

DOLCE ROCKS: Integrating Geoscience Ontologies with DOLCE

Boyan Brodaric

Geological Survey of Canada
brodaric@NRCan.gc.ca

Florian Probst

University of Muenster
f.probst@uni-muenster.de

Abstract

Conceptual representations are being developed within many geoscience domains to aid semantic-enabled scientific computing, e.g. geology, geophysics, hydrology, marine science, planetary science. These representations often make different ontological assumptions, causing their integration to be impeded. This is particularly problematic for science issues that involve cross-domain knowledge, such as those related to climate change, biodiversity, and hazards risk. Emerging foundational ontologies have the potential to alleviate this problem by providing a coherent and complete conceptual basis for domain representations. In this paper we present work-in-progress in which the DOLCE foundational ontology is used to integrate two geoscience knowledge representations, the GeoSciML schema and SWEET ontology, to enable cross-domain scientific computing. The preliminary results indicate good conceptual coverage by the foundational ontology, minimal conflict and overlap between the domain ontologies, alternative approaches for aligning with the foundational ontology, and several issues with the domain and foundational ontologies. An OWL-DL encoding is in progress and testing via data integration is planned.

1. Introduction

The geosciences have recently begun deploying cyber-enabled resources for many scientific activities. Several large projects are significantly advancing cyberinfrastructure as well as associated geoscience knowledge, e.g. GEON (geology; www.geogrid.org), LEAD (weather; <https://portal.leadproject.org>), SCEC (earthquakes; <http://epicenter.usc.edu/cmeportal/>), VSTO (solar-terrestrial; <http://vsto.hao.ucar.edu/>). These advancements reflect the dual aims of scientific activity within cyberinfrastructure (or e-science): promotion of scientific creativity for knowledge discovery, and increased efficiency in carrying out scientific tasks. In the geosciences these aims are manifest in activities such as the identification of geospatial entities, the inference of their formative histories, the study of foundational processes, and the development of general theories and classifications that explain the materials, processes and objects of the solid earth, atmosphere, oceans and planets.

Knowledge representations are important components of cyberinfrastructure. They are being used to aid the discovery, integration and transfer of data, information and knowledge. Key representations include conceptual

schemas for databases and data transfer formats, web service signatures, automated workflow specifications, as well as representations of wider geoscience knowledge such as models and theories. Ontologies are a special kind of representation that partially account for the conceptualization upon which the previously listed components are based. As such they serve to either semantically annotate these components, or constitute part of them. However, while ontologies and the other representations are being developed within many geoscience disciplines, very little work has been carried out to integrate them within a foundational ontology to provide a rigorous and coherent framework in support of cross-disciplinary e-science.

In this paper we investigate the potential for the DOLCE foundational ontology (Gangemi, et al., 2003, Masolo, et al., 2003) to integrate two well-known geoscience representations: the GeoSciML schema (an XML-based data transfer specification; Sen & Duffy, 2005) and SWEET (an OWL-based ontology for broad geoscience knowledge; Raskin & Pan, 2005). The objective is to produce a unified ontology in which the GeoSciML and SWEET representations are aligned to DOLCE and to each other. In Section 2 we describe a motivating example; Section 3 discusses related work; Section 4 outlines the approach taken for the integration; Section 5 describes our progress towards the integrated ontology; Section 6 describes the evaluation, issues, and implementation plans; and Section 7 concludes with a brief summary.

2. Use-case scenario

Scenarios in which it is essential to integrate knowledge, information and data across various geoscience domains are plentiful. A representative scenario is the calculation of water contamination vulnerability for a geographical area, which uses information from hydrology, geology, and the built environment:

- sources of contamination (usually human artifacts such as farms or factories);
- channels for contaminant flow (hydrologic network, geologic fracture network);
- susceptibility of the rocks to contamination (geologic units, rock types, qualities (e.g. permeability), wells).

Each of these data sources is typically maintained by different agencies in isolated databases. Calculation of

water contamination vulnerability then requires discovery and integration of data from these multiple sources and domains, within a single knowledge environment. A foundational ontology is a promising candidate for integrating these domain fragments. It can be used to identify and resolve conflicts in the original representations, leading to a coherent integrated ontology that can semantically annotate the associated databases and web services required for the calculation.

3. Related Work

Geoscience knowledge is represented informally in scientific artifacts such as papers, reports, maps, and textbooks. More formal representations include:

- schema: e.g. NADM (2004); Richard, S.M (2006); Cox & Richard (2005); Brodaric & Gahegan (2006);
- ontologies: e.g. Babaie (2006); Bermudez, Graybeal, Arko (2006);
- linguistic structures: (glossaries, thesauri, taxonomies), e.g. Olsen, et al. (2007);
- computational workflows, e.g. Ludäscher, et al. (2006);
- logical theories, e.g. Pshenichny, et al. (2003).

These differ in terms of the formality and expressiveness of their representation, and in the intended generality of their contents. The GeoSciML schema is represented in UML and denotes the general entities and relations typically found on geologic maps—it is a relatively narrow but deep representation of a fragment of geoscience knowledge. Conversely, the SWEET ontology contains broad classes¹ for geoscience entities expressed in the Web Ontology Language (OWL)—it is a relatively wide representation of geoscience knowledge, and has the potential to contain GeoSciML as an extension. Overlap between SWEET and GeoSciML is then likely to occur at the lowest levels of the SWEET hierarchy and at the upper levels of the GeoSciML hierarchy. Both GeoSciML and SWEET are developed bottom-up: SWEET from linguistic structures such as thesauri, and GeoSciML from existing database schema. SWEET has been extended to other geoscience domains, but it has not been integrated into a foundational ontology.

Neither SWEET nor GeoSciML are developed top-down from rigorous philosophical principles such as those utilized by foundational ontologies, e.g. DOLCE, BFO, GFO, SUMO and Sowa's (Masolo, et al., 2003; Grenon & Smith, 2004; Herre, et al., 2006; Pease, A. 2006; Sowa, 2000). Such foundational ontologies are intended to apply

to all domains, rather than to some aspect of one domain, and they are normally expressed with high rigor as a formal logical theory. They do differ in terms of their philosophical underpinnings, leading to nuanced variations in content, and they also differ in their expressivity, such as the nature of their logical languages. General comparisons of some of these foundational ontologies can be found in Masolo, et al. (2003) and Mascardi, et al. (2007). DOLCE and BFO in particular show promise for extension to geospatial and geoscience domains, in that spatiality is a key criteria used to distinguish between their most general entities: only endurants are located in physical space, while perdurants are located in time. Abstract entities are those that have no location in physical space or time. While BFO includes components for geographical entities, DOLCE includes aspects for physical constituents and abstract spaces that might apply to scientific classifications.

Although the merging of ontologies has been extensively studied (Noy, 2004), including the use of an intermediary ontology to align source ontologies (Mitra et al., 2005), relatively minimal work has been carried out to align existing geoscience ontologies via foundational ontologies: e.g. Babaie, (2006) examines BFO for applicability to geological entities, Bittner (2007) aligns ecosystem classifications with a formal foundational theory, and Probst (2006; 2007) presents an extension to DOLCE that accounts for the spatial dimensionality of qualities to help align geospatial domain ontologies to a foundational ontology. None of these approaches use a foundational ontology to integrate more than one existing geoscience ontology. This work is therefore novel in the use of the DOLCE foundation ontology to integrate two existing and widely recognized geoscience knowledge representations.

4. Approach

SWEET 1.1 and GeoSciML 2.0 were selected for several reasons: both enjoy wide participation from the geoscience community; both are publicly available and well documented; and both are representative of significant trends in geoscience knowledge representation for e-science, i.e. data transfer schema design (GeoSciML) and ontology development (SWEET). They also represent different levels of abstraction with SWEET containing the more general classes. Only representative fragments of SWEET and GeoSciML were selected for integration—these included rock bodies and their constituent materials from GeoSciML, and physical bodies, materials, processes, events and qualities from SWEET. Because GeoSciML is essentially a logical representation containing technologic artifacts, reverse engineering of its conceptual model was initially required. As with these domain representations, the choice of DOLCE 2.1 Lite-Plus (OWL 397) was also governed by its extensive documentation, easy accessibility, availability in OWL format, and its potential suitability to represent materials and scientific classification systems. DOLCE includes four core entities:

¹The notions concept, category and class are widely used in different contexts for different purposes. In the remainder of this paper we follow OWL terminology and use “class” to refer to an abstraction that can be instantiated in one or more entities, and relation to mean an association between entities of the same or distinct abstractions.

endurants (e.g. physical bodies, amounts of matter), perdurants (e.g. events, processes, states), qualities (e.g. color) and abstracts (e.g. quality spaces such as the Munsell color space, and regions within it such as *red*).

The integration of ontologies requires alignments and mappings between ontology elements, in this case classes and relations. An alignment is realized by establishing an *is-a* relation between a domain ontology element and a foundational ontology element. A mapping between elements of distinct ontologies is realized by establishing an *equivalence* or *similar-to* relation. As SWEET contains many classes and relatively few relations, its integration emphasized class alignments and mappings; in contrast, GeoSciML's rich relations and few classes led to an emphasis on relation alignments and mappings.

Two approaches to integrating ontology elements were considered: extensional and intensional. In extensional approaches integration is established by mapping and alignment of the collections of instances (i.e. extensions). In contrast, intensional strategies develop integration by mapping and aligning ontology elements. Both extensional and intensional approaches require rich input: either many instances or substantial class or relation structure (e.g. axioms, constraints, cardinalities). Due to the unavailability of instances and the relative paucity of the structure, we used an intensional approach in which mappings and alignments were developed by manually comparing the informal definitions and related elements (e.g. superclasses, subclasses, relations) of SWEET and GeoSciML to each other and to DOLCE's formal representation. Because alignment of the domain representations with the foundational ontology emphasized different elements, the domain representations were first individually aligned with the foundational ontology, and then mapped and aligned to each other.

As a general principle, alteration of the original ontologies was disallowed in order for them to remain independent. Ideally this means that classes or relations in the domain ontology should be mapped and aligned to the foundational ontology, and to each other. A problem arises when a class or relation in the domain ontology is deemed to be a superclass or super-relation in one of the other ontologies, as this would contravene the alteration principle. Strict adherence to the principle would then require either insertion of the class as a sibling class, or relation, in the integrated ontology, or omission of the class or relation from the integrated ontology.

The tools deployed included UML and Protégé-OWL: the original ontologies were browsed in Protégé, and the alignments and mappings were first diagrammed in UML-like syntax with an OWL-DL encoding now in progress.

5. The DOLCE ROCKS Ontology

DOLCE + GeoSciML: The alignments from the GeoSciML fragment to DOLCE are obvious and complete, in the sense that each GeoSciML class is readily aligned to a DOLCE class, e.g. a *GeologicalUnit* is-a *Physical-Body*,

an *EarthMaterial* is-a *Amount-of-Matter*, a *GeologicalEvent* is-a *PhysicalPhenomenon* and each GeoSciML relation is readily aligned to a DOLCE relation, once a single new relation is added to DOLCE to denote the relationship between a physical artifact and the physical event that produced it (*physical-product-of*). Because GeoSciML is not originally represented as an ontology, only its original classes and the aligned DOLCE relations are represented in the integrated ontology. By way of example, the integrated *CompoundMaterial* class is shown below, using UML-like syntax in which DOLCE classes and relations are presented in italics:

Amount-of-Matter

EarthMaterial

CompoundMaterial

part: *EarthMaterial*

plays: *CompositionPart*

generic-constituent: *Particle*

generic-constituent-of: *GeologicUnit*

participant-in: *GeologicProcess* [0..*]

classified-by: *Lithology* [1..*]

host-of: *Fabric* [0..*]

has_quality: *CompositionCategory* [0..*]

has_quality: *PhysicalQuality* [0..*]

has_quality: *MetamorphicQuality* [0..*]

Rock

has_quality: *ConsolidationDegree*

UnconsolidatedMaterial

has_quality: *ConsolidationDegree*

Challenges in aligning GeoSciML to DOLCE include:

- reverse engineering an ontology from the GeoSciML logical schema which contains artifacts introduced to decrease the size of the XML encoding, such as the duplication of a small number of qualities;
- the *proportion* quality inherent in the *part-of* relation, as in *x* is 10% *part-of* *y*, due to the fact that DOLCE does not yet account for relational qualities;
- scientific classifications of physical objects, as in *granite* classifies a rock, due to ambiguity about the nature of a scientific classification: is it a physical entity, a social/mental artifact, or a region in a quality space?

The relation quality challenge is handled by introducing the relational quality to a role concept. The role concept is then played by one of the participants in the relation. For example, to represent *x* is 10% *part-of* *y*, where *x* and *y* are *GeologicUnits*, the *proportion* quality is added to a *GeologicUnitPart* role concept. This enables *GeologicUnit* *x* to play the role of *GeologicUnitPart* with a *proportion* value of 10% in its *part-of* relation to *GeologicUnit* *y*.

The scientific classification challenge results in two valid approaches: understanding the types within a classification as a region in a physical quality space, or understanding

types in a classification system as role concepts. In the former, a quality refers to the subject of classification (e.g. *lithology*) and the value of that quality (e.g. *granite*) refers to an individual type that is an abstract region in a quality space. In the latter, scientific classifications are concepts (e.g. *granite* is-a *lithology*) which *classify* an enduring (*EarthMaterial*). Both approaches lead to similar questionable side-effects: central classes such as types of processes (e.g. *igneous process*) end up as roles or abstract regions. This results from the need to explicitly characterize a classification (e.g. that *granite* is produced by an *igneous process*). In the quality approach it results in indirect qualities of qualities whose values are abstract regions (e.g. *igneous process* is the "value" of an indirect quality of *lithology*); likewise, because physical qualities cannot inhere in social objects, in the concept approach physical qualities must essentially be duplicated as quality-like entities (called *parameters*) to characterize a specific classification (e.g. a rock is characterized by a *grainsize* quality, while a rock classification such as *granite* is characterized by a *grainsize* parameter).

DOLCE + SWEET: the integration of the SWEET fragment to DOLCE is relatively obvious and complete, as illustrated in Table 1. The main challenge involves, as above, representation of scientific classifications. The main benefit involves inheritance of DOLCE's rich conceptualization. This helps rationalize ontology structure. For example: (note: $x < y$ denotes y is-a x)

- **Relations:** *MixedSubstance < Rock* and *Solid < Rock* rationalizes to *MixedSubstance < Rock* and *Rock participates-in (only) Solid > State*;
- **Roles:** *Contaminant < Dust* and *Particulate < Dust* rationalizes to *Particulate < Dust plays Contaminant > Role* (in some situation);
- **Unions:** *EarthRealm* rationalizes to the union of *Physical-Body* and *Feature* subclasses, hence some subclasses of *EarthRealm* are subclasses of *Physical-Body* (e.g. *BodyofGround*) and others are subclasses of *Feature* (e.g. *SeaFloor*); also for *SunRealm* (e.g. *Corona* is-a *Physical-Body*, but *CoronaHole* is-a *Feature*);
- **Instances:** *EarthRealm < PlanetEarth* rationalizes to *PlanetEarth instance-of Physical-Body*;
- **Orphans:** each orphan class (lacking superclasses) obtains a superclass, e.g. *Basalt, Ordovician*;

Note the first three rationalizations potentially alter the class hierarchy of SWEET by introducing an alternative DOLCE superclass to a SWEET class. Following our alteration principle we do not disconnect from the original SWEET superclass, but recommend a SWEET revision.

Table 1: some SWEET-DOLCE alignments.

DOLCE	= SWEET	< SWEET
Physical-body		BodyofGround, WaterBody
Feature		SeaFloor, CoronaHole
Material-Artifact		Infrastructure, Dam, Product
Physical-Object		LivingThing, MarineAnimal
Amount-of-Matter	Substance	
Activity		HumanActivity
Physical-Phenomenon	Phenomena	
Process	Process	
Role		Contaminant
State		StateOfMatter
Quality		Quantity, Moisture
Physical-Region		Basalt
Temporal-Region		Ordovician

DOLCE + SWEET + GeoSciML: the integration of the two domain representations with each other, and with the foundational ontology, is relatively uncomplicated, due to their different levels of abstraction. This enables many GeoSciML classes to become subclasses of SWEET classes, as shown in Table 2. Semantic precision is also enhanced via the addition of GeoSciML superclasses to a very few SWEET classes: e.g. *RockBody < GeologicUnit < Aquifer*. Resolving the problem that emerges from multiple inheritance is not considered here. The end result is greater connectivity between the domain ontologies, such that the unified result is greater than the sources: this is evident in the statement *Rock participates-in (only) Solid > State*, which cannot be stated in any of the original ontologies, and in which each element inherits supplementary aspects from the other ontologies (e.g. *Rock* now has GeoSciML's qualities, DOLCE's *participates-in* relation to SWEET's *State < Solid*). It is also evident in the cross-disciplinary example involving *Aquifer generic-constituent Rock has-quality Permeability*, which also cannot be stated in the originals and which is required for calculation of water contamination vulnerability in the use-case scenario. However, the equivalent classes are problematic in that they introduce superclasses into SWEET, e.g. *MixedSubstance < Sand* (SWEET) and *EarthMaterial < UnconsolidatedMaterial* (GeoSciML) ideally lead to

MixedSubstance < *UnconsolidatedMaterial* < *Sand*. In keeping with the alteration principle, *UnconsolidatedMaterial* and *Sand* are retained as siblings.

Table 2: Aligning DOLCE, SWEET and GeoSciML

DOLCE	= SWEET	< SWEET	= GeoSciML	< GeoSciML
Physical-body		BodyofGround< RockBody		GeologicUnit < Aquifer
Amount-of-Matter	Substance < MixedSubstance< Rock		EarthMaterial< Comp.aterial< Rock	
Physical-Phen.	Phenomena < SolidEarthPhen.< ...< Earthquake			GeologicEvent
State		StateOfMatter		
Quality		Quantity < Age		eventAge
Physical-Region		Basalt		
Temporal-Region		Ordovician		

6. Evaluation, Issues and Implementation

Evaluation: The integrated DOLCE ROCKS ontology is evaluated according to completeness, ontological precision, clarity, connectedness, and coherence. It is deemed complete in that each domain class or relation is aligned or mapped to a foundational class or relation, or their union. This results in increased ontological precision in that the resultant unified ontology possesses richer relations and classes, whose distinctions are now well articulated and founded on foundational principles, hence exhibiting improved clarity. Connectedness between the domain ontologies is also increased through the inheritance of relations from the foundational ontology. However, coherence suffers due to the alternation principle which prohibits changes to the domain ontologies, resulting in (a) some domain classes with superclasses in both the integrated and domain ontology, or (b) sibling classes which should be related as subclasses. Making the necessary revisions to the original ontologies would result in increased coherence. In these ways DOLCE ROCKS meets the described objectives and use-case needs.

Issues: several issues with DOLCE are encountered:

DOLCE Qualities: DOLCE classes can have unary qualities—they involve only the quality bearing endurant or perdurant, e.g. a particular piece of rock has a size quality, color quality, mass quality, amongst others. However, it is not fully evident how relational qualities emerging between more than one endurant or perdurant can be specified, e.g. proportion, distance, direction. Our

solution using Roles is tentative and this overall issue requires more attention. Further, it is not fully specified how qualities can have indirect associations, e.g. being the product of participation in a process. This impedes the specification of geoscience qualities: e.g. a rock type quality (i.e. *lithology*) is classically defined in part according to several indirect associations such as being the product of a process type, hosting a certain fabric type, and being constituted by a certain particle type, as well as by unary qualities such as particle size.

DOLCE Quality Spaces: Quality spaces cannot be defined by DOLCE, only regions within those spaces can be identified, e.g. it is possible to indicate that the rock type quality region *granite* occurs within a space of minerals or chemicals, but there is no clear way to specify the quality space itself. Related to this is the inability to contain aspects of measurement for such spaces such as units of measure. Semantic reference spaces are introduced by Probst (2006; 2007) to address this issue, but we have not yet implemented them in DOLCE ROCKS.

DOLCE Concepts: The grounds for categorizing entities as concepts, abstract regions, or subclasses of endurants, perdurants, and qualities, are ambiguous. This becomes apparent with scientific classifications: is *granite* a classification (concept) of a rock (an amount-of-matter), is it the value (region) of a quality inherent in a rock, or is it a subclass of rock? Selecting any of these approaches leads to seemingly unnecessarily complex ontology structures.

Implementation: implementation of DOLCE ROCKS within a geospatial data interoperability environment is a potential future activity. Several emerging systems with which we are engaged might be utilized. This includes Canada's National Groundwater Database (<http://ngwd-bdnes.cits.rncan.gc.ca/service/ngwd/exploration>) in which detailed water classes would be added to DOLCE ROCKS to enable data discovery and integration. DOLCE ROCKS would then serve as the central ontology onto which geological and hydrological database contents could be mapped and aligned, in support of cross-disciplinary data usage. Another consideration is the SWING project (<http://www.swing-project.org>) in which DOLCE ROCKS might facilitate the discovery, composition and calling of geospatial web services in support of decision-making for sustainable exploitation of natural resources.

7. Conclusions

We describe preliminary results in the development of the DOLCE ROCKS ontology. DOLCE ROCKS is generated to investigate the applicability of using a foundational ontology (DOLCE), to integrate geoscience knowledge representations (the SWEET ontology and GeoSciML schema). The preliminary results indicate good conceptual coverage by the foundational ontology, minimal conflict and overlap between the domain ontologies, alternative

approaches for aligning with the foundational ontology, and several issues with some approaches in the foundational and domain ontologies. Because of the breadth of its content, DOLCE ROCKS has good potential to link geological knowledge with other geoscience domains. An OWL-DL encoding is in progress, and potential future activities include use of the integrated ontology in geospatial data interoperability environments.

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