume of rock, a surface, or a displacement structure (Fig. 2). A fault is seldom an isolated planar object. Faults commonly form a group of fault surfaces and their intervening rocks that extend in a three-dimensional region. Therefore, following the OntoClean analysis methodology (Guarino and Welty, 2009), the term *fault* carries several distinct identities, and *being a fault* is non-rigid because it can acquire or lose its instances depending on the situation or the geologists' perspectives. In the following section, we will consider the concept of fault as a deformed volume, a surface, and a spatial arrangement structure, which are distinct ontological entities.

3.1. Fault as a deformed volume

The term "fault" commonly designates a shear fracture with spatial separation, accommodating relative movements parallel to its surface. As Fig. 2 shows, the basic architecture of a fault consists of a ***fault core*** surrounded by ***fault walls***. Caine et al. (1996), Shipton et al. (2006), Wibberley et al. (2008), Woodcock and Mort (2008), Braathen et al. (2009), Gabrielsen et al. (2017), Torabi et al. (2019), Torabi et al. (2020), and Fossen (2020) have described faults as deformed volumes. The main fault elements are:

- ***Fault zone***: the deformed zone that accommodates the fault movement.

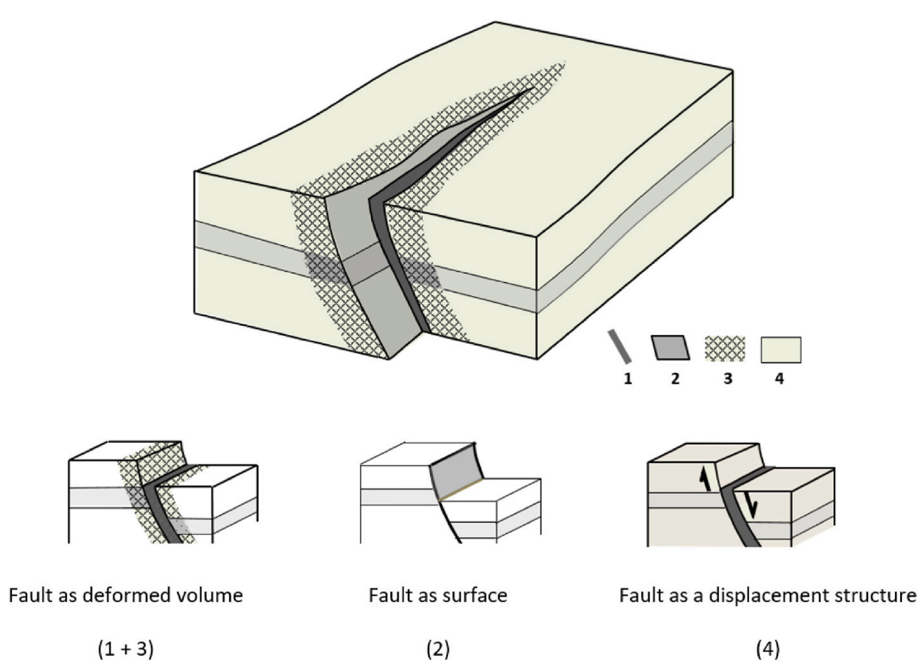


Fig. 2. Basic elements related to the concept of a fault. The figure above shows a fault model with four elements: 1. Fault core, 2. Fault surface, 3. Damage zone, 4. Fault walls. The three small figures at the bottom highlight the different aspects of faults.

- ***Fault core***: a millimeter to decameter-wide zone that absorbs most of the brittle deformation. It totally or partly consists of elongated discontinuous rock bodies (*Fault Core Membranes)* constituted of specific cohesive or non-cohesive ***fault rocks***. A fault core can also contain ***lenses***.
- ***Damage zone:*** zone containing the brittle, deformed parts of the fault walls alongside *the fault core*. The damaged area mainly consists of fractures, deformation bands, and minor subsidiary faults. Damage diminishes outward from the fault core.
- ***Slip surface***: a smooth polished surface bounding a wall damage zone on the fault core side. It often bears structures like *slickensides, slicken lines,* or *chatter marks*, which may indicate the direction of the last displacement along the fault.

3.2. Fault as a surface

At the mapping scale, geoscientists consider faults as simple surfaces. On seismic cross-sections, horizon picking results in clouds of points on which they can build various types of surfaces for 3D earth modeling purposes (Perrin and Rainaud, 2013). We characterize fault surfaces by their cross-section shapes, spatial orientation (fault surface dip angle and azimuth), and mutual relationships. Table 1 shows some common types of these surfaces.

3.3. Fault as a spatial displacement and arrangement

The relative movement along the fault surface modifies the positions of contiguous points across the fault walls. The displacement is commonly revealed by offsets of rock layer traces on the fault wall surfaces. A fault may be active during different geological periods, and the architecture of a fault is the result of the accumulated displacements. Geologists define fault age as the last geological period during which the fault was active. A growth fault is a fault that forms because of faulting and sedimentation operating simultaneously. We identify a growth fault by layers having unequal thicknesses on the two fault walls. Table 2 shows the main fault types.

Faults are generated by brittle shear deformation processes. In a simplified view, a fault is often the result of the displacement of rigid blocks. However, in general, displacement is not uniform along the fault surface. Geologists measure the displacement by considering the maximum separation along the fault surface. For planar faults, the fault block displacement (net slip*)* is usually described by considering its component in the slip surface and a plane perpendicular to the fault strike.

3.4. Fault system

In most cases, a fault is not an isolated entity but is part of a fault system. A fault system generally comprises a few major faults (characterized by large displacement) and associated minor faults as its parts. Minor faults are oriented in parallel or conjugate directions with respect to the major faults. A minor fault is synthetic when its sense of slip is the same as the associated major fault and antithetic if it is opposite (Fig. 3A). Fig. 3B shows an example of a duplex fault system. A fault ontology should describe the entities related to these aspects of individual faults and fault systems and specify their nature and mutual relationships.

4. The geofault ontology

This section introduces our methodology for building the GeoFault ontology and the main modeling options. Subsequently, we provide a comprehensive description of the ontology. We construct the GeoFault ontology with knowledge engineers and geologists following the steps (Fig. 4) defined in the NeOn Methodology scenarios 1, 2, and 4 (Suárez-Figueroa et al., 2015).

4.1. Preliminary steps

Specification of the ontology goal and scope (step 1).

Table 1
Various fault surfaces are classified by their shapes in the cross-section view, dip angles, and spatial arrangement patterns (Van der Pluijm et al., 2004).

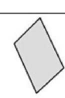
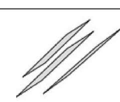
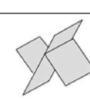
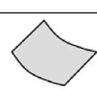
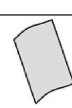
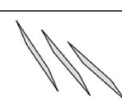
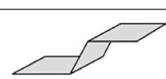
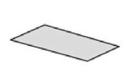
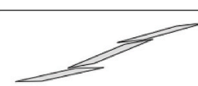
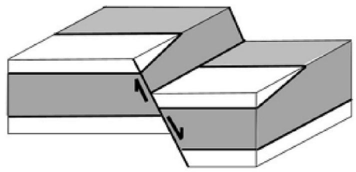
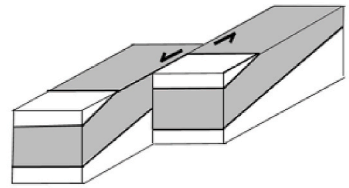
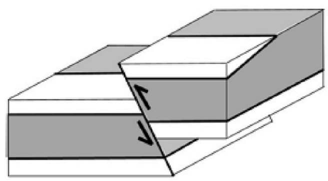
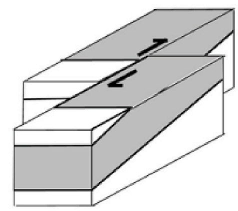
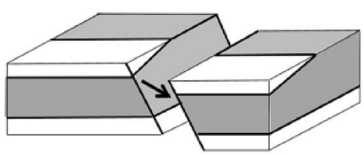
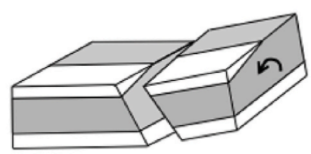
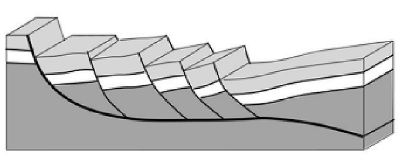
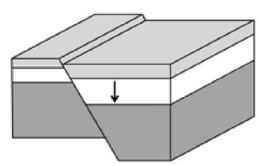
SINGLE FAULT		FAULT ARRAY	
Cross-Section Shape	Dip Angle	Spatial Arrangement	
 Planar	 Vertical	 Parallel	 Conjugate
 Curved (listric)	 Steep (dip fault)	 En echelon	 Anastomosed
 Composite	 Low angle	 Relay	 Flower

Table 2
Main types of faults. The black arrows indicate the movement direction of the block (fault wall).

 Normal	 Left-lateral strike-slip
 Reverse	 Right-lateral strike-slip
 Oblique	 Rotational
 Detachment fault	 Growth fault

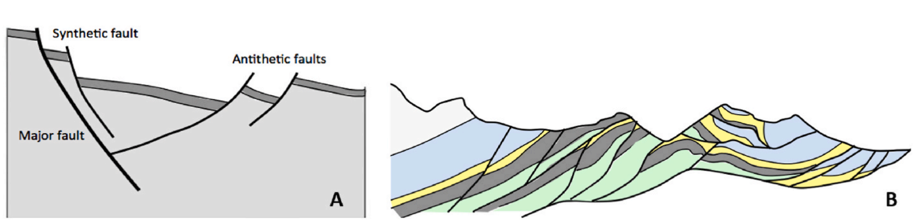


Fig. 3. Examples of different fault systems. A: Conjugate normal fault systems. The major fault shows the largest displacement. Both synthetic and antithetic faults are minor faults with smaller displacements than major faults. B: A complex duplex assemblage formed by reverse (thrust) fault. Different colors represent different lithological units.

- The ontology aims to enable the integration of fault data. It must model the knowledge attached to faults and their various aspects: deformed volumes, surfaces, and spatial arrangements.
- It should be built under a top-level ontology to allow future expansion and integration.

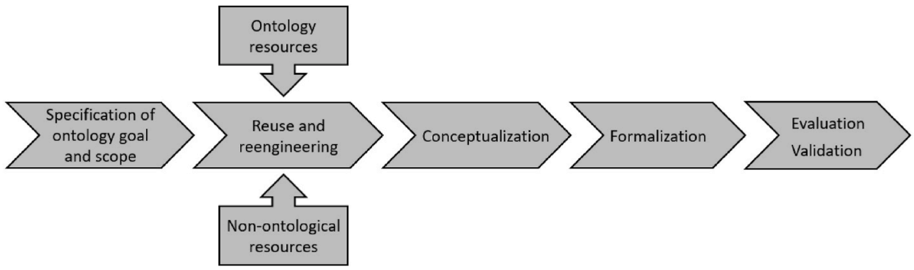


Fig. 4. Five major steps for constructing the GeoFault ontology based on NeOn Methodology scenarios 1, 2, and 4 (Suárez-Figueroa et al., 2015). In step 2, we considered ontological and non-ontological resources.

- It should consistently describe various branches of knowledge at the same level and remain simple. The ontology addresses the knowledge attached to faults "stricto sensu" resulting from brittle shear deformation in the upper crust and excludes ductile deformation generated at depth.
- The ontology intends to be descriptive; it will avoid using terms describing specific faulting processes and focus on observable fault characteristics. Terms like *normal/reverse faults* will be preferred to *extensional/contractional faults* since terms such as normal and reverse are structural. In contrast, extensional and contractional are inhered and associated with processes.
- The ontology relates to outcrop/regional seismic scales (10^{-2} to 10^{5} m). Therefore, it does not consider larger orogenic and plate tectonics scales or the microscopic scale.
- We have organized the ontology as a subsumption taxonomy of entities, following the principles of Ontoclean (Guarino and Welty, 2009) and the best practices for terminology definition and classification described in Chapter 4 of the BFO book (Arp et al., 2015). We specialized the GeoCore rigid entities in a subsumption taxonomy of material entities with proper identity and associated to them the further dependent entities, such as roles, qualities, relations, and dispositions.

Identification of ontology and non-ontological resources (step 2).

The second step involves identifying the vocabulary we should add to the ontology. We have operated the non-ontological vocabulary identification in two ways:

- We first used a traditional "manual" method, which gathered the various terms identified by the professional geologists who participated in the work. We conducted this vocabulary identification by examining the research papers recommended by the experts that present the definitions of the various terms. We elucidated them through interviews.
- Second, we selected a list of ten well-referenced textbooks on faults or, more generally, on structural geology. We selected four that included vocabulary lists in an electronic format (Van der Pluijm et al., 2004; Davis et al., 2011; Fossen, 2016; Mukherjee, 2020) and used them for a semi-automated vocabulary search. We selected one hundred and one terms present in the vocabulary lists of at least three of these textbooks. We then "cleaned" this list by eliminating the terms not referring to the fault domain but to subfields like geological processes, ductile shear, plate tectonics, folds, and geomorphology. Seventy-one terms remained in the list, of which sixty-five were already in the manually defined list. The six remaining terms were not essential, but we retained them as candidates for the ontology vocabulary.
- To ensure the coverage of the selected terms within the geology community, we applied the term frequency analysis method from Holden et al. (2019). This involves examining the term frequencies of concepts related to faults in over 2000 recent academic paper abstracts from various journals, all of which use "fault" as a keyword. We then compared the top sixty terms obtained from this analysis with the expert-selected list. After excluding terms not in the scope, such as basin, tectonic, or micro-fracture, the high-frequency term list can be easily correlated with the vocabulary list made by geologists. This comparison confirmed that we have not missed high-frequency academic terms from our compiled list.

At the end of this vocabulary search, we included around seventy fault-related terms in the ontology, following the principles of the terminological definition of BFO to represent the consensual fault knowledge shared by the geology community.

We have chosen the BFO/GeoCore package as the basis for ontological resources and also adopted some further developments proposed by Garcia et al. (2020) and Cicconeto et al. (2022). Finally, we have completed the terminology by including some useful relations defined in the Spatial Relation Ontology developed by Cicconeto et al. (2020) and adopted the age relations (older, younger, coeval) of RESQML.

4.2. Ontology conceptualization, formalization, implementation, and validation

4.2.1. Conceptualization (step 3)

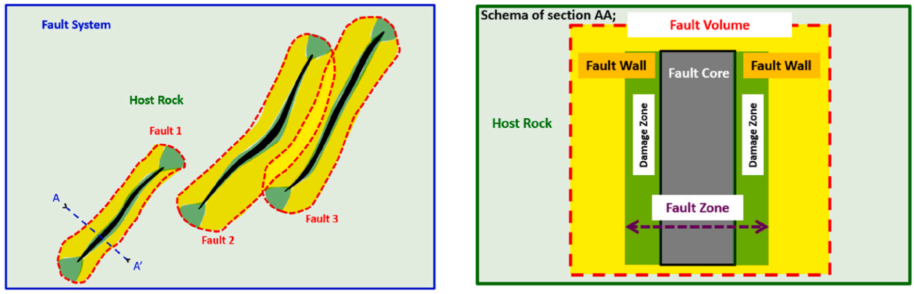
We associated and categorized the collected vocabulary with the BFO/GeoCore framework to build the ontology and linked the concepts by object properties.

Characterizing material parts of rigid faults that provide their own identities like *Fault Zone*, *Fault Core*, *Damage Zone,* and *Fault Walls* as *BFO: material entity* is straightforward. We further considered that the *Fault Zone* is a *BFO: object*, corresponding to the whole material deformed by the faulting process. *Fault Core* and *Damage Zone* are *BFO: objects* that are parts of a *Fault Zone*. *Fault Wall* is not a *BFO: object* because it has no specified external boundary. We have considered it a *BFO: fiat continuant part* related to some *GeoCore*: *geological object* (e.g., a layer, a stack of stratigraphic units or an intrusive body). Fig. 5 shows the parthood relationships between these fault components.

The term fault surface has two possible meanings and identities:

- Some geologists use this term to describe the material slip surface where displacement occurs. With this meaning, the surface is *a BFO: material entity* corresponding to a part of the Fault Wall. We designate this entity by the non-ambiguous term: *Physical Slip Surface.*
- Some geomodelers who consider faults at the mapping scale use this term to designate the 2D immaterial surface that represents faults in their models. With this meaning, Fault Surface is a 2D immaterial surface related to the Fault Zone. Since we conceived the GeoFault ontology for geo-modeling, we exclusively use *Fault Surface* as *BFO: two-dimensional fiat continuant boundary.*

Our model distinguishes between the material *Physical Slip Surface* and the immaterial *Fault Surface* and specifies the links between the two entities. This distinction, supported in the top-level ontology, is an advantage compared to the GeoSciML/RESQML models that collapse



Spatial organization,

Vertical Topological organization

Fig. 5. Various components of a fault and their spatial arrangements. The right-hand figure shows the topological organization in the cross-section AA' related to Fault 1. In the ontology, Fault Volume refers to what is inside the red dashed line (i.e., fault zone + wall). We did not simply use the term "fault" to represent this concept to avoid ambiguity.

both entities and allow inconsistent inference of properties.

The GeoCore category *Geological Structure (BFO: generically dependent continuant)* allows a concise description of the fault spatial arrangements. We defined three kinds of GeoCore: *geological structure*:

- *Fault Structure* describes the spatial positions and relationships of the geological blocks separated by the fault (3D description). Fault structure characterizes (is ontologically dependent on) a fault as such. A fault is a rock volume that is the bearer of a fault structure.
- *Fault System Structure* describes the arrangement of fault volume within a fault system.
- *Fault Array Structure* describes the pattern of the various fault surfaces of a fault system.

We describe the various properties of the material and immaterial fault entities as *BFO*: *quality, role,* and *disposition.* In addition, we model the spatial fault orientation by referring to the *BFO: three-dimensional spatial region* for the fault location.

Since we conceive the ontology for geologists and modelers aware of geology, we have retained the vocabulary used by geologists. Therefore, some ontology classes have names that do not fully reflect their ontological nature. For example, we have defined fault zone or damage zone as actual *GeoCore: geological object* and not as *BFO: fiat object part.*

4.2.2. Formalization, evaluation, and validation (steps 4 and 5)

We conducted step 4 (formalization) in parallel with step 3. We provided formal definitions for each of the entities considered in GeoFault. Each definition comprises an ontological classification and an elucidation of its geological significance. The definitions are presented in natural language in an Aristotelian definition style to make them understandable to potential users. To make the ontology operative (step 5), we described it in OWL 2 language and validated it with competency questions across two use cases.

4.3. GeoFault ontology framework

We present the ontology framework in several relational schemas in Figs. 6–10.

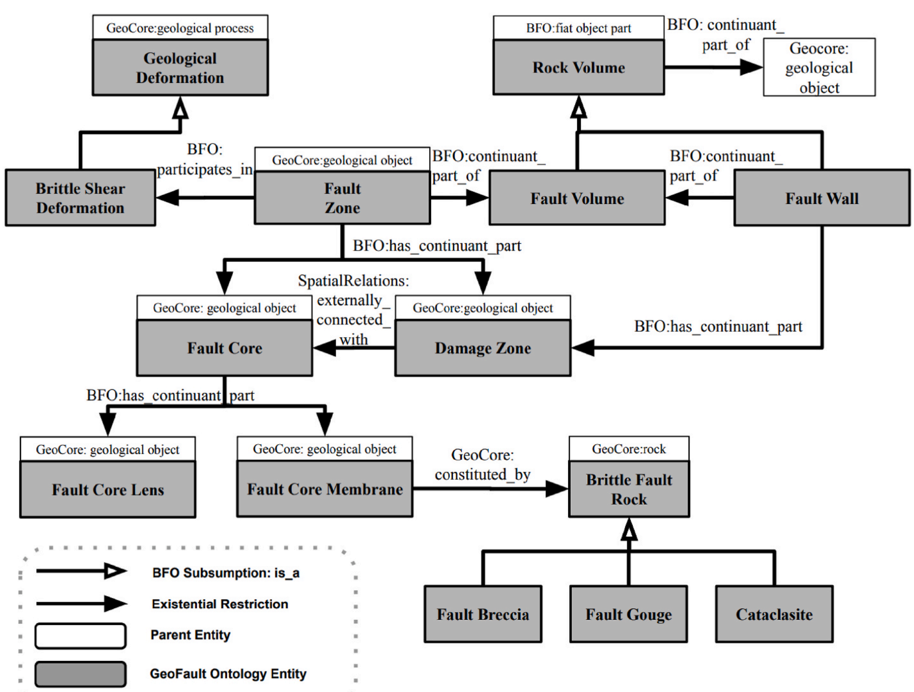


Fig. 6. Part of the ontological framework showing the material entities related to "fault." Definitions of Fault Zone, Fault Core, Damage Zone and Brittle Fault Rock are listed in the text, and the rest of the definitions are in the appendix.

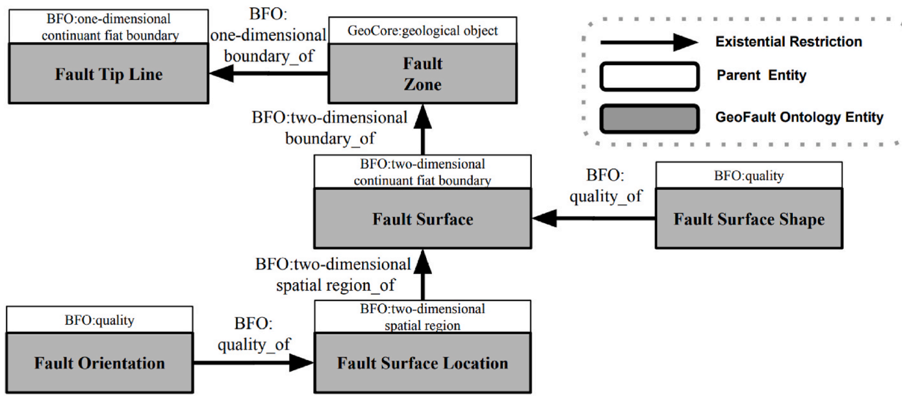


Fig. 7. Part of the ontological framework showing the entities associated with Fault Surface. Definitions of Fault Surface and Brittle Tip Line are listed in the text, and the rest of the definitions are in the appendix.

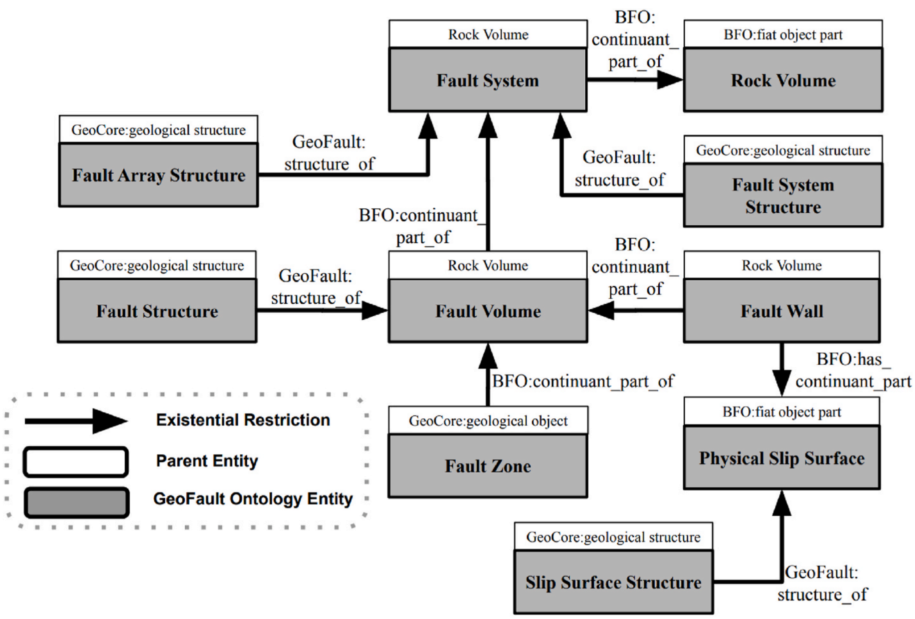


Fig. 8. Part of the ontological framework showing the entities considered to describe the structures that are patterns of a single fault volume and a fault system. Definitions of Fault System, Fault Structure, Fault System Structure, and Physical Slip are listed in the text, and the rest definitions are in the appendix.

- Fig. 6: fault objects, object parts *(BFO: material entities),* and their generative processes;
- Fig. 7: fault surfaces *(BFO: immaterial entities)* and their orientations and shapes;
- Figs. 8 and 9: fault structures *(BFO: generically dependent continuant)*;
- Fig. 10: fault and fault material properties *(BFO: specifically dependent continuant).*

In Figs. 6–8 and 10, the black arrow is the existential restriction between two entities, and the prefix of each existential restriction indicates the original ontology of the term. For example, in Fig. 6, the existential restriction between the Damage Zone and Fault core means: Every Damage Zone is externally connected with at least one Fault Core (DamageZone $\sqsubseteq \exists$ externallyConnectedWith FaultCore), and externallyConnectedWith is from SpatialRelations ontology.

This section provides a few definitions as examples to help readers understand the relational schemas; the complete definitions list is in Appendix 1. In the appendix, all definitions are in Aristotelian format, using bold characters to represent the ontology classes, prefixes to indicate the original ontology of the classes and italics to represent relations. We had special care in defining each new entity by specializing a previously defined entity in some of the reused ontology (BFO, GeoCore, and Geological Relation Ontology), including new qualities, relations, or axioms. There are no self-explanatory terms or circular definitions. In Figs. 6–8 and 10, existential restrictions are marked with prefixes to indicate which ontology originates them. We provide more detailed definitions of the related superclasses, relations, and complementary axioms in the supplementary documents attached: definition list and code availability (owl file).

1. **Fault Zone:** a **GeoCore:geological object** that is *continuant_part_of* some **Fault Volume.** A **Fault Zone** *participates_in* some **Brittle Shear Deformation.** It materializes a physical discontinuity and a visible sharp shear displacement.
2. **Fault Core:** a **GeoCore:geological object** that is *continuant_part_of* some **Fault Zone**, *generated_by* some **Brittle Shear Deformation**, and *constituted_by* some **Brittle Fault Rock.** It accommodates the high-strain major shear displacement.
3. **Damage Zone:** a **GeoCore:geological object** that is *continuant_part_of* some **Fault Zone,** *externally_connected_with some* **Fault Core,** and *continuant_part_of* some **Fault Wall.** It accommodates the low-strain brittle deformation.

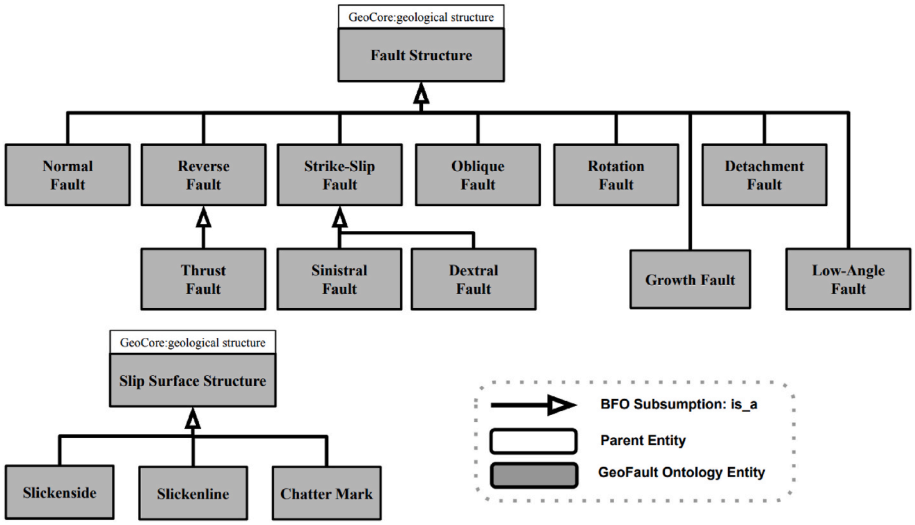


Fig. 9. Entities that are subsumption of Fault Structure and Slip Surface Structure. The definition of Fault Structure is listed in the text, and definitions of the rest entities are in the appendix.

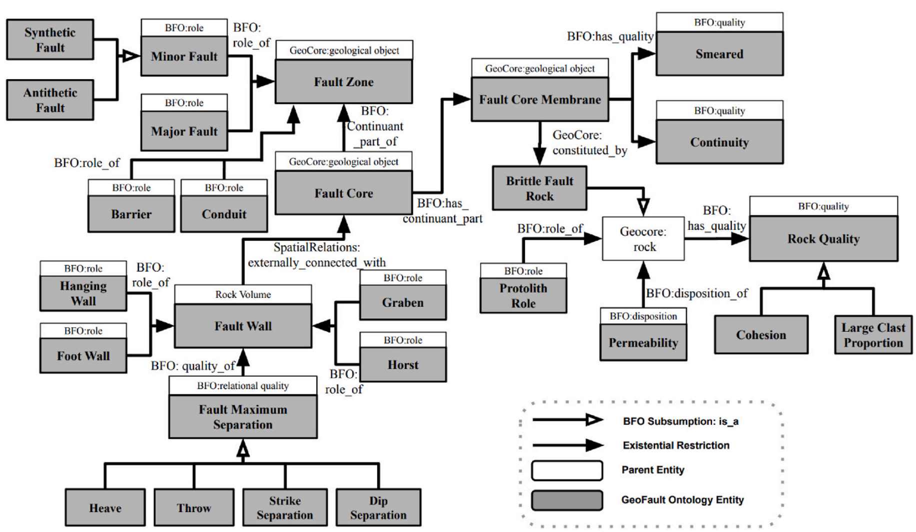


Fig. 10. Part of the ontological framework showing entities specifically depend on fault fault-related concepts. Definitions of Barrier, Conduit, Hanging/Foot Wall, and Major/Minor Fault are listed in the text, and the rest of the definitions are in the appendix.

4. **Brittle Fault Rock:** a **GeoCore:rock** that is *generated_by* some **Brittle Shear Deformation.** Fault Breccia, Fault Gouge, and Cataclasite are subclasses of Brittle Fault Rock.
5. **Fault Surface:** a **BFO: two-dimensional continuant fiat boundary** that is related to a **Fault Zone.** It corresponds to the locus surface of the points that are equally distant to the two Fault Walls of the related Fault Zone.
6. **Fault Tip Line:** a **BFO: one-dimensional continuant fiat-boundary** that is the locus of the points of the **Fault Zone**, where the shear displacement goes to zero.
7. **Fault System:** a **Rock Volume** that *has_continuant_part* some and minimum 2 **Fault Volume.**
8. **Fault Structure:** a **GeoCore:geological structure** that is *structure_of* some **Fault Volume.** It is a pattern that describes the mutual positions and orientations of the Faut Walls and the Fault Surface. (the subclasses of Fault Structure are presented in Fig. 9).
9. **Fault System Structure:** a **GeoCore:geological structure** that is *structure_of* some **Fault System.** It describes the spatial arrangement among the **Fault Walls** of **Fault Volumes**, which are *continuant_part_of* a **Fault System.**

Subclasses: Horst & Graben, Duplex, Positive, and Negative Flower Structures.

10. **Physical Slip Surface**: a **BFO: fiat object part** that is *continuant_part_of* some **Fault Wall** and *externally_connected with* some **Fault Core.** It is the external physical surface part of the wall along which a fault slip occurs.
11. **Barrier** and **Conduit:** a **BFO:role** that is *role_of* some **Fault Zone.** A fault zone is barrier or conduit when it allows fluid flow or blocks fluid flow.
12. **Hanging Wall** and **Foot Wall**: a **BFO:role** that is *role_of some* **Fault Wall**, realized by the wall position above or below the fault surface to which the wall is related.
13. **Major Fault** and **Minor Fault**: a **BFO:role** that is *role_of* some **Fault Zone.** A Fault is major if its displacement is large compared to that of some others. It is minor if it is small compared to others' displacement.

5. Evaluation and validation

After the conceptualization step, we implemented the GeoFault ontology in the OWL 2 language[7] (Motik et al., 2009) using the ontology editor Protégé[8] (Musen, 2015). We verified the consistency using the HermiT[9] reasoner (Shearer et al., 2008). We also used our ontology in an in-house ontology-driven data entry application, *SiriusGeoAnnotator*[10], to test the suitability of GeoFault for annotating fault knowledge in geological images.

SiriusGeoAnnotator is an ontology-driven web application that allows users who work with geological images to easily upload the image data and interactively annotate the data by clicking the target feature on the image. The SiriusGeoAnnotator functionality loads the OWL 2 domain ontology at the application start-up and supports the functionality using the semantics provided by the ontology. This ontology is classified and processed using the HermiT reasoner and the RDFox[11] triple store, which allows the application to decide which annotation options and suggestions to present to the users. This setting permits the user to construct a knowledge graph that describes the essential content of the image. These knowledge graphs support information searching, automatic geological reasoning, image data retrieval from a large dataset, and building annotated image corpora for machine learning image classification and recognition.

Besides syntactic and logic verification, we evaluate the capability of describing fault knowledge on an interpreted outcrop photograph (use case 1) and on an interpreted seismic cross-section (use case 2) by building knowledge graphs in both Protégé and SiriusGeoAnnotator (loaded with the GeoFault Ontology).[12] We describe these cases in the next sections.

5.1. Use case 1: Maiella Mountain (outcrop cross-section)

Use case 1 is related to the site of the Maiella Mountain (Abruzzo, Italy) studied by Johannessen (2017) and Torabi et al. (2019). It is interesting because it includes different types of faults and associated descriptions of the rock material of the fault cores. Fig. 11 shows the studied outcrop with interpreted geological features:

- A group of normal faults (F 1–5 and F8) dipping towards the East,
- a group of strike-slip faults (F6, F7, F9),
- fault breccia, fault gouge, and slip surface appear in fault F1,
- and fault breccia show in fault F7.

Fig. 12 shows the knowledge graphs of the geological features from use case 1 described by the GeoFault ontology and outlines the relationships between instances. We used it to solve the following competency questions:

CQ 1: Search one or several strike-slip and dip-slip faults with a core that has some breccia;
CQ 2: Find the location of this or these faults in the outcrop.
CQ 3: Does this or these faults belong to any fault system group? If yes, which group?

Considering the information in Fig. 12, the competency questions can be solved as follows:

- Fault Breccia is present in Fault Core 1 and Fault Core 7.
- Following the orange path in Fig. 12, we see that Fault Core 1 is part of Fault Volume FV 1, which has a normal fault structure. Therefore, Fault 1 does not answer CQ1.
- Following the blue path in Fig. 12, we see that Fault Core 7 is part of Fault Volume FV 7, which has a strike-slip fault structure. Therefore, **Fault 7 answers CQ 1.**
- Considering the green links between FV 7, FV 9, and FV 6, we see that FV 7 is located East of FV 9 and West of FV6. FV 9 is also West of FV 6. Therefore, the answer to the CQ2 is that **F7 is located between F6 and F9.**
- By following the green path in Fig. 12, it is clear that FV7 is part of the Strike-Slip Fault Group, which answers **CQ3.**

5.2. Use case 2: Northern Horda Platform, North Sea (seismic cross-section)

Use case 2 is from the seismic interpretation by Mulrooney et al. (2020) of a North Sea site (North Horda platform). The primary data we considered are related to the EW seismic cross-section NNST 84-05 shown in Fig. 13. We added complementary cross-sections and a legend to understand the local setting better.

The interpretation of the NNST84-05 cross-section identifies the following:

- Three major faults from West to East: Tusse Fault Zone (TFZ), Vette Fault Zone (VFZ), and Øygarden Fault Complex (ØFC).
- Two second-order fault systems: the Triassic-Cretaceous (TK) and Eocene-Miocene (EM).

Fig. 14 shows the knowledge graph of the geological features from use case 2. We used it to answer a series of competency questions related to the Øygarden Fault Complex (Zone):

CQ 4: What type of fault is it?
CQ 5: What kind of surface shape does it have?
CQ 6: Is it a major or a minor fault?
CQ 7: To which geological block does its hanging wall belong?
CQ 8: What is its age relative to the other faults in the site?

Considering the information in Fig. 14, the competency question can be solved:

CQ 4 Answer: Following the blue path, we see that the Øygarden Fault Zone is part of the ØFC Volume, which corresponds to a **normal fault**.

CQ 5 Answer: Following the purple path, the fault surface related to the Øygarden fault zone is the ØFC fault surface with a **listric (curved) geometry**.

CQ 6 Answer: The orange link shows that the Øygarden fault zone plays a major fault role. It is a **major fault**.

CQ 7 Answer: Following the red path, we see that the hanging wall of the Øygarden fault zone is the ØFC west wall, which is part of the **Smeaheia block**.

CQ 8 Answer: Following the green path, we see the ØFC Volume belongs to the 1st Order fault system, which is older than the TK fault system, which is older than the EM fault system. The Øygarden Fault Zone is a part of the **oldest fault system** on the site.

5.3. Evaluation of the use of the SiriusGeoAnnotator

Using SiriusGeoAnnotator, we annotated the geological knowledge in use cases 1 and 2 with two geology students without semantics experience. As a result, the users have manually annotated all instances without any new concepts in the Abox.

Throughout the evaluation, we observed that SiriusGeoAnnotator makes it possible to structure an annotating interface and to load a top-level based domain ontology without burdening the user with top-level ontological terms such as BFO occurrent or continuant. The

[7] OWL 2: https://www.w3.org/TR/owl2-syntax/.
[8] Protégé: http://protege.stanford.edu/.
[9] HermiT: https://www.cs.ox.ac.uk/isg/tools/HermiT/.
[10] SiriusGeoAnnotator: https://sws.ifi.uio.no/project/sirius-geo-annotator/.
[11] RDFox: https://www.oxfordsemantic.tech/product.
[12] SiriusGeoAnnotator loaded GeoFault ontology: http://158.37.63.37:8081/gic.

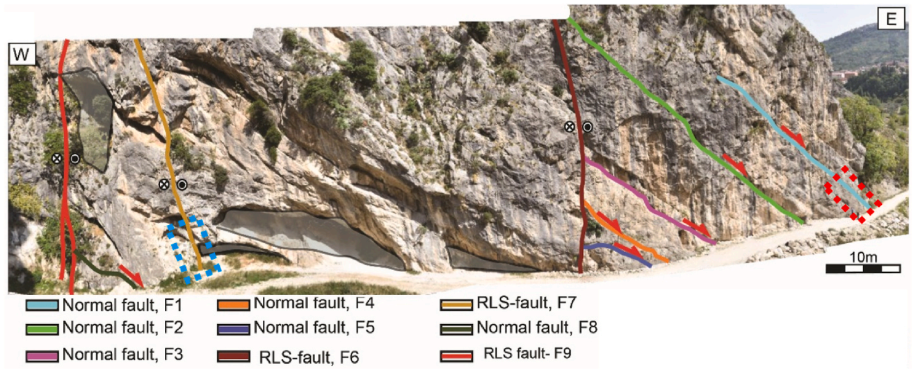


Fig. 11. A view of the studied Maiella Mountain outcrop with interpreted fault features. The authors found fault breccia in the area marked by blue dashed fault lines F7. Fault breccia, fault gouge, and slip surface are in the area marked by red dashed lines of fault F1 (Torabi et al., 2019). RSL stands for right-lateral strike-slip (dextral) fault.

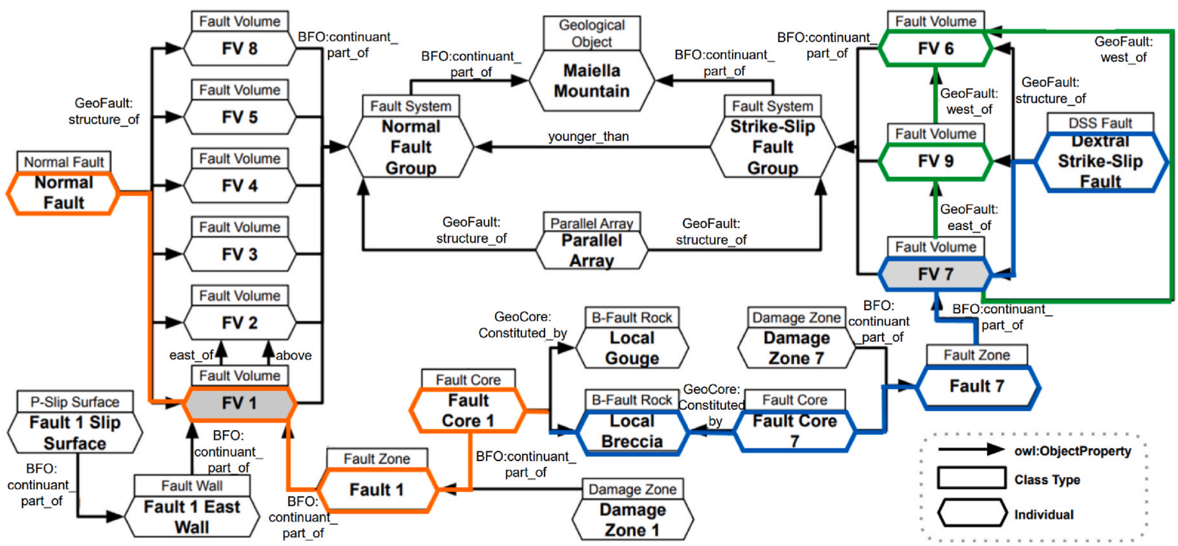


Fig. 12. This graph drawn by the authors depicts semantic triples generated by the annotation of use case 1. The colored lines indicate the ontological links for solving the competency questions (B-Fault Rock: brittle fault rock, FV: fault volume, DSS Fault: dextral strike-slip fault, P-Slip Surface: physical slip surface).

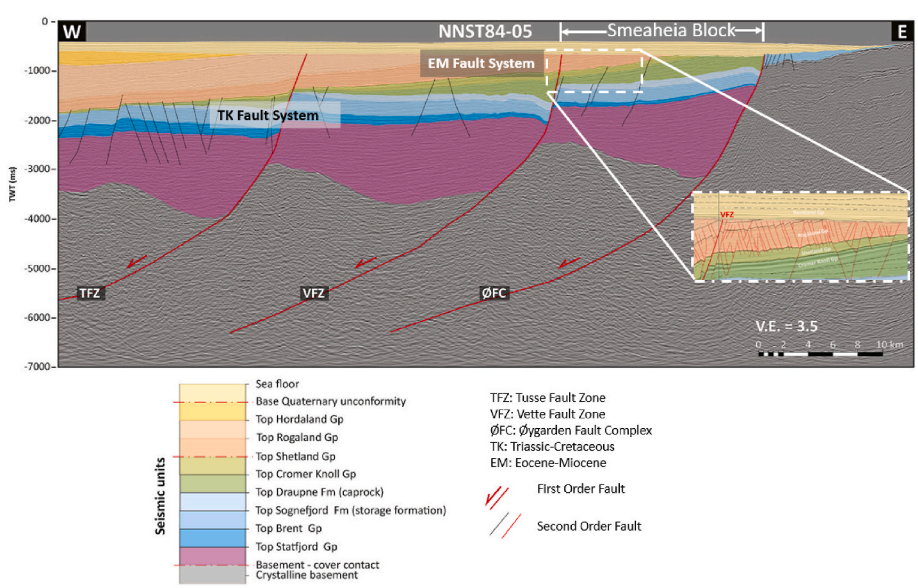


Fig. 13. Northern Horda Platform: seismic interpretation of cross-section NNST 84–05, three fault systems are noted: 1st order fault system, Triassic-Cretaceous (TK) fault system, and Eocene-Miocene (EM) fault system (modified from Mulrooney et al., 2020).

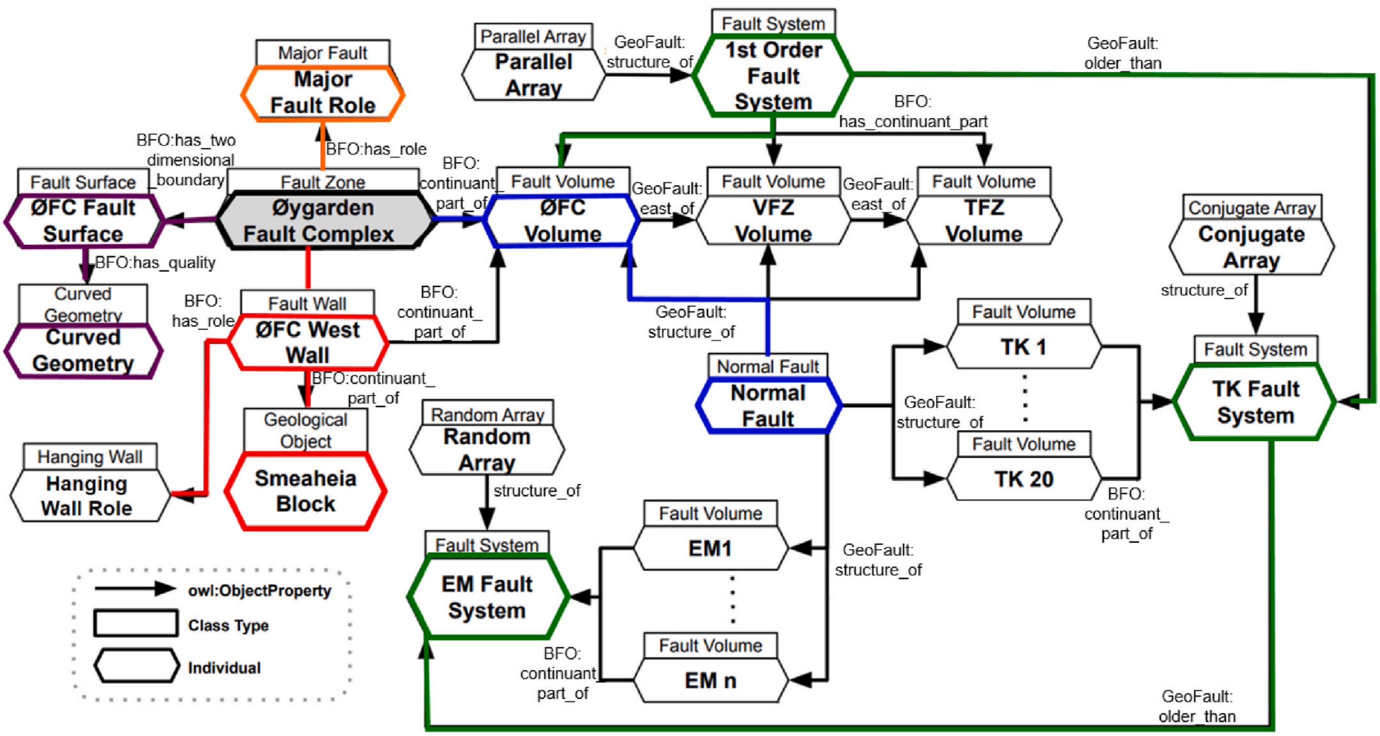


Fig. 14. The graph drawn by the authors depicts the semantic triples generated by the annotation of use case 2 (Northern Horda Platform). The colored lines indicate the ontological links used to solve the competency questions.

SiriusGeoAnnotator is an easy-to-use tool and allows domain users to annotate fault knowledge in images. We have demonstrated that the knowledge model GeoFault sufficiently captures fault knowledge.

However, the SiriusGeoAnnotator still requires end users to understand some ontological relations between entities, such as "quality of" and "disposition of," which are unnecessary and cumbersome.

Future work is necessary to perfect the user interface in order to use an ontologically correct domain model that adheres to an upper ontology and allows end users to navigate it easily and naturally.

6. Conclusion

This work demonstrated the benefits of ontological analysis in a complex geological concept: Fault. We deconstructed the concept to understand what geologists mean when referring to faults. A fault can be a specific rock volume or a larger scale surface having various shapes. Geologists also may conceive a fault as a structural feature specifying the spatial relationships between the material volumes separated by the fault surface (e.g., normal fault). In a fault system, fault structures specify volume arrangements (e.g., duplex) and surface arrangements (e.g., parallel array). All these conceptualizations of a fault are correct and dynamically applied for geologists when doing geological description and interpretation. In our project, we have tried to make these differences explicit to process the descriptions of cases with the correct semantics.

The GeoFault ontology exclusively addresses the brittle deformation domain of the upper crust considered at different scales, excluding the continental and microscopic scales. It covers basic fault knowledge with precise definitions from ontological and geological perspectives. The ontology was modeled in the OWL 2 language and validated by two use cases and an in-house application.

We have chosen the BFO/GeoCore package as the top-level ontology, given its adherence to realism, which aligns with the idea of a descriptive system. Allowing the integration of the material and structural aspects of fault is a decisive advantage of the BFO/GeoCore package. Compared to existing knowledge models, GeoFault has the advantage of unambiguously representing individual faults and fault systems at the material and structural levels and specifying how these levels are related. It benefits quantitative and qualitative analyses, such as those applied by Cullis et al. (2019) and Yu et al. (2021).

Although GeoFault brings some enhancements compared to GeoSciML and RESQML, it is still a limited model that fails to consider shear deformations in the brittle and ductile deformation domains. Also important is modeling the processes that generate these deformation structures, allowing a more sophisticated automatic interpretation. Future work could address these issues to extend the usefulness of GeoFault to other related geoscience domains. We hope the GeoFault Ontology will provide a helpful knowledge model for all practitioners, geologists, and engineers who must deal with faults.

Code availability

The OWL file of GeoFault and two use cases validation can be found in the online repository: https://github.com/Yuanwei-Q/GeoFault-Ontology.

The SiriusGeoAnnotator with loaded OWL file and annotated instances of the two use cases are available here: http://158.37.63.37:8081/gic

Authorship contribution statement

Yuanwei Qu collected geological knowledge, elaborated the ontology model, wrote the original draft, and organized the ontology validation. Michel Perrin jointly elaborated the ontology model, conducted validation, and operated the paper redaction. Anita Torabi provided the basic geological information, consisting of a list of reference papers and suggested geological case studies. She also reviewed and edited the paper to ensure geological consistency. Mara Abel and Martin Giese also reviewed and edited the paper to ensure ontological consistency and review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link to my code in the Code Availability section

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cageo.2023.105478.

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