A spatial relation ontology for deep-water depositional system description in Geology

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Abstract. *In the construction of geological models, it is crucial to specify the spatial relations between the represented entities, which support the understanding of the 3D distribution of the rock bodies. In this paper, we propose an ontological model, based on the GeoCore ontology and the Basic Formal Ontology (BFO), which defines a set of spatial relations between geological objects, amounts of earth materials, sites, boundaries, and other geological entities. We discuss a modeling case study of a deep-water channel-levee occurrence of the Karoo basin data from South Africa. The result of this work is an ontology that supports software applications in the determination of the physically possible spatial distribution of reservoir geological bodies.*

1. Introduction

In geological data interpretation, experts identify geological entities in the raw data and specify relations between them [Garcia et al. 2020]. Spatial relations are particularly decisive in geological reasoning because they support the representation of the 3D distribution of the rock bodies and, hence, the interpretation of the processes that generated these entities. For example, when a sedimentary rock layer is placed above an adjacent layer in a depositional sequence, the geologist infers that the former is younger than the later. In this context, it would be helpful to have a common terminology and criteria to classify and instantiate qualitative spatial relations on geological entities.

In this paper, we review a small collection of ontological models that define spatial relations. These ontologies were designed for other domains where the spatial distribution of objects is relevant. Then, we select a set of spatial relations that are useful for describing the spatial distribution of geological entities. With these relations, we build a new ontology of geological spatial relations, which modelers can use in many geological descriptions of several sub-domains. The geological entities that we relate are defined in the GeoCore ontology [Garcia et al. 2020]: a core ontology designed to specify a general set of concepts in the Geology domain, such as Geological Object, Earth Material, Geological Boundary, and others. We use the GeoCore ontology as the base ontology for our work. GeoCore, in its turn, uses the Basic Formal Ontology (BFO) [Arp et al. 2015] as a foundational ontology. We ground our spatial relation definitions in these two ontologies.

With the geological spatial relations defined, we describe a case study on a subset of the Karoo basin's geological data described in [Hodgson et al. 2011]. In this study, we instantiate the rock bodies as Geological Objects of GeoCore ontology and spatially relate the instances according to the observations. The result shows that the ontology allows an expressive and formal description of spatial relations in the Geology domain.

This work is structured as follows. In Section 2, we examine some works that define spatial relations. In Section 3, we introduce the GeoCore ontology. In Section 4, we review the ontological notions of relations that we use in this work. In Section 5, we describe the geological spatial relations ontology. In Section 6, we describe the case study made using the Karoo basin data subset. In Section 7, we conclude this paper and present future work ideas.

2. Spatial relation ontologies

The work of [Hudelot 2005] proposes a set of ontologies for semantic image interpretation. One of these ontologies describes the spatial relations between objects. It defines three main categories: topological relations, orientation relations, and distance relations (see Figure 1 for a complete view of the relations taxonomy). For topological relations, the ontology imports the spatial relation concepts from RCC-5 (Region Connection Calculus) and RCC-8 theories [Clarke 1981, Cohn and Hazarika 2001]. Both theories define foundational topological relations based on connection relations, in that two objects are connected if they share at least a point. Table 1 presents the definitions of these topological relations. The orientation relations are defined as proposed by [Freeman 1975], who described four primitive relations: *Left of*, *Right of*, *Above*, and *Below*. The relations *In Front of* and *Behind* are also commonly used; nevertheless, the authors do not define them because their work deals with two-dimensional image interpretation. These relations express where an object is located relative to another based on an assumed frame of reference, which can be an external coordinate system, the observer, or an object. The ontology also defines four distance relations: *Very Close*, *Close*, *Far*, and *Very Far*. These relations express the distance of an object relative to another. They depend not only on the absolute positions of both objects but also on their relative sizes, shapes, and the assumed frame of reference. In these relations, the frame of reference can be an external spatial arrangement, the observer, or one aspect of the objects (e.g., their sizes).

[Cohn and Renz 2008] review an extensive set of notions for qualitative spatial representation and reasoning, focusing on symbolic and qualitative descriptions. Their work addresses and integrates many different aspects of spatial representation. The *mereotopological* aspect integrates mereology (theory of parthood) and topology. This aspect considers that two spatial entities are connected if the intersection of the spaces occupied by both is not empty. A spatial entity x is a part of y if and only if whatever entity connected to x is also connected to y. Examples of mereotopological relations are *overlaps*, *equals*, *proper part of*, *tangential part of*, *boundary part of*, and others. These relations resemble and also extend the RCC-8 relation set. The authors state that there are many situations where mereotopological relations alone are insufficient, so they introduce the *directional* aspect of spatial relations. Direction relations specify the orientation

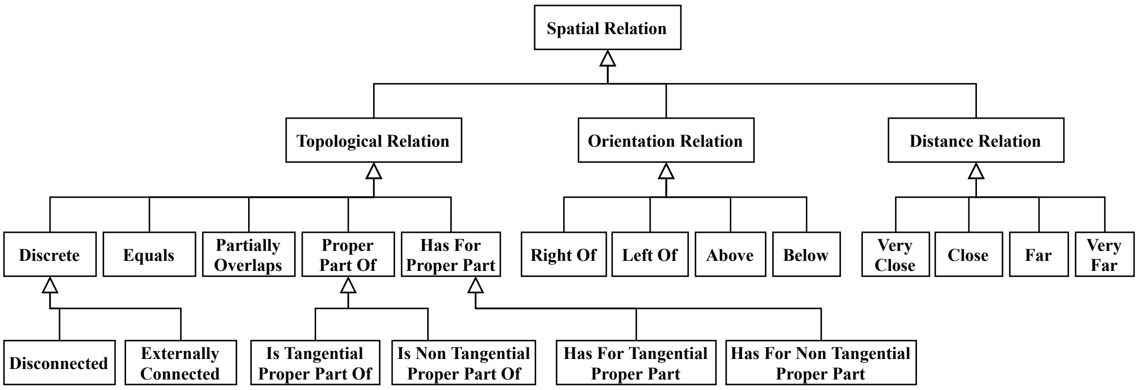


Figure 1. The taxonomy of spatial relations as proposed by [Hudelot 2005].

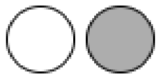
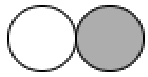
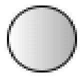
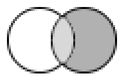
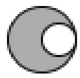
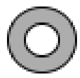
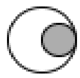
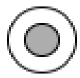
RCC-5	RCC-8	Meaning	Image
DR(x,y)	*DC(x,y)*	*x* is disconnected from *y*	
	EC(x,y)	*x* externally connected with *y*	
EQ(x,y)	*EQ(x,y)*	*x* is identical to *y*	
PO(x,y)	*PO(x,y)*	*x* partially overlaps *y*	
PP(x,y)	*TPP(x,y)*	*x* is a tangential proper part of *y*	
	NTPP(x,y)	*x* is a non-tangential proper part of *y*	
PP-i(x,y)	*TPP-i(x,y)*	*x* tangentially contains *y* as a proper part	
	NTPP-i(x,y)	*x* non-tangentially contains *y* as a proper part	

Table 1. The topological spatial relations, as defined in RCC (Region Connection Calculus) theories.

OGC Simple Features	Egenhofer	RCC-8
equals	equal	EQ
disjoint	disjoint	DC
intersects	¬disjoint	¬DC
touches	meet	EC
within	inside ∨ coveredBy	NTPP ∨ TPP
contains	contains ∨ covers	NTPP-i ∨ TPP-i
overlaps	overlap	PO

Table 2. Equivalence between spatial relations of OGC Simple Features, Egenhofer, and RCC-8 relation sets [Battle and Kolas 2012].

of a primary object with respect to a reference object and a frame of reference. One example of a frame of reference that can be used is the cardinal reference system (cardinal directions N, S, W, and E). Other notions that this work introduces are *distance and size* (e.g., x is twice as big than y), *shape*, and *mereogeometry*, which extends mereology with geometrical concepts.

The work of [Battle and Kolas 2012] discusses the GeoSPARQL standard, which aims to address issues of geospatial data representation and access by providing primitives for the formal description of geospatial data and the ability to query and filter on the relationships between geospatial entities. The specification defines a vocabulary to represent features, geometries, and their relationships. A *feature* is an entity in the real world with some spatial location, while a *geometry* is a geometric shape used as a representation of a feature's spatial location. Examples of features are parks, airports, monuments, and restaurants. The relationships are topological and are expressed using three distinct vocabularies: OGC Simple Features[1], Egenhofer [Egenhofer 1994], and RCC-8 [Cohn and Hazarika 2001]. Table 2 presents the equivalence between these different sets of relations. Their meanings are the same as earlier described in RCC-8.

In [Arp et al. 2015], the authors present the Basic Formal Ontology (BFO), a foundational ontology for scientific domains. It is designed to be small and describes a limited set of concepts that serves as a starting point to model specialized knowledge. Nevertheless, the ontology defines three spatial relations for general use: *Located In*, *Location Of*, and *Adjacent To*. Located In is a relation between two spatial entities, x and y, and a time t, in which the spatial region occupied by x is a part of the region occupied by y at t. In the same sense, Location Of is a relation in which the region occupied by x has the region occupied by y as a part. Adjacent To, in its turn, is a relation that expresses the proximity of the regions occupied by x and y at t.

3. The GeoCore ontology

In [Garcia et al. 2020], the authors propose the GeoCore ontology, which is a core ontology designed to define a set of very general concepts that permeate the whole domain of geological entities. The authors offered a sound and general-use ontology that helps to integrate knowledge related to distinct domains of Geology, Geophysics, and Reser-

[1] `https://www.ogc.org/standards/sfa`

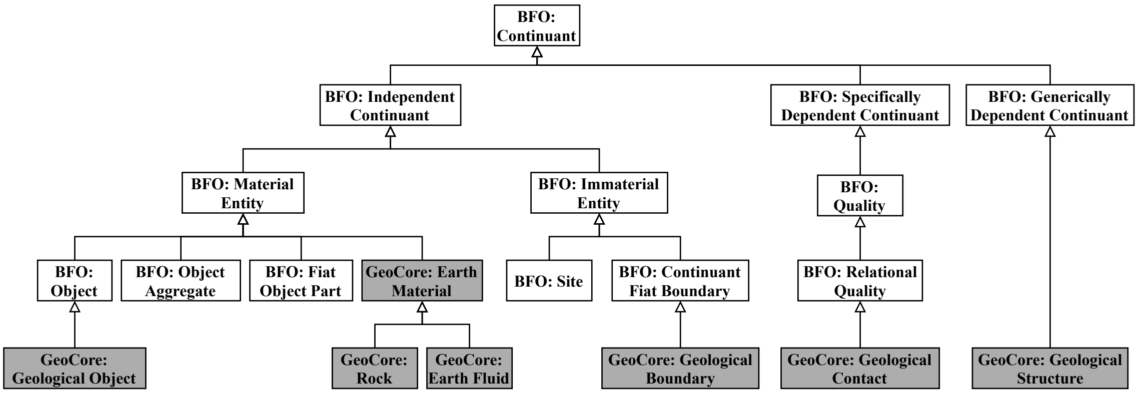


Figure 2. The hierarchy of the GeoCore concepts [Garcia et al. 2020] that supports this work.

voir Engineering. It specializes the concepts of Object, Material Entity, Continuant Fiat Boundary, and others of the BFO ontology [Arp et al. 2015] in terms of geological concepts. The GeoCore ontology aims to cover the main concepts, but it is not a complete partition, allowing the user to specialize and include dependent continuants such as qualities. Therefore, users can take advantage of the concepts of both GeoCore and BFO to build specialized ontologies (see Figure 2). OWL (Ontology Web Language) implementations of GeoCore[2] and BFO[3] are available in web repositories.

In GeoCore, a *Geological Object* is a BFO Object generated by some Geological Process and constituted by some Earth Material. An *Earth Material* is a BFO Material Entity of natural matter, either solid, fluid, or unconsolidated, that is also generated by some Geological Process. *Constituted By* is a relation between a Geological Object and an Earth Material in which the object is made of the material (e.g., a well core is constituted by rock). A *Rock* is a solid and consolidated Earth Material made of polycrystalline, monocrystalline or amorphous mineral matter or material of biological origin. An *Earth Fluid* is a fluid Earth Material, e.g., water, gas, and oil.

A *Geological Boundary* is a BFO Continuant Fiat Boundary corresponding to a physical discontinuity of any nature, located on the external surface of a Geological Object. A *Geological Contact* is a BFO Relational Quality that inheres in two Geological Objects whose boundaries are adjacent to each other. A *Geological Structure* is a Generically Dependent Continuant that describes the internal arrangement of some Geological Object, i.e., the configuration of and mutual relationships of its different parts (e.g., a geological fault). GeoCore also defines *Geological Process*, *Geological Time Interval*, and *Geological Age*, which are not covered by this work.

4. Ontological notions of relations

Before modeling the spatial relations, we shall present the ontological notions of relations that we use in this work. In this work, a *relation* is a binary predicate that connects two entities [Guarino et al. 2009]. Relations have a direction, i.e., if a relation r connects x to y, it does not necessarily imply that r connects y to x. A relation can connect two

[2] `https://github.com/BDI-UFRGS/GeoCoreOntology`
[3] `https://github.com/BFO-ontology/BFO`

universals, two particulars, or a particular to a universal[4] [Arp et al. 2015].

Here, we use the properties of *transitivity*, *symmetry*, *reflexivity*, and *inversion*, according to the definitions of [Arp et al. 2015], to support our definitions. We also use the notion of *subrelation* as defined in OWL[5]. Given two relations r and r_s in which r_s is a subrelation of r, if r_s relates x to y, it implies that r relates x to y. Subrelations do not necessarily share the same properties, e.g., r can be transitive while r_i is not.

In [Fonseca et al. 2019], the authors analyze relations concerning different types of truthmakers (entities which relations hold by virtue of them) and propose two orthogonal distinctions which we use in this work: *internal/external* and *descriptive/non-descriptive*. An internal relation is definable in terms of their relata's intrinsic properties, such as a comparative relation like "John is taller than Mary". In contrast, an external relation cannot be defined in terms of their relata' intrinsic properties. An example of it is a marriage relation, whose truthmaker is composed of the partners' mutual commitments and obligations. A descriptive relation holds by virtue of some aspect of the relata, such as the aforementioned "John is taller than Mary" example. On the other hand, a non-descriptive relation holds by virtue of the entities as wholes, e.g., a relation of existential dependence between a quality and its bearer.

5. A spatial relation ontology for deep-water depositional system description

To build a spatial relation ontology for the Geology domain, we first need to decide what kinds of spatial relations we intend to model. As reviewed in Section 2, there are several conceptual categories described in the literature: topological, directional, mereotopological, geometrical, etc. To select the intended relations appropriately, we shall define a list of competency questions that will guide our decisions. Competency questions are queries, either in a natural or a formal language, that an ontology should be able to represent and answer [Uschold and Gruninger 1996]. The competency questions for our ontology are:

1. What geological objects are externally connected to this geological object?
2. What geological objects are spatially discrete from and above this geological object?
3. What geological objects are proper spatial parts of this geological object?
4. What geological objects are externally connected to and either on the left or on the right of this geological object?
5. What sites have this geological object as a proper spatial part?

We divide our presentation into two main categories: (1) mereotopological relations, and (2) directional relations. These two categories are sufficient to satisfy the competency questions above.

All relations described by the ontology connect particulars that instantiate the type *Independent Continuant (BFO)*. We made this modeling decision because Independent Continuant is a universal which covers all the types of geological entity that we introduced

[4]Here, we assume that a *universal* is an entity that can have instances, while a *particular* does not have any instance [Guarino et al. 2009].

[5]In OWL, subrelations are described as *subproperties*. What here we call "relations" are represented as "object properties" in OWL. See `https://www.w3.org/TR/2004/REC-owl-features-20040210/#subPropertyOf` for more details.

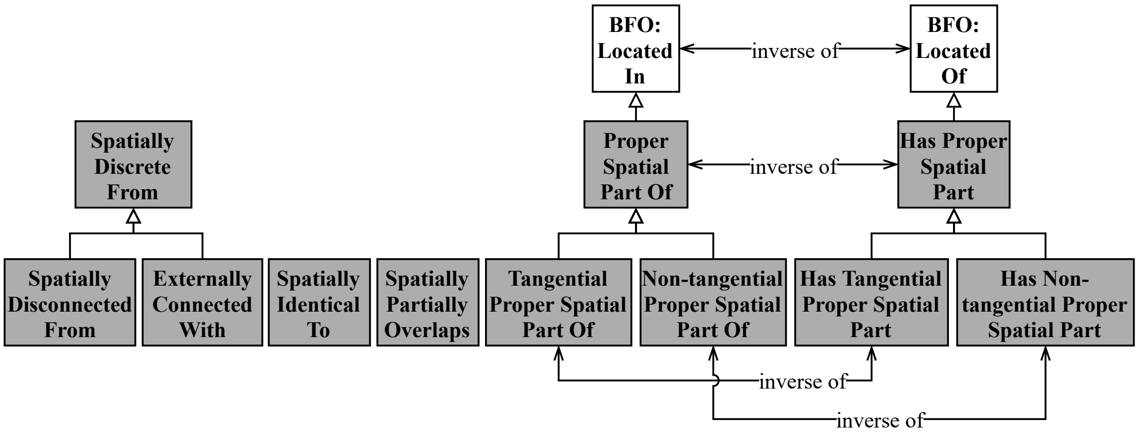


Figure 3. The mereotopological relations defined in this paper.

in Section 3 and intend to relate: Geological Objects such as rock bodies, Sites such as channels and holes, Geological Boundaries that delimit Geological Objects, and Fiat Object Parts of rock bodies.

In the sense of [Fonseca et al. 2019] (see Section 4), we consider that all relations are external and descriptive. "External" denotes that spatial relations occur by virtue of the positions, sizes, and shapes of the relata concerning each other, and "descriptive" indicates that these aspects are not the relata themselves.

An OWL implementation of the geological spatial relations ontology can be found in the web repository[6].

5.1. Mereotopological relations

This set of mereotopological relations (Figure 3) brings the concepts from RCC-5 and RCC-8 described in Section 2.

Definition 1 (Spatially Discrete From) A symmetric spatial relation between two *Independent Continuants* (BFO) in which both do not share the same spatial region, either wholly or partially.

Definition 2 (Spatially Disconnected From) A symmetric subrelation of **Spatially Discrete From** (def. 1) between two *Independent Continuants* (BFO) whose external boundaries are not adjacent.

Definition 3 (Externally Connected With) A symmetric subrelation of **Spatially Discrete From** (def. 1) between two *Independent Continuants* (BFO) whose external boundaries are adjacent.

Definition 4 (Spatially Identical To) A symmetric spatial relation between two *Independent Continuants* (BFO) in which both occupy precisely the same spatial region.

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

Definition 5 (Spatially Partially Overlaps) A symmetric spatial relation between two *Independent Continuants* (BFO) in which both share a part of the spatial regions they occupy.

Definition 6 (Proper Spatial Part Of) A transitive subrelation of *Located In (BFO)* between two *Independent Continuants* (BFO), x and y, in which the spatial region that x occupies is entirely inside the spatial region that y occupies. It is the inverse relation of **Has Proper Spatial Part** (def. 9).

Definition 7 (Tangential Proper Spatial Part Of) A subrelation of **Proper Spatial Part Of** (def. 6) between two *Independent Continuants* (BFO) whose external boundaries are adjacent. It is the inverse relation of **Has Tangential Proper Spatial Part** (def. 10).

Definition 8 (Non-tangential Proper Spatial Part Of) A subrelation of **Proper Spatial Part Of** (def. 6) between two *Independent Continuants* (BFO) whose external boundaries are not adjacent. It is the inverse relation of **Has Non-tangential Proper Spatial Part** (def. 11).

Definition 9 (Has Proper Spatial Part) A transitive subrelation of *Location Of (BFO)* between two *Independent Continuants* (BFO), x and y, in which the spatial region that y occupies is entirely inside the spatial region that x occupies. It is the inverse relation of **Proper Spatial Part Of** (def. 6).

Definition 10 (Has Tangential Proper Spatial Part) A subrelation of **Has Proper Spatial Part** (def. 9) between two *Independent Continuants* (BFO) whose external boundaries are adjacent It is the inverse relation of **Tangential Proper Spatial Part Of** (def. 7).

Definition 11 (Has Non-tangential Proper Spatial Part) A subrelation of **Has Proper Spatial Part** (def. 9) between two *Independent Continuants* (BFO) whose external boundaries are not adjacent. It is the inverse relation of **Non-tangential Proper Spatial Part Of** (def. 8).

5.2. Directional relations

This set of directional relations (Figure 4) is based on the concepts of [Freeman 1975]. For geological models, it makes sense to assume an *extrinsic* frame of reference. In this paper, we consider the observer's relative location as the frame of reference for simplicity reasons. However, this assumption limits data integration because instances that assume different relative locations cannot be integrated. This limitation can be better worked in the future, possibly by adopting a coordinate reference system as of [Battle and Kolas 2012] as the frame of reference.

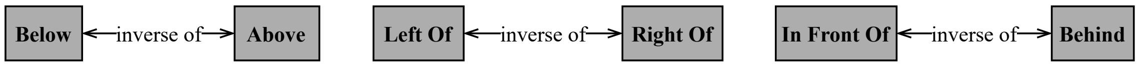


Figure 4. The directional relations defined in this paper.

Definition 12 (Below) A spatial relation between two *Independent Continuants* (BFO), x and y, in which x has a location lower than the location of y in the vertical axis corresponding to the same frame of reference. It is the inverse relation of **Above** (def. 13).

Definition 13 (Above) A spatial relation between two *Independent Continuants* (BFO), x and y, in which x has a location higher than the location of y in the vertical axis corresponding to the same frame of reference. It is the inverse relation of **Below** (def. 12).

Definition 14 (Left Of) A spatial relation between two *Independent Continuants* (BFO), x and y, in which x has a location to the east of the location of y in the horizontal axis corresponding to the same frame of reference. It is the inverse relation of **Right Of** (def. 15).

Definition 15 (Right Of) A spatial relation between two *Independent Continuants* (BFO), x and y, in which x has a location to the west of the location of y in the horizontal axis corresponding to the same frame of reference. It is the inverse relation of **Left Of** (def. 14).

Definition 16 (In Front Of) A spatial relation between two *Independent Continuants* (BFO), x and y, in which x has a location that makes it nearer than y in the longitudinal axis corresponding to the same frame of reference. It is the inverse relation of **Behind** (def. 17).

Definition 17 (Behind) A spatial relation between two *Independent Continuants* (BFO), x and y, in which y has a location that makes it nearer than x in the longitudinal axis corresponding to the same frame of reference. It is the inverse relation of **In Front Of** (def. 16).

6. The Karoo basin case study

Here, we discuss the practical application of the spatial relations ontology defined in Section 5. For this purpose, we use a subset of geological data (see Figure 5) extracted from the Karoo Basin dataset of [Hodgson et al. 2011]. The Karoo basin shows an exposed outcrop of a large deep-water channel-levee system originated predominantly by turbidity currents. This subset contains three delimited channel-form units named *channel elements*, which compose a greater channel-form named *channel complex*. Immediately to the left of the channel complex, there is another unit named *external levee*.

We instantiate each unit, single or composite, as a GeoCore *Geological Object*. With the objects instantiated, we can establish the spatial relations among them. The assertions are made here as follows:

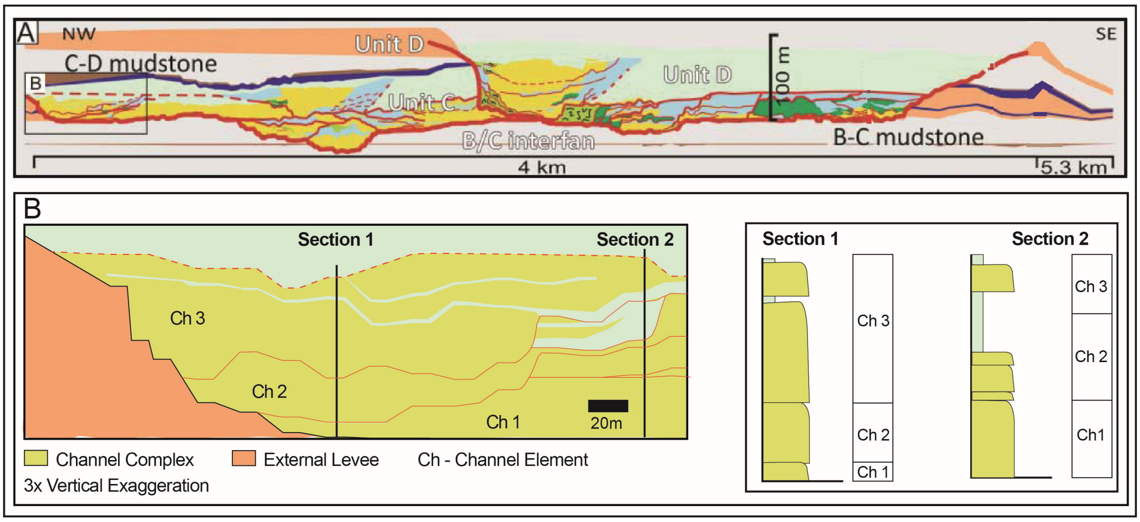


Figure 5. The subset of Karoo basin geological data on this work's case study, modified from [Hodgson et al. 2011].

1. the channel complex is related to the three channel elements by Has Tangential Proper Spatial Part relation;
2. channel element 1 (Ch 1) is Externally Connected With and Below channel element 2 (Ch 2);
3. channel element 1 (Ch 1) is Spatially Disconnected From and Below channel element 3 (Ch 3);
4. channel element 2 (Ch 2) is Externally Connected With and Below channel element 3 (Ch 3);
5. the external levee is Externally Connected With and Left Of the channel complex.

An OWL implementation of this case study can be found in the same OWL file that contains the geological spatial relations ontology (see Section 5). These assertions and the inferences made on them are illustrated in the diagram of Figure 6. The inferences were generated by the HermiT OWL Reasoner[7], which is embedded in the Protègè ontology editor[8].

It is possible to notice that the formal relations defined in the ontology are considerably expressive. With a few assertions, it is possible to make inferences that express the geological entities' spatial structure. For example, in Figure 6, we can see that a "externally connected with" assertion from "channel element 1" to "channel element 2" generates at least three inferences ("externally connected with" in the opposite direction and "spatially discrete from" in both directions). Such a model allows the representation of the rock bodies in computer applications, the execution of semantic queries, determination of spatial inconsistencies on the sedimentary bodies descriptions, and detection of analogous deposit architecture, among other benefits.

In sedimentary bodies like those represented here, geologists make associations between spatial relations and hierarchical orders of geological objects. Objects that have the same hierarchical order are always spatially discrete from each other, such as channel

[7]http://www.hermit-reasoner.com/
[8]https://protege.stanford.edu/

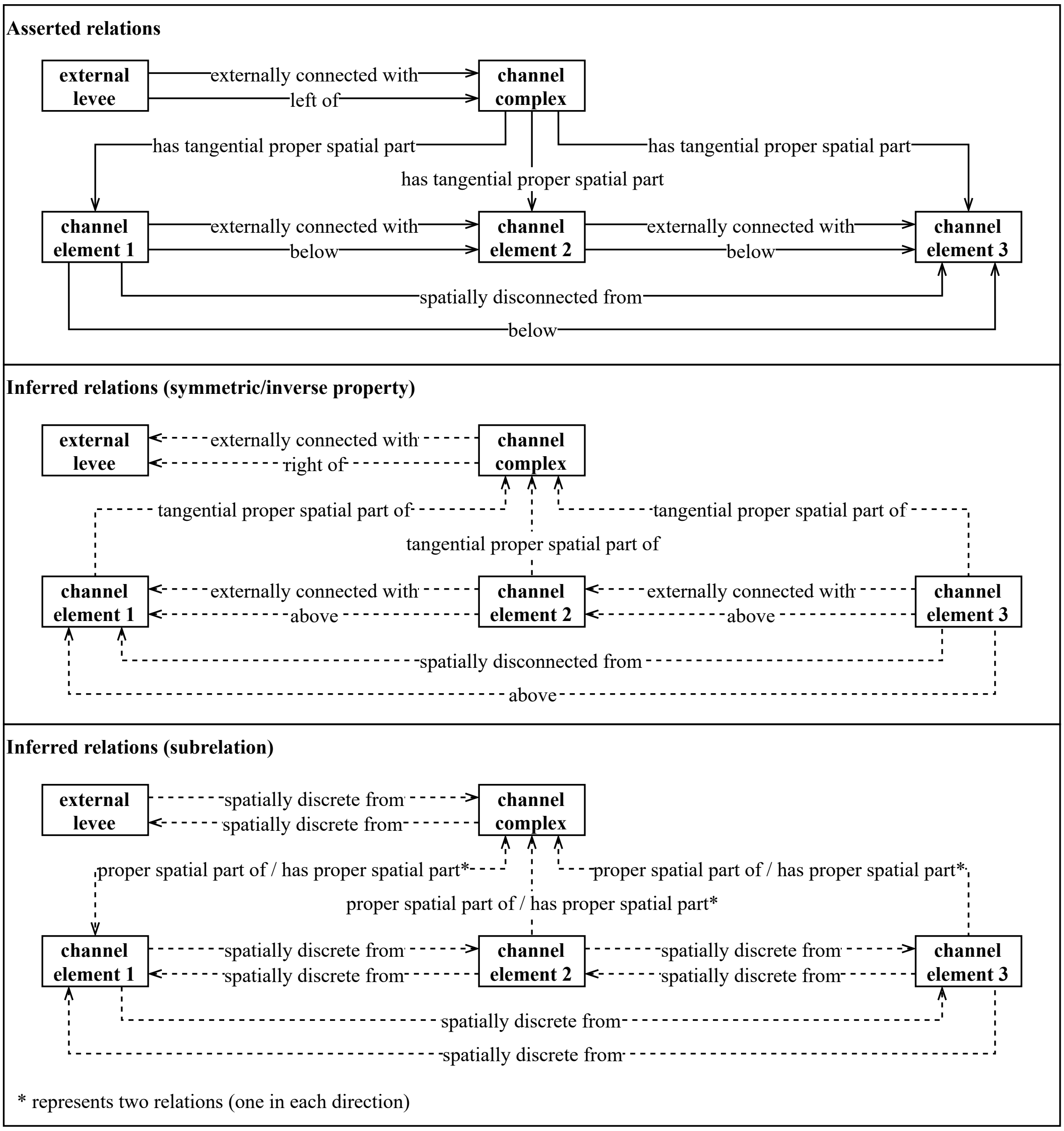


Figure 6. The relations between the Karoo subset's geological objects. The continuous lines indicate asserted relations, i.e., relations that we formally specified between the particulars. The dashed lines indicate inferred relations, i.e., relations that were generated by automatic reasoning.

elements 1, 2, and 3. One can establish the relative age between the objects only if they are externally connected, e.g., channel element 2 is younger than channel element 1 in the image's frame of reference. If an object is a proper spatial part of another, it necessarily has a lower hierarchical order, such as the channel elements in relation to the channel complex.

7. Conclusion

This paper presented an ontological model of spatial relations between the geological entities defined by the GeoCore ontology. We reviewed spatial relations from other ontological models and selected those that we considered useful in describing the spatial distribution of the geological entities. The formal relations showed themselves expressive in the sense that a few assertions derived several inferences that described the geological entities' spatial structure.

Our case study demonstrated how this ontology could help in the systematic description of geological object instances containing spatial distribution information. This kind of information, if formally modeled, supports automatic reasoning to detect inconsistent reservoir 3D models and helps in determining similar architecture of fan analogous systems during the reservoir characterization in the petroleum exploration activity.

This work is inserted in a larger project that proposes a domain ontology for the systematic description of the geometrical, architectural, and lithological properties of deep-water deposits. The model is conceived to support a visualization system that will help the geologists explore the possibilities of spatial distributions of channels and other elements in deep-water sedimentary environments, constrained by the semantics of geometry and spatial relations between bodies. The tool will allow geologists to compare different occurrences to find analogous, determinate patterns and tendencies, statistic or clustering comparison, and others.

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