Practicing an ontology spectrum for geological data interoperability

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Practicing an ontology spectrum for geological data interoperability

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Abstract

Interoperability of geological data receives considerable attention in recent years and different types of ontologies (i.e., an ontology spectrum) have been studied and applied. There are several key challenges faced by current and potential practices of an ontology spectrum in the field of geology: (1) Modeling and encoding of ontologies; (2) Multilinguality of geological data and ontologies; (3) Flexibility and usefulness of ontology-based applications; (4) Mediation and evolution of geological data and ontologies. This paper reviews our works addressing these challenges in the past three years, concludes findings and proposes directions for future works.

1 Background and motivation

Recording "physical structure and substance of the earth, their history, and the processes which act on them"[1], geological data is not only essential for the studies of our mother planet, but also acts as building blocks in approaches addressing key societal challenges, such as resources exploration and management (Agterberg, 1989; Bonham-Carter, 1994; Carranza, 2009), urban development (Culshaw et al., 2009; Dai et al., 2001), climate change (Anandakrishnan et al., 1998; Gerhard et al., 2001), water quality (Pipkin et al., 2008; Roy et al., 2001; Sharpe et al., 1987), and hazard mitigation (Bell, 2003; Michael and Eberhart-Phillips, 1991), etc.

In the Digital Age (Kleppner and Sharp, 2009), computer-based hardware and software have been widely used in the capture, renewal, transmission, integration, analysis, evaluation and publication of geological data. Compared to the digital geological data deluge in nowadays, underdeveloped are effective approaches for promoting geological data interoperability, which however is an essential condition for efficient information retrieval and knowledge discovery in studies and applications using geological data (cf., Asch, 2005; Brodaric and Gahegan, 2006; Gahegan et al., 2009; Loudon, 2000; Richard et al., 2003). Challenges of data interoperability can arise at different levels, such as systems (i.e., network and services), syntax (i.e., language and encoding), schemas (i.e., modelling and structure), semantics (i.e., content and meaning), and pragmatics (i.e., use and effect) (Bishr, 1998; Brodaric, 2007; Harvey et al., 1999; Ludäscher

[1] Oxford Dictionaries Online, http://oxforddictionaries.com/view/entry/m_en_gb0332440#m_en_gb0332440 [Accessed March 21, 2011]

et al., 2003; Sheth, 1999). Accordingly, the geological data interoperability in this dissertation is defined as the ability of geological data provided by a data source to be accessed, decoded, understood and appropriately used by external users.

Ontologies in computer science are defined as shared conceptualizations of domain knowledge (Gruber, 1995; Guarino, 1997), which originate from the study of being in philosophy. Ontologies have been extensively studied in recent years to address data interoperability issues in different domains, such as genetics (Ashburner, 2000), geographical information (Frank, 2001), soil classification (Rossiter, 2007), and solar-terrestrial physics (Fox et al., 2009), etc. It was increasingly discussed (Borgo et al., 2005; McGuinness, 2003; Obrst, 2003; Uschold and Gruninger, 2004; Welty, 2002) that an ontology spectrum, covering ontology types with varying semantic richness (Figure 1), is worth being kept in mind when people are building and using ontologies.

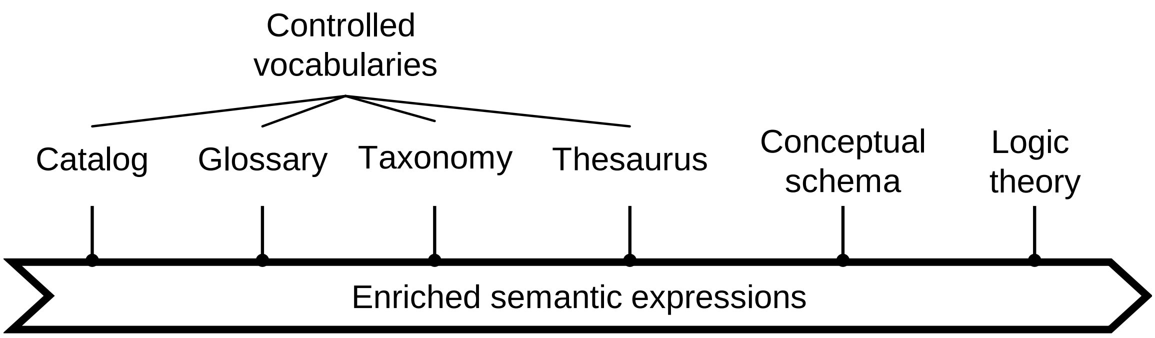

Figure 1: Ontology spectrum (adapted from Borgo et al., 2005; McGuinness, 2003; Obrst, 2003; Uschold and Gruninger, 2004; Welty, 2002).

In the field of geological ontologies, there were already examples of controlled vocabularies (e.g., Bibby, 2006; Ma et al., 2010; Richard and Soller, 2008), conceptual schemas (e.g., Brodaric, 2004; NADM Steering Committee, 2004; Richard, 2006) and logical language-based formal ontologies (e.g., Ludäscher et al., 2003; Raskin and Pan, 2005; Tripathi and Babaie, 2008), etc. In several recent projects, different types of ontologies have been applied to provide featured functions in national or regional geological data infrastructures, thereby promoting geological data interoperability and facilitating information retrieval and knowledge discovery in applications. The AuScope[2] project built vocabulary-based services for querying geological maps, which overcame differences in geoscience terms due to language, spelling, synonyms and local variations and, thus, help users to find desired geological information of Australia (Woodcock et al., 2010). The NADM model (NADM Steering Committee, 2004) was proposed as a reference schema in the NGMDB[3] project (Soller and Berg, 2005) for promoting collaborations among geological map databases in the United States. The OneGeology (1G) [4] project adopted the GeoSciML (Sen and Duffy, 2005) as a common conceptual schema and online exchange format, which improved the exchange/integration of online geological maps

[2] http://www.auscope.org [Accessed March 21, 2011].
[3] http://ngmdb.usgs.gov [Accessed March 21, 2011]
[4] http://www.onegeology.org [Accessed March 21, 2011].

distributed globally (Jackson, 2007). GeoSciML was also applied in the OneGeology-Europe (1G-E) [5] project and, compared to the 1G, the 1G-E extended vocabulary-based services and enabled multilingual annotation and translation of geological map contents among 18 Europeans languages (Asch et al., 2010; Laxton et al., 2010). Approaches similar to 1G were also applied in the USGIN[6] project in the United States (Allison et al., 2008) and the GIN-RIES[7] project (Brodaric et al., 2009) in Canada to address interoperability of geoscience and groundwater information, respectively. In the GEON[8] project, formal ontologies were used to mediate conceptual schemas of heterogeneous geological maps and enable semantic integration among them (Baru et al., 2009; Ludäscher et al., 2003).

In aforementioned studies and application projects, substantial progress has been made in developing geological ontologies and using them to mediate heterogeneous geological data, in which the capability of ontologies for promoting geological data interoperability is commonly acknowledged. A technical trend in these projects is deploying works in the environment of the Semantic Web (cf. Berners-Lee, 2001; Hendler, 2003) and developing ontologies with Web-compatible global standards (e.g., eXtensible Markup Language (XML) or sub-languages of XML, like W3C® proposed Simple Knowledge Organization System (SKOS), Resource Description Framework (RDF) and Web Ontology Language (OWL), etc.).

Despite the impressive progress in building and using different types of geological ontologies, the attempt of using an ontology spectrum to promote geological data interoperability still faces vast challenges, among which several key ones are selected for consideration in our works:

(1) Modeling and encoding of ontologies – modeling transforms humans' tacit knowledge of a domain into concepts and relationships, and encoding implements the modeling with symbols/languages in a context (cf., Kuhn, 2010). Modeling can generate varied semantic richness of ontologies and encoding is related to the environment in which ontologies are used, whereas this is less discussed in the field of geology;

(2) Multilinguality of geological data and ontologies – geological units are naturally independent of language borders, but geological data are not, whereas commonly agreed multilingual ontologies are limited in many subjects in geology (cf., Asch and Jackson, 2006), and applications of multilingual geological ontologies with online geological data are underdeveloped;

(3) Flexibility and usefulness of ontology-based applications – incorporating ontologies into state-of-the-art technologies in geo-information science (e.g., OGC® web service standards[9], algorithms of information retrieval (e.g., Baeza-Yates and Ribeiro-Neto, 2011), conceptual

[5] http://www.onegeology-europe.org [Accessed March 21, 2011].
[6] http://www.usgin.org [Accessed March 21, 2011].
[7] http://www.gw-info.net [Accessed March 21, 2011].
[8] http://www.geongrid.org [Accessed March 21, 2011].
[9] http://www.opengeospatial.org/standards [Accessed March 21, 2011].

mapping (e.g., Noy, 2009) and data visualization (e.g., Fox and Hendler, 2011), etc.) can explore more potential of ontologies for promoting interoperability of geological data, but the usefulness of developed functions also needs evaluations;

(4) Mediation and evolution of geological data and ontologies – heterogeneous geological data can be mediated in a short-term period, but data are continuously flowing and updating in a long-term perspective and, thus, paradigms are needed to address the interoperability of geological data underpinned by ontologies in an evolving environment.

In order to explore approaches to address aforementioned challenges by conducting case studies of several types of ontologies, and to seek strategies and methods for deploying the ontology spectrum properly in practices to promote geological data interoperability, a PhD dissertation work was started in 2008 and is supposed to finish by the end of 2011. Several sub-subjects in this work have been published as peer-reviewed papers in journals or conferences. This paper reviews the finished works, concludes findings and proposes directions for future works.

2 Practices with an ontology spectrum and results

In the past three years, we have conducted studies on geoscience vocabularies (Ma et al., 2010c), multilingual thesauri (Ma et al., 2011b), conceptual schemas (Ma et al., 2010a; Ma et al., 2010b), RDF/OWL-based ontologies (Ma et al., 2011a), and the collaborations of geoscience ontologies (Ma, 2010).

(1) Modeling and encoding of ontologies

Ontologies can be encoded in different formats (i.e., syntactic variability) according to the requirements of local actions, whereas concise or precise definitions (i.e., semantic variability) of concepts and their interrelationships in an ontology depend on the works of modeling, in which the global thoughts of interoperability should be addressed if local geological data is underpinned by the built ontologies and is going to be shared.

In Ma et al. (2010c), a pure hierarchical structure was used in a controlled vocabulary to organize professional terms of 27 subjects in mineral exploration geodata. This structure is simple but is functional enough, because the vocabulary was mainly used to promote standard terms in databases of mining projects. The vocabulary was encoded as spreadsheets to support applications in relational databases. Each term in the vocabulary was labeled with both Chinese and English names and was tagged with a unique alphanumerical code. Moreover, several national standards were adapted in the vocabulary to improve the interoperability of the vocabulary and the mineral exploration geodata standardized by it.

Compared to the 27 subjects covered by the controlled vocabulary in Ma et al. (2010c), the thesaurus in Ma et al. (2011b) was much smaller because it focused on the subject of geological time only. Hierarchical and ordinal relationships between geological time concepts were both represented in the thesaurus, and annotations were collected to define those concepts. The ordinal hierarchical structure and the annotations of the thesaurus were encoded with an extended SKOS model and later used in a pilot system to explain the meanings of geological time concepts to users. Similar to the actions of adapting national standards in the controlled vocabulary in Ma et al. (2010c), the thesaurus in Ma et al. (2011b) adopted the International Stratigraphic Chart as the basic conceptual reference, and it collected many synonyms of geological time terms to mediate heterogeneous geological data.

The RDF/OWL-based ontology of geological time scale in Ma et al. (2011a) was updated from the thesaurus in Ma et al. (2011b). This ontology defined chronostratigraphic units (i.e., Eonothem, Erathem, System, Series and Stage) as classes, and then all geological time concepts were instances of these classes. It refined the ordinal hierarchical structure by replacing the relationships “skos:broader” and “skos:narrower” in the thesaurus with “gts:subsetOf” and “gts:supersetOf”, respectively. The ontology also collected more annotations of geological time concepts from international standards and commonly used glossaries, and used them to develop featured functions with online geological maps in a pilot system.

Because of the diverse relationships between classes, sets and instances defined inside, the object-oriented models of borehole metal-grade intervals and composites in Ma et al. (2010a, 2010b) had a more complicated structure than that of the controlled vocabulary in Ma et al. (2010c) and the thesaurus in Ma et al. (2011b). The relationships of generalization, aggregation, association and dependency used in the models were more explicit. They were derived from a group of second-order logic statements and then encoded with UML schemas, which in turn were used to transform the designed models into computer programs of a pilot system. Although annotations of symbols in the models were collected, they were not included in the UML schemas, but used in the user interface of the pilot system to explain the meanings of symbols. The two key attributes – metal-grade and length – of borehole intervals and composites in the models were related to the profitability and minability of ore bodies outlined using the borehole composites. Such attributes were compatible with global standards for mineral resources estimation and, thus, improved the interoperability of the developed models and the results of compositing borehole metal-grade intervals.

(2) Multilinguality of geological data and ontologies

There are three core requirements for a multilingual geological ontology: accurate, consistent, and complete. The multilingual labeling method is easier for use than interlingual mapping in building ontologies, whereas the former also requires that terms in different language share a common conceptual structure. In the environment of the Semantic Web, multilingual geological ontologies are functional for alleviating linguistic barriers of geological data, as Web-based technologies are quickly evolving and geological data is increasingly put online.

While inaccuracy, inconsistency and incompleteness are challenges faced by multilingual thesauri of many subjects in geology, the thesaurus in Ma et al. (2011b) concentrated on the subject of geological time scale. It did not follow an alphabetical sequence in the arrangements of terms. Instead, it took the International Stratigraphic Chart as a basic conceptual reference and arranged chronostratigraphic terms in an ordinal hierarchical structure. Because the International Stratigraphic Chart is in English, the thesaurus used English terms to set up an initial structure and then labeled terms in other six languages to it. In this way the accuracy and consistency of the thesaurus were achieved, and the completeness was partly achieved because there were synonyms of these multilingual terms to be collected. The thesaurus used an extended SKOS model for encodings, which not only represented the ordinal hierarchical structure but also provided properties to encode chronostratigraphic terms as preferred labels and geochronological terms and synonyms as alternative labels. A pilot system was set up to recognize and translate geological time terms from online geological maps. Results show that properly deployed multilingual geological thesauri are functional for alleviating linguistic barriers among online geological data and improving their interoperability.

Although the RDF/OWL-based ontology in Ma et al. (2011a) updated both object and datatype properties from the thesaurus in Ma et al. (2011b) to make an enriched representation of geological time scale, its multilingual labels were inherited from the thesaurus in Ma et al. (2011b). The difference was that the multilingual labels in the ontology of Ma et al. (2011a) were not used for translation, but for the recognition of geological time concepts no matter in which of the seven languages they were encoded. The pilot system in Ma et al. (2011a) developed a function of annotations by quoting the ontology, but currently these detailed annotations are in English only.

The size of the controlled vocabulary in Ma et al. (2010c) was much bigger than that of the thesaurus in Ma et al. (2011b). The developed controlled vocabulary adapted several national standards in China and provided terms in Chinese and English. In case studies in a mining group, the controlled vocabulary was used to standardize geo-databases for mineral exploration uses. Records in a standardized database were translated from Chinese into English easily by using the controlled vocabulary.

(3) Flexibility and usefulness of ontology-based applications

Ontologies store conceptualizations of domain knowledge. If a group of people work in the same domain, and they commonly agree definitions of domain concepts and their interrelationships, then an ontology can be built and used as a knowledge reference in those people's works. In such a situation, ontology-based applications can be developed to support and improve data interoperability in actual works within a context (e.g., a working group, an institution or a network, etc.). The usefulness of these applications for data interoperability – their capabilities to help people to access, decode, understand and appropriately use data – should be evaluated according to the objective of data interoperability in a certain context.

In Ma et al. (2011a), a RDF/OWL-based ontology of geological time scale was built and several functions underpinned by the ontology were developed. One featured function based on the ontology was automatic annotations for geological time concepts recognized from online geological maps (i.e., WMS layers). Besides this, a Flash animation of geological time scale was built to visualize the ontology, and then more interactive functions were developed based on the Flash animation. One of them was changing the layout of the animation automatically following input queries of geological time concepts recognized from online maps. Other interactive functions included using the animation to show legends of geological time features of online maps, and using the legends as operation panels to filter out and generalize geological time features in the maps. Several cases of conceptual mappings, such as "Lower Cambrian = Terreneuvian + Series 2" and "Middle Cambrian = Series 3", were addressed in these functions. Since the ontology, the Flash animation and the WMS map layers were all developed with Web-compatible formats, it was efficient to combine them together. The aforementioned functions were included in a pilot system and tested by participants in a user-survey. Results show that these functions are helpful for users to understand and to explore geological time contents in online geological maps.

Although the thesaurus in Ma et al. (2011b) had a same topic – geological time scale – as that of the ontology in Ma et al. (2011a), the works in Ma et al. (2011b) highlighted the functions developed for multilingual translations of geological time concepts recognized from online geological maps. These functions translated not only the geological time terms but also short annotations of the terms and the operational instructions on the user interface. Another group of functions described in Ma et al. (2011b) was the methods of characteristic-oriented term retrieval developed in JavaScript programs for recognizing geological time concepts. The accuracy and functionality of these functions were proved in a pilot system. These methods of term retrieval were also used in Ma et al. (2011a).

The controlled vocabulary in Ma et al. (2010c), though not used online, were functional for standardizing geo-databases used in mineral exploration projects and improved their interoperability with extramural projects. With the standardized geo-databases, some efficient functions were developed. One example function described in Ma et al. (2010c) was the automatic mapping of borehole logs.

In Ma et al. (2010a, 2010b), the object-oriented and data-flow models were ontologies resulted from the modeling with second-order logic statements. The programs developed with C++ were based on these models, and they helped people to conduct compositing works and distinguish between different types of meta-grade composites in the results. The properties, classes and sets in the models were consistent with commonly used international standards for mineral resources assessments and, thus, the compositing results generated by the programs were interoperable with other projects.

(4) Mediation and evolution of geological data and ontologies

Ontologies have been proven functional in mediating heterogeneous geological data and improving their interoperability, either at local or global scales. Nevertheless, people’s understanding of the earth is evolving and their conceptualizations of geological knowledge are not fixed. Such evolutions in ontologies also affect the contents of geological data if they are underpinned by the ontologies. While the diversity in geological studies and conceptualizations should be allowed and protected, it is also desirable that local geological data and ontologies can be understood and used by people in other contexts. Regular semantic negotiations and updates of a common ontology among local contexts in the same domain is an effective paradigm to achieve this objective.

It was discussed in Ma (2010) that both geological data and ontologies are continuously affected by contexts in which they are built and organized. The issues of geological data interoperability were considered in a flowing environment and one-station-stop approaches were not suitable for solving challenges in these issues. In this regards, the topic of pragmatic interoperability was proposed in Ma (2010). A model of information agents, object facts and subjective dimensions was designed to represent the pragmatic contexts of geological data and ontologies. Second-order logic statements were used to encoded objects in this model, based on which a procedure of semantic negotiations was conducted for approaching pragmatic interoperability among distributed geological data and ontologies. The methods discussed in Ma (2010) were used in the national mineral potential assessment project of China and the results prove that these methods are effective for improving geological data interoperability among the 47 working groups in this project.

Although the main topic of Ma et al. (2010c) was different from that of Ma (2010), it was also proposed that a controlled vocabulary should have an open structure in order that new terms can be added when they are found in actual geological works. In addition, Ma et al. (2010c) discussed that negotiations and collaborations among stakeholders in the same or related knowledge domains are helpful in promoting wider acceptability and interoperability of a controlled vocabulary.

The issues of collaborative modeling and/or pragmatic interoperability were not discussed in Ma et al. (2011b), but it was raised in this chapter the basal time boundary of Quaternary as a notable case of the evolving geological time ontology. This case show that properties and/or meanings of concepts in geological ontologies and data may change in a long-term perspective. If such issues are not properly addressed, confusions and misunderstandings may arise between mismatched ontologies and data.

3 Main contributions

The main contributions of our works are:

This study addresses the importance of distinguishing while bridging modeling and encoding in works of geological ontologies. The practices of “global thoughts and local actions” in the modeling and encoding of several types of geological ontologies in this study provide experiences and lessons for other on-going or in-preparation works of geological ontologies, as well as ontologies of non-geological domains.

This study explores how to use the method of multilingual labeling to build accurate, consistent and complete multilingual geological ontologies. The case study of multilingual thesaurus of geological time scale uses English terms as the basic reference while others as labels. In actual works, terms in any language can be used as the basic reference if the terms in different languages share a common conceptual structure. The pilot system in Ma et al. (2011b) shows that multilingual geological ontologies encoded in Web-compatible formats have great potential to improve the interoperability of online geological data.

This study develops flexible functions underpinned by ontologies, such as automatic mapping of borehole logs, annotations and animations showing details of geological time concepts, conceptual mappings between geological terms, filtrations and generalizations of spatial features in geological maps, etc. These functions are proven useful to help both geologists and nongeologists to understand contents in geological maps and conduct further operations. By these works, the dissertation expresses an opinion that users of geological data consist of not only geologists and earth scientists, but also other scientists and the general public, and there is still a lot of work to do if stakeholders want to improve the understandability of their geological data for more users.

This study discusses the pragmatic interoperability of geological data in actual works and proposes semantic negotiations as an approach to address this issue. It puts the issues of geological data interoperability in a long-term perspective and suggests that geological data interoperability issues should be addressed sustainably.

As a whole, this study provides a route map for stakeholders who are willing to use ontologies to promote geological data interoperability.

4 Future works

Based on the outcomes of our works, several directions can be proposed for the future works.

The developed RDF/OWL-based ontology of geological time scale can be enriched. Terms and annotations in more languages can be labeled, and more synonyms and conceptual mapping examples can be collected in this ontology.

RDF/OWL-based multilingual ontologies of other geological domains can be developed, such as rock types, mineral types and fossils, etc.

Conceptual mapping/matching between ontologies developed in this study and ontologies developed by others can be further explored. Mapping between ontologies in the same knowledge domain can potentially provide efficient approaches to address issues of geological data interoperability.

New methods for building geological ontologies can potentially be explored. Due to the chosen domains and application requirements, the ontologies developed in this study followed the second-order logic and hierarchical classifications. Nevertheless, other methods such as fuzzy logic and facet classification may be tested for building ontologies of some domains in geology.

More applications of ontologies with latest geo-spatial technologies can be developed and tested. Functions of reasoning with geological ontologies can be further explored. Moreover, geo-spatial technologies are fast evolving and more and more new methods and technologies are being raised, such as WFS, WPS, CSW and KML, etc. Appling these technologies together with ontologies can lead to more novel functions.

New elements or subdivisions of existing elements can be proposed to enrich the current model of a pragmatic context, and fuzzy logic and/or other methods can be used to rebuild the semantic negotiation procedure, which is currently based on second-order logic.

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