The Multiple Applications of a Mature Domain Ontology

Mara Abel[1], Joel Carbonera[1], Sandro Fiorini[1], Luan Garcia[1], Luiz Fernando De Ros[2]

[1]Informatics Institute, [2]Geoscience Institute
Universidade Federal do Rio Grande do Sul (UFRGS)
PO 15.064 – 91.501-970 – Porto Alegre – RS – Brazil

{marabel,jlcarbonera,srfiorini,lfgarcia,lfderos}@inf.ufrgs.br

Abstract. *Ontologies have been growing in importance regarding their reusability for distinct applications, since this allows amortizing the significant cost of development of a knowledge base. Large portions of knowledge models now are modelled as ontologies and these portions are shared through several applications. Considering the immature stage of the methodologies of Ontology Engineering and the considerable short space of time for evolving fully operational domain ontology, few reports of real cases of ontology reuse are found in the literature. This article describes a mature domain ontology for Petrographic description and the several knowledge-based applications that it supports. The ontology development started in the 90's and it is still in evolution, both by extending vocabulary as by improving the rigor of the conceptual modelling approaches. We analyze here the impact that each new application has caused over the ontology, requiring improvements and modifications in the original model.*

1. Introduction

Building a fully operational domain ontology is a long time and resource-consuming effort that can keep a team of professionals dedicated for years in refining and improving the knowledge modelled. The team usually demands professionals of the domain along with knowledge engineers and software analysts, whose combined profiles can cover the requirements of expert knowledge, formal correctness, semantic richness and efficiency, required for such knowledge-based applications.

This effort can be rewarded by the several uses that a heavy domain ontology can support if its development has followed methodological approaches that guarantee a high level of generality and modularity of the modelled ontology. Each possibility of reuse brought by the development of a new knowledge-based system in the same domain can amortize the cost of development and maintenance of the domain ontology.

Much has been said about the advantages of building a well-founded domain ontology regarding the potential software applications that can be supported by ontologies. However, ontology engineering is still a recent area of research, and its technological products are just starting to be delivered and evaluated.

Kop in [Kop 2011] discusses the limitations in adopting an existent domain ontology as the basis for a new knowledge-based application. Different views over the domain and ontological choices driven by diverse goals require significant adaptations on the ontology, which are hard to be accomplished by knowledge engineers. The author claims that the reuse can be assured by the involvement of the domain expert in the ontology adaptation. Confirming the Kop claim, the adaptation of ontology to support new applications was successful applied in the several Geology projects described here, in this article. Still, the motivation for ontology reuse can go beyond the reuse of an available formal piece of knowledge. Shah [Shah *et al.* 2014] has described a framework to help the reuse of a biomedical ontology with the intention of helping the integration of distinct specialties in Medicine thought a common knowledge-based framework of software. Nevertheless, the cost or utility motivation for ontology reuse and the possibilities of reducing the cost of knowledge-based applications by recycling existent ontologies still face the problems of correctness of the ontology modelling [Guarino & Welty 2002], quality of documentation [Simperl *et al.*2011] and the further modifications of a shared ontology that can impact the maintenance of applications [Tsalapati *et al.* 2009].

Our experience shows that, despite of the cost of developing fully operational domain ontologies, the possibilities of reuse of the artifact outspreads the costs and effort of the development.

In order to contribute to the understanding of the potential uses of domain ontologies in knowledge-based applications, this article analyses the actual uses of a mature domain ontology whose development started on 90's and is being continuously enhanced. We described the commercial and non-commercial software applications and how each new application has affected the original definition of concepts and the improvements that were done in order to keep compatibility and modularity among the several supported software families.

2. The PetroGrapher project

The Petrography domain ontology was the main product of the PetroGrapher project developed by the Intelligent Database Group of Federal University of Rio Grande do Sul, Brazil, from 1995 to 2007 [Silva 1997; Abel 2001; Mastella 2004; Victoreti 2007]. The domain ontology was aimed to organize and represent the Geology vocabulary required to support the quality evaluation of clastic and carbonate petroleum reservoirs through petrographic analysis. An intelligent database application – Petroledge® system[1] - was developed to support the petrographer through the task of reservoir description and interpretation. The original ontology published in [Abel 2001] was a partonomy of 21 geological terms (Figure 1), whose attributes and values added another 1500 terms to the initial model. The terms were structured mainly through the *part of* relationship. The more significant hierarchies refer to the mineral constituents: *Detrital* and *Diagenetic composition* classes and subclasses (not detailed in Figure 1). The concept *Diagenetic composition*, its attributes and domain of possible values are detailed in Figure 2. The Figure illustrates the frame-based formalism adopted in the knowledge representation and exemplifies the level of detail in which the ontology was formalized. The knowledge representation formalism was chosen intended to facilitate the mapping of the concept representation to a relational database model, since the database acts as the repository of the domain ontology. The Figure 2, in particular, shows the attributes *Location* and *Paragenetic Relation*, which express the spatial relationships that a diagenetic mineral has with its neighborhood that can be visually recognized by the geologist. The *Diagenetic composition* concept and attributes are essential for the several interpretation tasks described in the Section 3.

[1] Petroledge, Petroquery, Hardledge, RockViewer and Petrographypedia are trademarks of ENDEEPER Company. The suite of ontology-based applications described in this paper can be known in www.endeeper.com/products.

Basically, petrographic evaluation refers to the formal description of visual aspects of a rock sample, as they appear in naked-eye analysis and under an optical microscopic. Starting from the petrographic features that are discerned, the petrographer infers the possible geological interpretation(s) of the rock, which will strongly influence the method of evaluation of the potential of the geological unit as an oil reservoir. The geologist analyses the physicochemical conditions, called *diagenetic environment*, in which the rock was possibly produced, according to the features that would have been imprinted in the rock by the conditions of this environment.

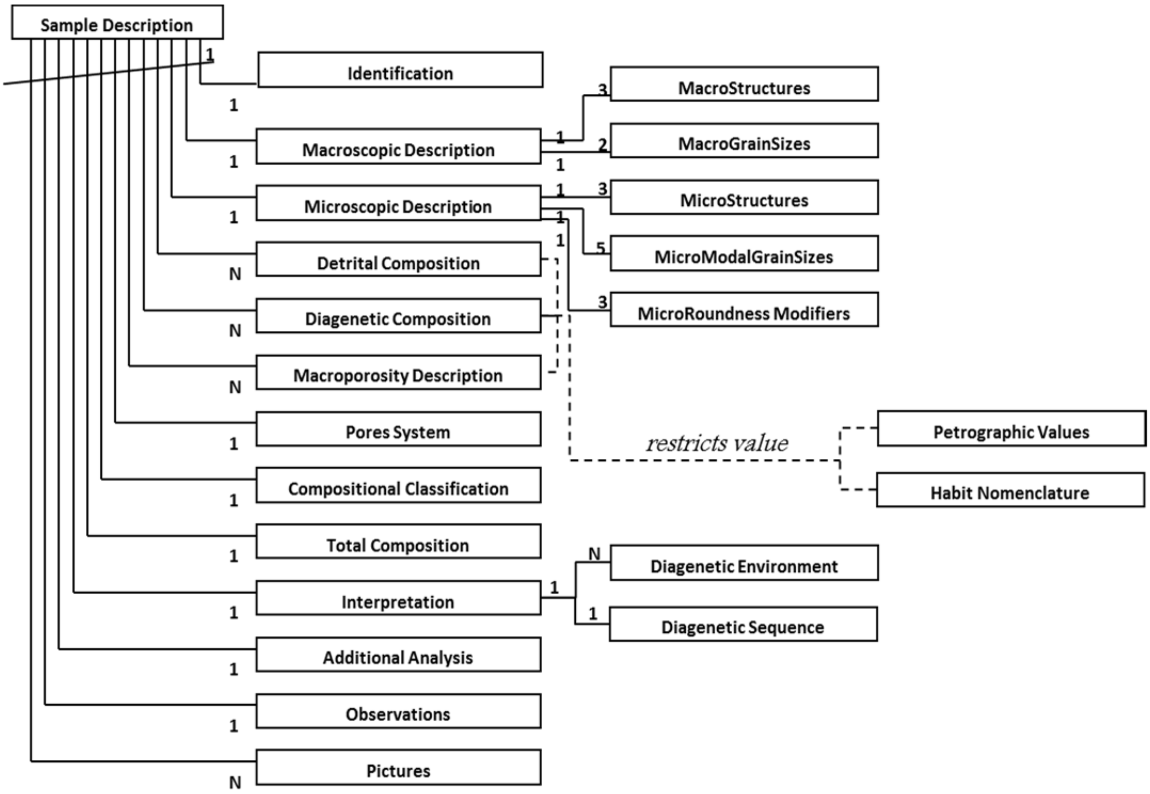

Figure 1. Main concepts of the ontology of Petrography for petroleum reservoir. The boxes describe the concepts and the arcs represent the *part-of* relationship.

The greater challenge in building knowledge application in Geology is that the explicit part of the knowledge that can be expressed through words is just a part of the body of knowledge applied in interpretation. Most of the data relevant for geological interpretation of oil reservoirs consist of visual information that have no formal denomination and are learnt through an implicit process during training and field experience. These features without names constitute the implicit body of knowledge, also called *tacit knowledge* by Nonaka and Takeuchi [Nonaka *et al.* 1995] when referring to the unarticulated knowledge that someone applies in daily tasks but is not able to describe in words. The articulated or *explicit knowledge* that we call ontology refers to the consciously recognized entities and how these entities are organized. Tacit and explicit knowledge should be seen as two separate aspects of knowledge that demands their own representational formalism and not different sorts of it.

Concept Diagenetic-Composition	
Is-a	Object
Part-of	Concept Sample-Description
Mineral Name	one-of **[Diagenetic-Constituent]**
Constituent Set	one-of [Silica, Feldspar, Infiltrated clays, Pseudomatrix clays, Authigenic clays, Zeolites, Carbonates, Sulphates, Sulfides, Iron oxides/hydroxides, Titanium minerals, Other diagenetic constituents]
Habit	one-of **[Habit-Name]**
Amount	range [0.0 - 100.00]
Nominal Amount	one-of [abundant, common, rare, trace]
Location	one-of [intergranular continous pore-lining, intergranular discontinous pore-lining, intergranular pore-filling, intergranular discrete, intergranular displacive, intragranular replacive, intragranular pore-lining, intragranular pore-filling, intragranular discrete crystals, intragranular displacive, moldic pore-lining, moldic pore-filling, oversized pore-lining, oversized pore-filling, grain fracture-filling, grain fracture-lining, rock fracture-filling, rock fracture-lining, concretions/nodules, massive beds/lenses]
Modifier	one-of [dissolved, zoned, fractured, recrystallized]
Paragenetic Relations	one-of [**Covering** <one-of [Diagenetic-Constituent]>, **Covering** <one-of [Detrital-Constituent]>, **Covered by** <one-of [Diagenetic-Constituent]>, **Replacing grain of** <one-of [Detrital-Constituent]>, **Replacing matrix of** <one-of [Detrital-Constituent]>, **Replacing** <one-of [Diagenetic-Constituent]>, **Replaced by** <one-of [Diagenetic-Constituent]>, **Alternated with** <one-of [Diagenetic-Constituent]>, **Engulfing** <one-of [Diagenetic-Constituent]>, **Engulfing** <one-of [Detrital-Constituent]>, **Engulfed by** <one-of [Diagenetic-Constituent]>, **Intergrown with** <one-of [Diagenetic-Constituent]>, **Overgrowing** <one-of [Diagenetic-Constituent]>, **Overgrowing** <one-of [Detrital-Constituent]>, **Overgrown by** <one-of [Diagenetic-Constituent]>, **Expanding** <one-of [Detrital-Constituent]>, **Compacted from** <one-of [Detrital-Constituent]>, **Within intergranular primary porosity, Within intergranular porosity after** <one-of [Diagenetic-Constituent]>, **Within intergranular porosity after detrital matrix, Within intragranular porosity in** <one-of [Detrital-Constituent]>, **Within intracrystalline porosity in** <one-of [Diagenetic-Constituent]>, **Within moldic porosity after** <one-of [Detrital-Constituent]>, **Within moldic porosity after** <one-of [Diagenetic-Constituent]>, **Within shrinkage porosity of** <one-of [Detrital-Constituent]>, **Within shrinkage porosity of** <one-of [Diagenetic-Constituent]>, **Within grain fracture porosity in** <one-of [Detrital-Constituent]>, **Within rock fracture porosity in** <one-of [Detrital-Constituent]>]
Paragenetic Relation Constituent Set	one-of [Silica, Feldspar, Infiltrated clays, Pseudomatrix clays, Authigenic clays, Zeolites, Carbonates, Sulphates, Sulfides, Iron oxides/hydroxides, Titanium minerals, Other diagenetic constituents, Detrital quartz, Detrital feldspar, Plutonic rock fragments, Volcanic rock fragments, Sedimentary rock fragments, Metamorphic rock fragments, Micas/chlorite, Heavy minerals, Intrabasinal grains, Detrital matrix, Other detrital constituents]

Figure 2. A detail of the attributes and domain values of the Diagenetic Composition concept represented in the ontology. The lists [Diagenetic-Constituent] and [Habit- Name] describe the specialized vocabulary that describes mineral names and formats of minerals modelled in a separated way for a question of modularity and reusability.

The Petroledge application was conceived in order to allow a user with a medium level of expertise to describe petrographic features in his/her own level of technical language. The system has the role of applying knowledge to recognize, within those ontologically described features, the items that can serve as diagnostic cues for higher levels of expertise in interpretation, in some imitation of a process of visual interpretation (but with even images being described symbolically). In order to achieve that, the knowledge model represents the connection between the features described using ontological vocabulary and those no-named features utilized by the experts to support interpretation. In other words, the model explicity represents the way in which the expert would *see* the same features seen and described by the user with support of ontology. The knowledge acquisition process and the way in which the knowledge was modeled and implemented in Petroledge system are described in [Abel *et al.* 1998].

3. Ontology-based applications

The long-term effort of building a detailed domain ontology in Petrography had the aim of developing a software application to support the highly specialize task of quality evaluation of petroleum reservoir. Petroledge features include an optimized support for the petrographic description of clastic and carbonate reservoirs and other sedimentary rocks. The system guides sample description, according to a systematic order, allowing the standardization and easy access to petrographic terminology for all aspects of description. The user will produce a structured description of the rock under analysis according to the knowledge model. The knowledge base is composed by the ontology and a set of distinct representational formalisms that describe the scheme of a description and the inferential knowledge applied by problem-solving methods [Gómez-Pérez & Benjamins 1999]. Each description is stored as a set of tuples of concept-attribute-value or any logical combination of concept-attribute-value. Records within a relational database are further processed by several problem-solving methods, each one intended to extract geological interpretation, such as, rock provenance, diagenetic environment of rock formation, original rock composition before diageneses, and others. This simple structure (frames + inferential relationships) is the base for supporting multiple applications.

The more powerful inferential formalism applied by Petroledge is the *knowledge graph*, which plays the role of a rule type (in the sense defined in [Schreiber *et al.* 2000]) in defining the inference paths of the problem-solving process. They were built as an AND/OR tree, where the root represents the interpretation and the leaves are instances of no-named visual features. By its side, each no-named feature is associated to a set of terms of the ontology that better describe the visual aspect of that evidence (Figure 3). This aggregate structure of knowledge and its cognitive significance was firstly defined as a *visual chunk* by [Abel 2001]. The k-graph as a whole represents how much each feature influences the choice of some particular interpretation as a solution for the interpretation problem. It also provides a connection between the expert-level knowledge and the shared ontology applied by the professionals on communication and daily tasks. A weight assigned to each feature assets the relevance of that feature to a particular geological interpretation. Twelve k-graphs represent the knowledge required by Petroledge system to automatically interpret the six possible diagenetic environments for clastic reservoirs. The reasoning mechanism of the Petroledge system exams the description of the user in the database searching for described features that match to each knowledge graph. When the weights of features are enough to support that interpretation, the diagenetic environment and the founded features are shown to the user.

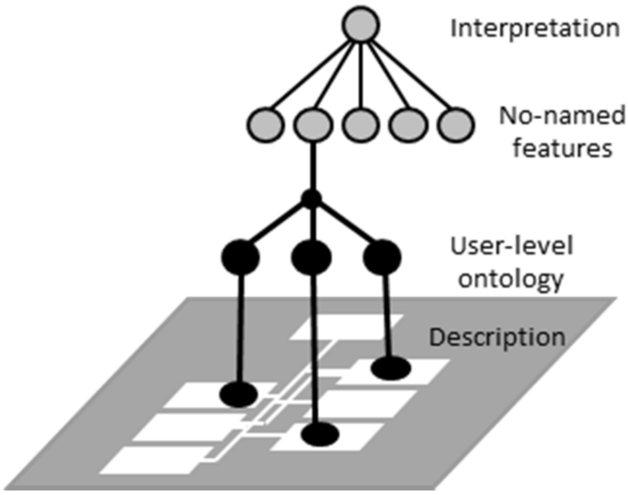

Figure 3. The knowledge graph describes the evidences that support geological interpretation and also links the expert level features to the set of terms in the ontology that describes the content of the evidence.

Figure 4 shows the visual chunk in the petrographic application that describes Diagenetic Dissolution and its internal representation as it is manipulated by the system.

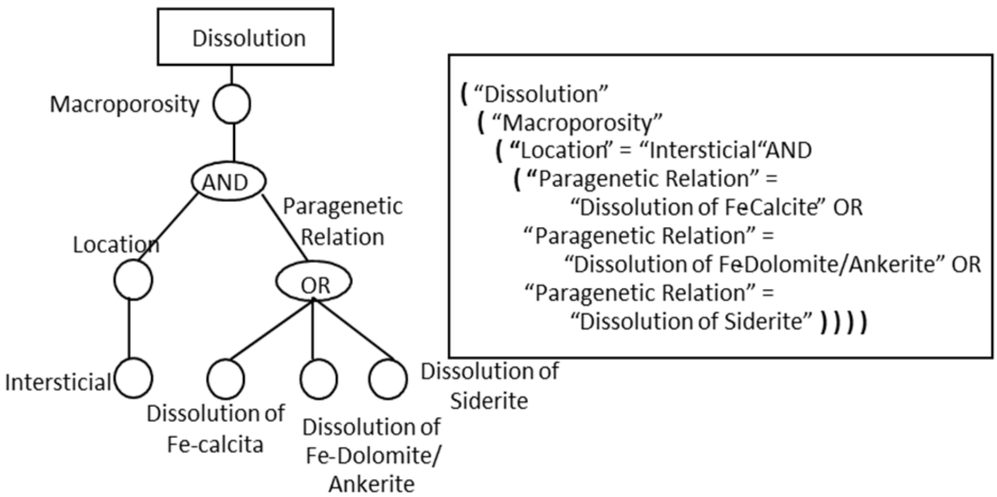

Figure 4. A representation of a visual chunk that describes the inference for Diagenetic Dissolution interpretation and its internal representation as manipulated by Petroledge.

Several other methods of reasoning were developed and applied over the Petrography ontology-based model. Each method requires its own inferential knowledge model and is called or not by the system in an independent way. Compositional classification and provenance interpretation apply numerical methods based on the proportion of minerals. Inferential rules can deconstruct the diagenesis and retrieve the original composition of sediments. Textural classification is based on the proportion of the size of grains. Geological rules can infer the proportion of intrabasinal and extrabasinal sediments.

A further expansion of the ontology model has allowed the modelling of diagenetic sequences, enabling new inference methods to extract the sequence of physicochemical events that has generated a reservoir rock from the spatial relations among mineral constituents [Mastella *et al.* 2007]. In order to support that, new concepts describing *events* and *temporal relations* were included in the model and their instances were defined. In addition, the *paragenetic relations* (showed in Figure 2) that describe mineral constituent associations had their spatial attributes detailed. A set of inference rules describes the relation between the mineral association and the event that has happened with the rock. A reasoning method reads the features described by the user and stored in the database and orders the events that have happened with the rock since the deposition of sediment and later consolidation of the rock. Figure 5 shows the graphical representation of the inference rule that allows ordering the generation of the mineral dolomite as being happened before the generation of mineral anidrite.

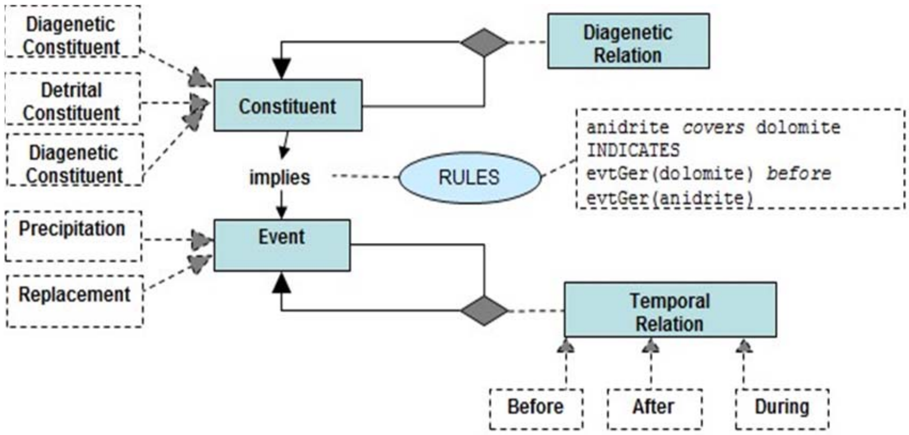

Figure 5. The model of inference rules for extracting sequence of events from the Petrography ontology model.

The flexibility of the ontology model allows each method being based on different inferential knowledge models that are applied by independent modules of software, according to the needs of a particular use of rock data.

Besides the several inference methods that were associated to the Petrography knowledge model, several other applications had been developed getting advantage of the strong and complete formalized vocabulary, even without being part of the Petroledge suite of software.

The Petroquery® application implements a query system over the rock description based on the ontology. Getting advantage of the vocabulary, the application offers to the user his/her own vocabulary for consultation restricting the option of words that are actually present in the database. The user builds SQL consultations by selecting the controlled vocabulary and retrieving the rock descriptions that includes the query arguments. With this support, the geologist can build domain specific consultations like "*Retrieve all rock samples that has dolomite replacing feldspar grains and anidrite within intergranular porosity*".

The controlled vocabulary of the domain ontology was also applied for labeling and indexing microscopic images of rocks in the RockViewer® system, developed in 2010. An editor allows the geologist to associate ontology-controlled text describing images of the rock. After the images being labelled, usually for an experienced petrographer, they are shared through a distributed database to be consulted. The system is used in corporate environment for geologist consultation of the many aspects of rocks that affect the quality of a petroleum reservoir. Figure 6 shows the interaction with RockViewer®. The terms of ontology describing the content of image and used for consultation are highlight in the image label.

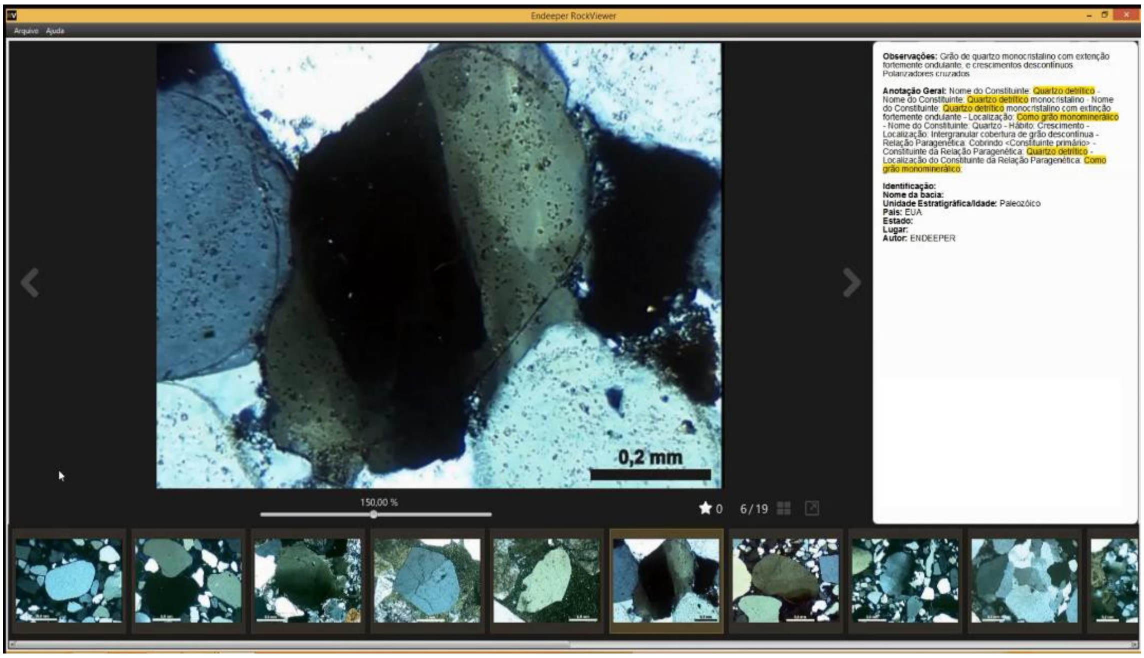

Figure 6. Domain ontology allows to indexing and recovering image content.

The original domain ontology covers the domain of rock-reservoir description. The knowledge schema models the structure of a reservoir description, while the mineral names and characteristics and textural aspects, that constitute the bulk part of ontology, were captured from the more general vocabulary of the Geology community, which supports several other Geology interpretation tasks. Based on this assumption, the ontology of Petroledge was extended to cover all types of rocks and a related knowledge-based application – Hardledge® system - was developed to support mining rock interpretation problems. This 2010's developed ontology was already extended, in 2013, to support the interpretation of magma placement history in sedimentary basins affected by tectonic events.

Other classes of software application can benefit by the reuse of available domain ontology. The web-based application PetrographypediA [Castro 2012] applies the ontology of minerals and their characteristics on microscope to build a visual all-type-of-rock atlas on-line to be freely consulted by the Geology community. As for RockViewer® application, the ontology of Petroledge and Hardledge® was used to label and index rock pictures taken in optical microscope.

A remarkable application of the Petrography domain ontology in the last year is related to the development of conceptual solutions to provide interoperability between reservoir modelling applications along with petroleum chain. The ontology is being used to make explicit the meaning of the geological concepts embedded in the software code and models in order to allow these objects to be recognized and applied to anchor the models of distinct suppliers [Abel et al. 2015b]. This initiative is being conducted by the Energistics[2] consortium in the definition of RESQML interchange standard [King *et al*. 2012]. Also, the PPDM association is applying the well-founded ontology for anchoring the concepts of data models and providing better support for data mapping among different application models [Abel *et al.* 2015a].

[2] ENERGISTICS is a global consortium that facilitates the development, management and adoption of data exchange standards for petroleum industry. RESQML is the data exchange standard for reservoir data. www.energistics.org.

4. The Petroledge Ontology Evolution

The knowledge model of Petrography was initially defined using a frame-based formalism whose general aspect was showed in Figure 2. Two requirements oriented the modelling definition: the understanding of the expert about the information required to produce a qualified rock description and the data management requirements for storage and retrieving a large number of descriptions in a corporate environment. The knowledge acquisition was strongly based on the collection of cases of previous descriptions. As a result, the original model was a flat representation of a *rock description* instead of focusing in the rigid geological concepts and the hierarchy that structure the world in the geologist mind.

The inadequacy of the original model was soon evidenced as much as the reasoning method for diagenetic environment interpretation was developed. To cope with the reasoning, the model was separated in three parts: the knowledge schema of the domain (the partonomy that aggregates each aspect of a rock that needs to be described, showed in Figure 1), the implicit visual knowledge applied by expert in supporting interpretation (later on, it was modelled through visual chunks and knowledge graphs), and the explicitly knowledge or the extensive list of mineral names, textural aspects, lithology nomenclature and the structural relationships that had further grown as the Petrography ontology. Although the knowledge model of rock description and the further extracted visual chunks are still in use in Petroledge and Hardledge® systems, most of maintenance done over the original knowledge model refers to the vocabulary extension and quality improvement of the ontology.

The subsequent evolution was demanded by the interpretation of event sequence that has generated the rock. It was necessary to identify through the domain ontology the upper level classes of the modelled concepts, such as *event*, *temporal relation* and *spatial relation*. This was done by aligning the ontology with other upper ontologies described in literature [Sowa 1995; Scherp *et al.* 2009] and then using the concepts of upper ontology to classify and organize the related concepts in the domain ontology. As a result, the study of the paragenetic relationships described in the Petrography model shows those that represent the spatial relationship between minerals that express the occurrence of an event. Formal definitions of temporal relations based on Allen relations [Allen 1991] were included in the ontology, as well as the definition of events in terms of Geology phenomena. The Allen relations and the definition of diagenetic events allow the extraction and ordering of the events that have transformed the sediments in a consolidated rock from the information described by the user in the rock description.

The RockViewer and PetrographypediA applications were the first Petroledge independent systems that were based on the ontology. As a consequence, these projects have required the ontology rebuilt as an independent artifact, stored in a separated database for further consultation. This reconstruction has produced a new model for the same domain knowledge expressed in the ontology. The rigid concepts (rock and mineral constituent) and their attributes have built the main framework of restructured ontology. New terms were added to expand the domain of application to new kinds of rock and new rock features

The more significant advance for the ontology development came with the use of ontology for improving the interoperability in the petroleum modelling chain by embodying geological explicit concepts and rock properties in RESQML standard. The previously described projects were developed under supervision of the original team of knowledge engineers. For the application into petroleum standards, the ontology needs to be used for several engineers from many distinct software suppliers around the world. The ontology needs to embody all restrictions requested to express the semantic of each geological term in order to avoid a flexible use with another meaning, which is one of the main sources of errors.

In order to support RESQML integration, each geological concept in the ontology was studied based on the metaproperties proposed by Guarino and colleagues in [Guarino & Welty 2001, 2002; Gangemi *et al.* 2003]. Physical objects, such as *lithological unit*, and amounts of matter, like *rock*, were identified and modeled in a separated way in the geological model. Usually these objects are collapsed or partially merged in the geological models resulting in the main source of problems in reservoir information integration, since many properties related to the substance, such as permeability, are associated to bodies of rock and incorrectly extrapolated by the simulation systems. In addition, the relevant attributes of the concepts that allow defining the identity of each entity were specified as well as their domain of values. The approach of conceptual spaces became the theoretical framework for modeling domain of attributes aiming reusability in other areas of applications into the Geology domain [Fiorini *et al.* 2015]. The ontological analysis of the main concepts of the ontology that are being integrated into RESQML standard can be found in [Abel *et al.* 2015b].

In addition, the problem of scale of analysis that was never an issue for the Petrography domain became central to support applications where the data is generated and consumed in distinct scale of analysis. Basin (105 meters), reservoir (103 meters) and well (10 meters) scales of studies have required that the range of numerical attributes and the symbolic values were extended to cover the new possibilities of the domain.

5. Conclusion

The Petrography ontology has been continuously evolving since it was proposed. From the initially two applications based on a set of twelve concepts, the model embodied a vocabulary as large as 7000 terms split in two idioms which is shared by more than a dozen applications.

This successful grown have been requiring continuous expansion in the number of modelled concepts. Keeping the consistency and integrity of the knowledge base after the inclusion of new concepts have requested periodic restructuring of the ontology organization, sometimes followed by deep changes in the philosophical view that orients the ontological decisions. These changes were especially significant on the first stages of ontology-based application developments and now, when the ontology is going to be integrated to the reservoir interchange standards. The rigor in making explicit the semantic of each vocabulary for a large group of users of diverse specialties driven by many distinct objectives is showing to be a challenge in terms of Ontology Engineering. Some studies about the modularity of ontologies and the possibility of offering specialized partial “views” to users according to their professional profile [Aparicio *et al.* 2014] have indicate some new directions for the ontology evolution.

Acknowledgments: PetrograGrapher project were supported by CNPQ and CAPES. The creation of commercial version of Petroledge and the Endeeper Co. was possible thanks to the grants of FINEP and FAPERGS. We thank Endeeper for providing the software detailed information described in this article.

6. References

Abel M. (2001). "The study of expertise in Sedimentary Petrography and its significance for knowledge engineering (in Portuguese)". In: *Informatics Institute,* UFRGS, Porto Alegre, p. 239.

Abel M., Castilho J.M.V. & Campbell J.A. (1998). "Analysis of expertise for implementing geological expert systems". In: *World Conference in Expert Systems*. Cognizant Communication Offices Mexico City, pp. 170-177.

Abel M., Lorenzatti A., Fiorini S.R. & Carbonera J. (2015a). "Ontological analysis of the lithology data in PPDM well core model". In: *19th International Conference on Petroleum Data Integration and Data Management*. Pennwell Houston.

Abel M., Perrin M. & Carbonera J. (2015b). Ontological analysis for information integration in geomodeling. *Earth Science Informatics*, 8, 21-36.

Allen J.F. (1991). Time and time again: The many ways to represent time. *International Journal of Intelligent Systems*, 6, 341-355.

Aparicio J.M.L., Carbonera J.L., Abel M. & Pimenta M.S. (2014). "Ontology View extraction: an approach based on ontological meta-properties". In: *IEEE international conference on tools with artificial intelligence - ICTAI 2014*. IEEE Limassol.

Castro E.S.E.D. (2012). PetrographypediA. The portal of Petrography. URL http://www.Petrographypedia.com/

Fiorini S., Abel M. & Carbonera J. (2015). Representation of part-whole similarity in geology. *Earth Science Informatics*, 8, 77-94.

Gangemi A., Guarino N., Masolo C. & Oltramari A. (2003). Sweetening WordNet with Dolce. *AI Magazine*, 24, 13-24.

Gómez-Pérez A. & Benjamins V.R. (1999). "Overview of knowledge sharing and reuse components: Ontologies and problem-solving methods". In: International Joint Conference on Artificial Intelligence(IJCAI-99), Workshop on Ontologies and Problem-Solving Methods (KRR5) (eds. Benjamins VR, Chandrasekaran B, Gomez-Perez A, Guarino N & Uschold M) Stockolm, Sweden.

Guarino N. & Welty C. (2001). "Identity and Subsumption". In: The Semantics of Relationships. An Interdisciplinary Perspective (eds. Green R, Bean CA & Myaeng SH). Springer Netherlands, pp. 111-126.

Guarino N. & Welty C. (2002). Evaluating ontological Decisions with Ontoclean. C*ommunications of the ACM* 45, 61 – 65.

King M.J., Ballin P.R., Bennis C., Heath D.E., Hiebert A.D., McKenzie W., Rainaud J.-F. & Schey J.C.S.P.E. (2012). Reservoir Modeling: From RESCUE To RESQML. SPE Reservoir Evaluation & Engineering, Society of Petroleum Engineers.

Kop C. (2011). "Domain expert centered ontology reuse for conceptual models". In. Springer Verlag Hersonissos, Crete, Greece, pp. 747-762.

Mastella L. (2004). "An event-based knowledge model for temporal sequence acquisition and representation in Sedimentary Petrography". In: *Informatics Institute*, UFRGS, Porto Alegre.

Mastella L.S., Abel M., Ros L.F.D., Perrin M. & Rainaud J.-F. (2007). "Event Ordering Reasoning Ontology applied to Petrology and Geological Modelling". In: Theoretical /Advances and Applications of Fuzzy Logic and Soft Computing.

(eds. Castillo O, Melin P, Ross OM, Cruz RS, Pedrycz W & Kacprzyk J). Springer-Verlag, pp. 465-475.

Nonaka I., Takeuchi H. & Takeuchi H. (1995). The knowledge-creating company: how Japanese companies create the dynamics of innovation. Oxford University Press, New York.

Scherp A., Franz T., Saathoff C. & Staab S. (2009). "F - A model of events based on the foundational ontology DOLCE+DnS ultralite". In: *K-CAP'09 - 5th International Conference on Knowledge Capture*. ACM SIGART Redondo Beach, CA, United states, pp. 137-144.

Schreiber G., Akkermans H., Anjewierden A., Hoog R.d., Shadbolt N., Velde W.v.d. & Wielinga B. (2000). Knowledge engineering and management:The CommonKADS Methodology. The MIT Press, Cambridge.

Shah T., Rabhi F., Ray P. & Taylor K. (2014). "A guiding framework for ontology reuse in the biomedical domain". In. IEEE Computer Society Waikoloa, HI, United states, pp. 2878-2887.

Silva L.A.L. (1997). "Intelligent database for petroghaphic analysis (In Portuguese)". In: *Informatics Institute*. UFRGS Porto Alegre, p. 114.

Simperl E., Sarasua C., Ungrangsi R. & Burger T. (2011). Ontology metadata for ontology reuse. *International Journal of Metadata, Semantics and Ontologies*, 6,126-145. Inderscience Enterprises Ltd.

Sowa J.F. (1995). Top-level ontological categories. *International Journal of Human Computer Studies*, 43, 669-669. Academic Press Ltd.

Tsalapati E., Stamou G. & Koletsos G. (2009). "A method for approximation to ontology reuse problem". In. Inst. for Syst. and Technol. of Inf. Control and Commun. Funchal, Madeira, Portugal, pp. 416-419.

Victoreti F.I. (2007). "Mapping and documentation of diagnostic visual features for interpretation in a knowledge-based system in Petrography domain". In: *Informatics Institute,* UFRGS, Porto Alegre.