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Design and Development of a Mineral Exploration Ontology

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DESIGN AND DEVELOPMENT OF A MINERAL EXPLORATION ONTOLOGY

by

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Under the Direction of Hassan A. Babaie

ABSTRACT

In this thesis, an ontology for the mineral exploration domain is designed and developed applying the Protégé ontology editor. The MinExOnt ontology includes a formal and explicit representation of the terms describing real objects, activities, and processes in mineral exploration. The stages used for these activities have various vocabularies, which are semantically modeled in this ontology with Web Ontology Language (OWL). The aim of the thesis is to show how ontologies can be designed and developed to help manage and represent geological knowledge. In addition to providing a general workflow for building the ontology, this thesis presents a simple user guide for the used software, including Protégé, used for ontology development, and Knoodl-OntVis, used for OWL visualization.

INDEX WORDS: Ontology development, OWL-Ontology Web Language, OWL visualization, Domain, Common controlled vocabulary, Knowledge sharing, Mineral exploration, Protégé, Knoodl

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DEDICATION

I dedicate this thesis to my precious husband, Dr. Yavuz Mentes for his infinite support and encouragement in my life. He is a practical fixer, excellent investigator, career explorer, and has a motivating personality. Also, he has a significant role for my geoscience career in the USA. I owe him for where I am in my career right now and what I have gained so far. I am deeply thankful to him for his patience and all his career advice that made me successfully tackle the difficulties. I am so grateful for being with him and sharing my life.

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CHAPTER 1: INTRODUCTION

Geologists use various field and laboratory methods to explain and depict Earth history, and to understand the processes that occur on the Earth. In a typical geological investigation, geologists utilize primary information related to petrology, stratigraphy, economic geology, structural geology, and other geological knowledge. Moreover, they rely on a wide variety of available resources such as database, scientific articles offering geological knowledge, and internal or external reports. The volume of these resources along with the knowledge geologists have is growing very fast as knowledge progresses, and more data is being acquired with the proliferation of sophisticated measuring and detecting devices. As the volume of the collected data increases, a need to efficiently manage and represent the data becomes more obvious since study of heterogeneous and unstructured knowledge is challenging, time consuming, costly, and inefficient.

The solution is generated in a global architecture where semantic plays a significant role to eliminate the obstacles originated from knowledge heterogeneity (Ameur et al., 2004). The basis and structure of knowledge should be organized and managed with the Semantic Web Technology, which is related to machine readable and understandable knowledge model – 'ontology'. This knowledge modeling and data structuring is done by identifying and properly defining a set of relevant concepts and relating them in the form of ontologies that characterize the knowledge in a given application domain (Navigli and Velardi, 2004). There has been a growing focus on Web Ontology Language (OWL) due to its ability to explicitly describe data semantics in a common way. Using, managing, and sharing knowledge about a specific domain

among humans by defining a common, controlled vocabulary allows knowledge to grow effectively under control.

Knowledge, the sum of known facts in the domain, is used by various industries related to geology, such as oil and gas, environment, hydrogeology, mining, and several others. Geological knowledge is traditionally organized to be understood by the people who deal with geology. In knowledge representation, the people who know the knowledge about a specific field are called 'domain experts' in the field of knowledge representation. Thus, someone who has enough knowledge and background about a specific geological domain can create the domain ontology related to it. In this study, mining industry is selected to develop the ontology.

Mining industry mainly aims to find and create a target having valuable profits. This can be achieved with comprehensive exploration studies. Exploration geology is a geological field that applies diverse geological knowledge for mineral exploration and involves geological studies for evaluation, management, and planning for future exploration and operational studies. With the growth of population and increasing need for minerals, more mineral exploration studies are carried out all over the world. In order to reduce exploration and production risks and cost, companies use and maintain various software tools, at great costs, for ensuring the quality of collected information, data analysis, and creating new knowledge. The knowledge, produced as a result of processing and interpreting the acquired data is generally embedded and hidden in technical reports, databases, and other types of files e.g., Excel spreadsheets. This has adverse effects on the scientific growth of the domain. Thus, there is an acute need to reach a common (i.e., consensual) way of formally and explicitly representing the geological mineral exploration entities (Rainaud et al., 2008). Moreover, according to Ma et al. 2010, the growth of diverse

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vocabularies of heterogeneous terms in different mineral exploration communities prevents geologists from efficiently using and reusing their data in mining projects. Although it may seem building the ontology plays a significant role solely for the business part of geology, it is important to appreciate the value of ontologies for the continuing scientific growth in the field. Thus, domain ontology applied for mineral exploration domain is useful not only for business part of geological studies but also for the scientific research.

The aim of this thesis research is to show how ontologies focusing on OWL can be designed and developed to help management and representation of geological knowledge and to improve the use and integration of heterogeneous geological data. The Mineral Exploration domain ontology provides a knowledge-based, semantically inter-related vocabulary representing the knowledge about mineral exploration and explicitly formalizes the semantic relationships between concepts, for example, of ore deposit and natural resource exploration. Since there is a need to acquire a common way of formally and explicitly representing terms about mineral exploration studies in mining industry, the stages taken during these activities are applied for the ontology development. It also provides a simple user guide for the software, including Protégé and Knoodl-OntVis, which are applied to develop ontology. The ontology produced in this study is non-proprietary, open source, and open access, and therefore can be used for industrial and research purposes.

CHAPTER 2: LITERATURE REVIEW

2.1. Ontology

Ontology is a machine-understandable knowledge model, which is built by explicit (clear, open) specification of the real objects or abstract concepts and their relationships in a specific domain. The term is borrowed from philosophy where ontology is a systematic account of existence (Gruber, 1993). According to Gruber, ontology should effectively communicate the intended meaning of the defined terms and relationships. It should be coherent, clear, and designed to anticipate the uses of the shared vocabulary, i.e., built for pragmatics.

Describing a common, shared vocabulary allows researchers to share information through integration of data. Ontology plays a significant role to make these machine interpretable descriptions of basic concepts and relations among them. According to Noy and McGuinness (2001), the reason why ontology is developed will be 'to share a common understanding of the information among people or software agents enables reuse of domain knowledge, make domain assumptions, separate domain knowledge from operational knowledge, and analyze domain knowledge'. In other words, it is used to more efficiently and formally share, reuse, and analyze knowledge (not just data), and to identify its implicit assumptions. It also defines the concepts, relationships, and other distinctions that are relevant for modeling a domain and plays an important role in different aspects of information system development (Pundt and Bishr, 2002).

Discovery and integration of resources such as data, articles, and Web documents from distributed data sets requires people know about the specific terminology and structure each database uses, and map each term against the schema of each data source. This may be manageable for a small number of data sources; but becomes very difficult and costly task when

many databases exist. Then, ontology can help computers to extract and aggregate information originating from different data sources in an efficient manner (Zhong et al., 2009). This approach helps people use their time efficiently. Instead of users searching for each of these terms in different data source, computers can do it significantly faster with the help of ontology that specifies those equivalent terms.

Ontology generates a common vocabulary that shows knowledge about a specific matter and provides list of terms in the subject. This matter or subject is referred as a 'domain' in an ontological terminology. The important thing creating ontology is ability to define relationships between the terms in the vocabulary. For example, geological structures, deformation mechanisms, stylolites, and pressure solution are 'concepts' in the Structural Geology domain, and are represented by a class in this ontology. The class of 'Stylolite' is a type of geological structure, and is represented as a subclass of the 'Geological Structure' class. Subclassing from the general to more specific classes forms the class hierarchy. Classes may be related to each other through properties. For example, stylolites are formed by the pressure solution deformation mechanism, which may be stated by the 'Pressure Solution forms Stylolite' statement. The 'forms' property, therefore, represents the relationship between pressure solution deformation mechanism and the stylolite (Zhong et al., 2009). These relationships provide a machine readable, semantic connection between the terms.

In geoinformatic research, geosciences data providers, semantic web researchers, and software developers collaborate on sharing topics of geoscience ontologies and language, building geoscience data models, and developing Semantic web applications for knowledge representation and management (Reitsma et al., 2009). In this way, common language in a specific topic is generated with the help of ontology under the directories of all experts.

2.2. Types of ontology

Ontologies may be categorized as domain ontology and upper ontology. A domain ontology (or domain-specific ontology) models the knowledge of a specific domain (field), or part of the world. It represents the particular meanings (semantics) of terms as applied to that domain. An upper ontology (or foundation ontology) is a model of the common objects that are generally applicable across a wide range of domains (Navigli and Velardi, 2004). For instance, NASA's SWEET ontology (Figure 2.1) is an upper ontology, which defines general terms and relationships. The scientific data collected during NASA's earth observation missions, and generated by NASA-sponsored Earth science research, are archived in a specific domain ontology data across the United States (Keller et al., 2006).

There are many upper-level ontologies developed in the Earth Sciences. One of them is the North American Geologic Map Ontology, which was generated by North American Data Model Design Team under the directory of the North American Geologic Map Data Model Steering Committee (NADMSC) with the aim of providing digital geological map database. It includes controlled vocabularies for geologic relations, geologic events, geologic units, geologic structures, earth materials, geologic processes, and geologic properties. (North American Geologic Map Data Model Steering Committee, 2004). Another upper ontology example in Earth Science is the Semantic Web for Earth and Environmental Terminology (SWEET) (Raskin, 2004). Its ontology has broad and very coarse coverage in Earth Systems Science, including concepts like space, time, Earth realms, physical quantities, phenomena, and events (Figure 2.1 and 2.2)
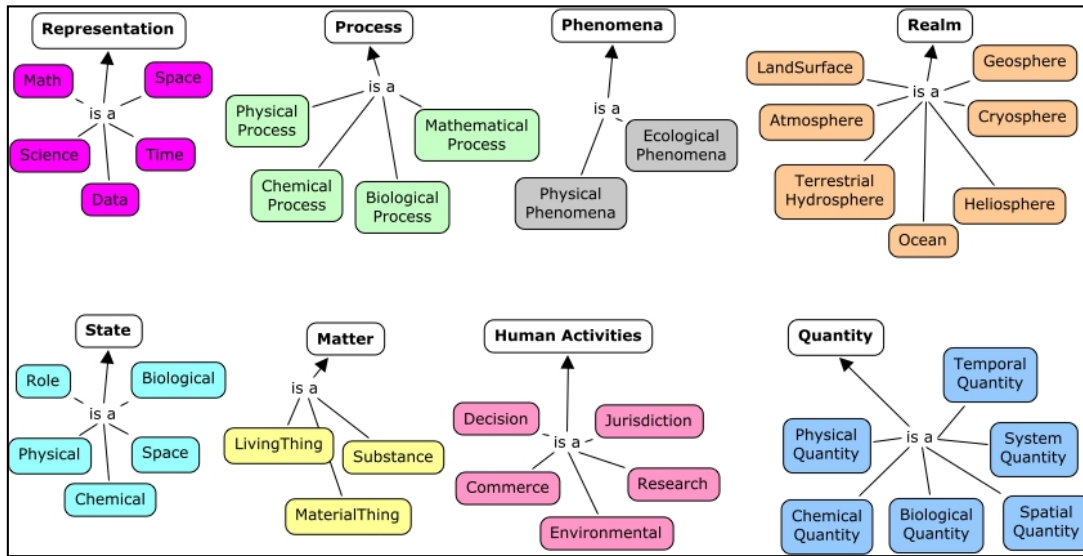
Figure 2.1. Semantic Web for Earth and Environmental Terminology (SWEET) (Raskin, 2004).
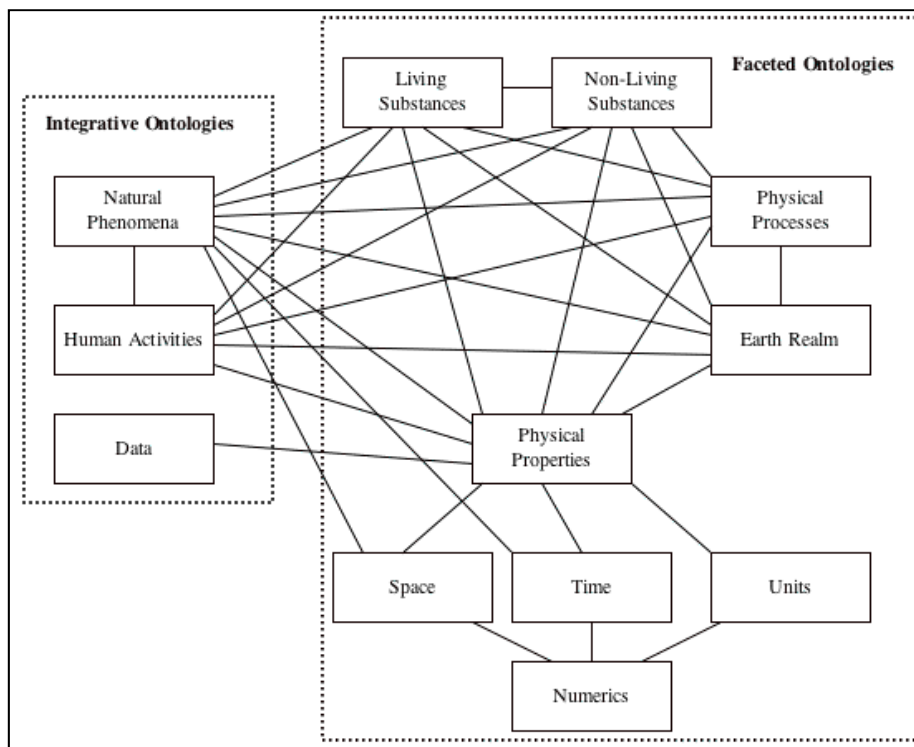
Figure 2.2. SWEET ontologies and their relationships (Raskin, 2004).

In addition to these upper ontologies, there are few domain ontologies in Earth Sciences that are built for specific purposes. It means that they are not upper ontology instead a kind of

domain ontology. Some case studies related to ontology or knowledge based applications for geosciences are listed below:

- Rock classification ontology (Struik, 2002).

- Safod Brittle Microstructure and Mechanisms Knowledge Base Ontology. (http://safod.gsu.edu:8080/safod/).

- Structural geology ontology (Babaie et al., 2006).

- e-WOK HUB project including various ontologies in the domain of geology provides capability of management of spatial information in an ontological database (Ameur et al., 2004).

- Geologic Age domain ontology.

- Ontology of fractures (Zhong et al., 2009). This study has some classes related to fractures (Figure 2.3).
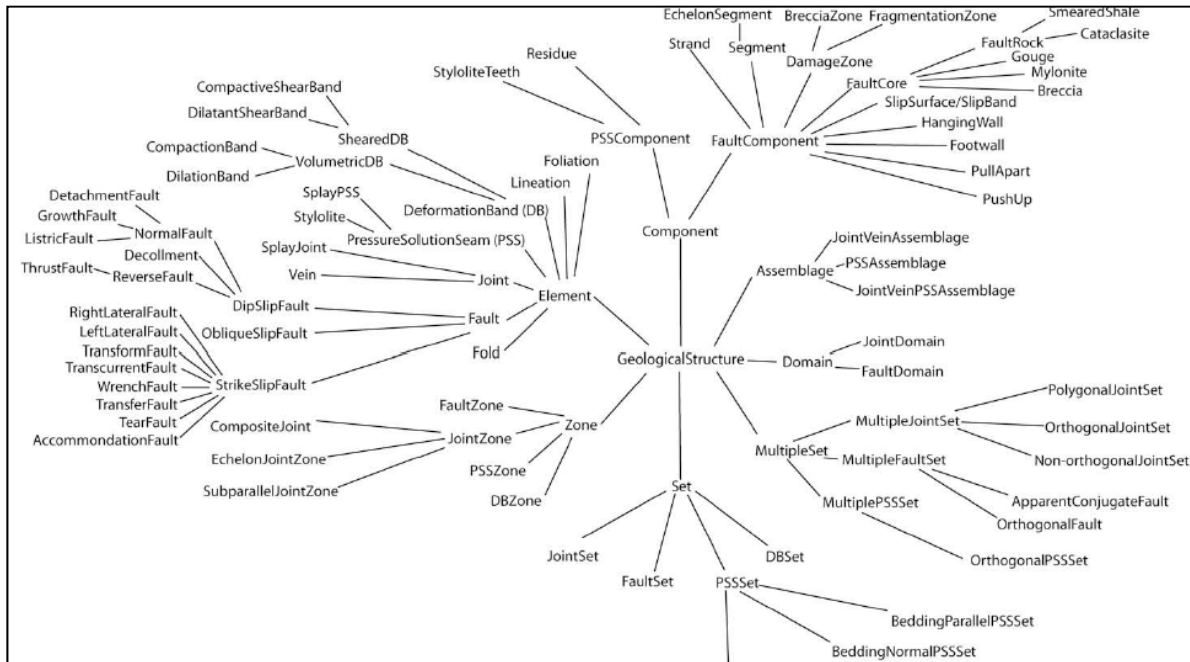
Figure 2.3. Class hierarchy of GeologicalStructure (Zhong et al., 2009).

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- Stream domain ontology for environmental monitoring using geographic information systems (Pundt and Bishr, 2002). Figure 2.4 shows the relationships among the terms in stream ontology.
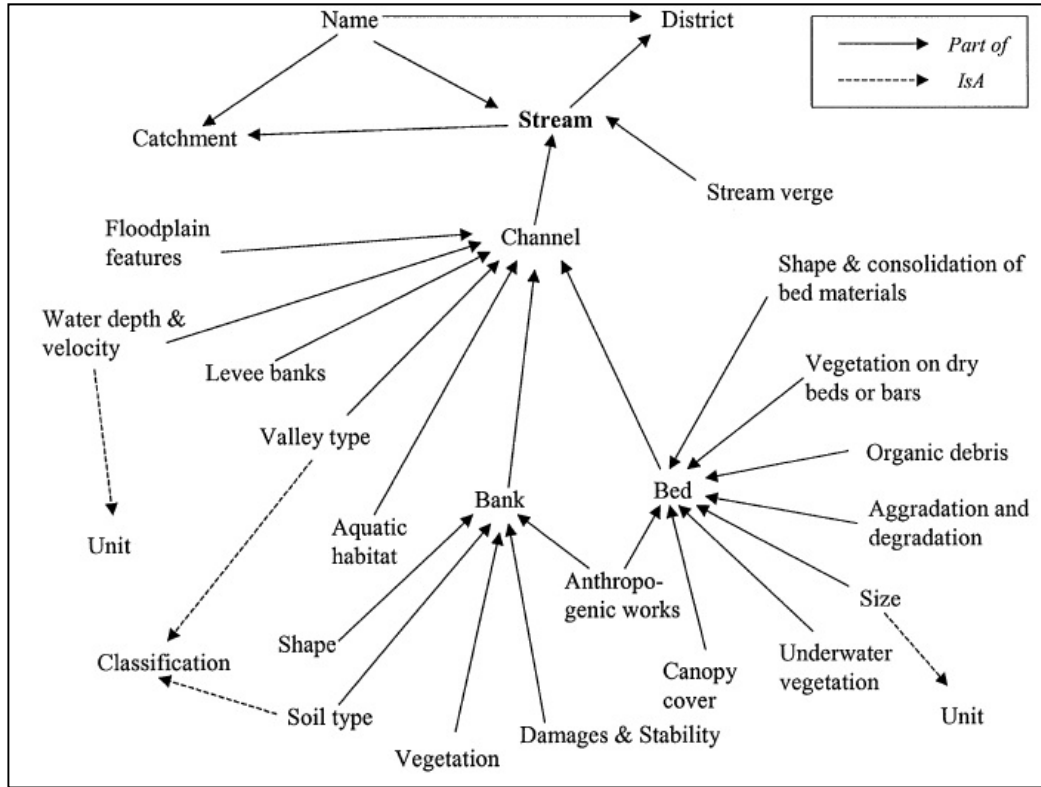
Figure 2.4. Domain ontology for category Stream (Pundt and Bishr, 2002).

- Geo-Ontology describes geological models for hydrocarbon exploration, production and modeling of reservoir using geological and geophysical data (Perrin et al., 2005).

- Earth modeling domain ontology for geological site qualification as CO_2 storage (Rainaud et al, 2008).

- The 'Gravity Contour Map' ontology, used generally for geophysical studies (Salayandia et al., 2006), is another example of the ontology application in geosciences.

- Grid based geological survey (Loudon and Laxton, 2007).

- GEON project including different domain ontologies. Lin and Ludascher (2005) discuss the prototype system developed in the GEON project for exploring data sets, querying registered data sets, and then integrating the maps at the end. The objective was to integrate available geologic data sets to provide a web-based interactive geological map to find the location where rock has a specified geologic age, composition, fabric, texture, or genesis property. They created five ontologies for their study (Geologic Age, Genesis, Texture, Fabric, and Composition). Figure 2.5 shows the relationship between the genesis and composition. It represents a part of composition classification, which is calcium and limestone as a Sedimentary Rock and Marble as a Metamorphic rock have this composition.
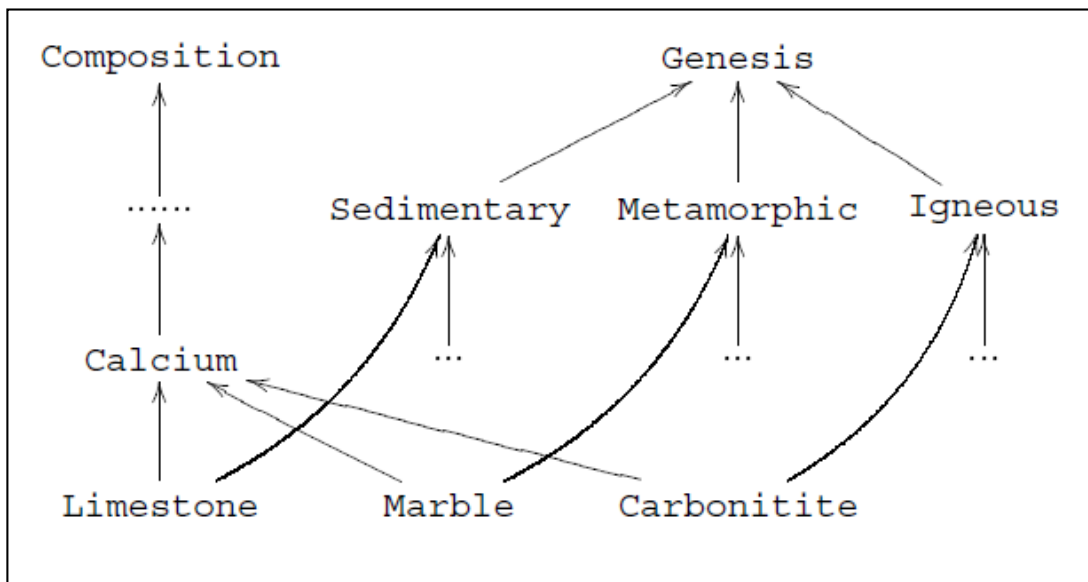
Figure 2.5. Composition and genesis relationship for ontologies (Lin and Ludascar, 2005).

2.3. Use and instantiation of ontology

After ontology is developed, the controlled vocabulary can be reused, merged, and integrated with various ontologies because of its interoperability with machine processible format. Efficient utilization of software languages in ontological studies enables this interoperability at high performance. Use of these existing ontologies can solve heterogeneity problems for various domain knowledge (Sinha et al., 2010).

Ontology facilitates the identification of the vocabularies in a domain and provides effective access to knowledge and data. The concepts or terms used in the ontology can be populated with instances or individuals of classes and their attributes with values. It is a kind of insertion of information into the knowledge base. Each agent can use their own data for the same ontology. The data populated in the ontology adds more meaning for the structured knowledge.

There are various applications for ontological studies. One of them related to geological knowledge base is mentioned in the research done by Xiaogang Ma in 2010. Part of this study is about 3D modeling of ore bodies for mining studies (Figure 2.6). In the figure, (a) represents classifying the significant assayed intervals in bold red along a borehole on a specific cross section; (b) shows combining each borehole results through the section like whole 2D profile of the section and creating composite intervals or composites; (c) represents making an interpolation and converting 2D to 3D ore body; (d) shows a model of objects, attributes and their relationships and represents connections among classes like BOREHOLE, MGINTERVAL, COMPOSITE, CSECTION, OREBODY (Ma, 2010). This study is a good example for how ontologies can be instantiated with values or other specific information. Figure 2.6 (d) shows UML diagrams for the entities in the ontology. 'BOREHOLE' should have specific attributes

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like borehole number, location coordinates, related project name, total depth and other required

information to identify a specific borehole. It can be variable and populated different for each

borehole. 'MGINTERVAL' and 'COMPOSITE' may contain grade values of several metals.

This shows a way how to relate a borehole in the beginning of mineral exploration studies to 3D

ore body at the end of mining extraction.
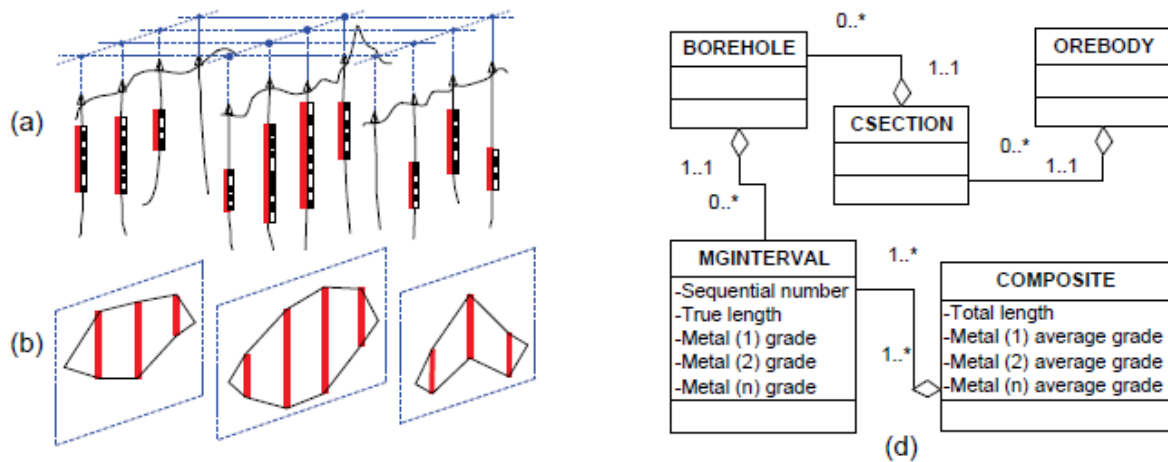
Figure 2.6. Concept of ore body modeling based on borehole ore composites derived cross sectional method (Ma, 2010).

2.4. Linked ontologies and data

Information stored in the current world wide web (WWW) is reached with the help of machines or computers. Their functionality is based on delivering and presenting the documents or archives describing various knowledge on the web. However, people are supposed to connect all the sources related to the topic and make an interpretation about it The Semantic Web, which is developed by Tim Berners Lee, can extend the current web so that knowledge can be related and linked to one another (Obitko, 2007). By doing this, computers can process the knowledge on the web and make a connection among information to help humans analyze knowledge easily.

Linking ontologies provides effective information sharing among knowledge and reusing via web-accessibility and interoperability. Then, knowledge can be widely used and accessed by means of linked ontologies.

In order to transform various web documents, reports, papers, and other publications into machine processible formats, linked data is used to make a connection among variable data in the cloud (Babaie and Raj, 2012). Therefore, ontologies should be published on the web. Linked data, which is a universal ontology-based data access, is generated by publishing and connecting structured data in machine processible format. This provides accessibility for people who reach other user's knowledge and data stored in many places (Sacco and Passant, 2011). It is boundless and can be used many times.

2.5. Terminology

The following terminology shows various terms related to ontology that are used throughout this project.

Attribute: It is a property, feature, or characteristic of a class (Corcho et al., 2006). It provides additional information for a class. For example, 'Sample' is a class having attributes for identifying a specific sample, like Sample ID (numeric value), Sample Number (numeric value), and Sample Type etc. These attributes provide specific information about a class. Also, 'Rock' as a class has several attributes like grain shape, grain size, texture and other properties.

Bidirectional relationship: Two-way relationship between two nodes both from A to B and from B to A. For example, there are two relationships between 'Laboratory' and 'Sample'. It can be either 'Laboratory analyzes Sample' or 'Sample analyzedBy Laboratory'.

Class: It is a concept or term or thing organized in taxonomies (Corcho et al., 2006). All classes are subclasses of owl:Thing, which is top class. It may include individuals, instances of class. In geology domain, 'Mineral', 'Rock', 'Core', 'Geologist' can be classes. 'Geologist' can be a subclass of 'Employee' under the 'Thing'.

Domain: It is a first component of the relation or a subject in RDF triple sentences (Corcho et al., 2006). For example, 'Exploration Company drills Drillhole' in this sentence, first part of the relation, which is 'Exploration Company' is a domain of this triple.

Also, 'Domain' can is the specific field of the study under the consideration in the ontology, which is 'Mineral Exploration Ontology – MinExOnt' in this research.

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Edge or arc: It is a graph element or a line connecting nodes. It is shown in the schemas in the UML diagrams.

Instance (Individual): It is an element or individual in ontology. Then ontology can be populated with instances of classes and their attributes with values (Corcho et al., 2006). For example, if the mining site is a class and Safford Mining Site in Arizona can be an instance.

Namespace: It is a collection of URIs in which every resource name is locally unique (Hoekstra, 2009). Two different communities may have same thing but this conflict can be eliminated using unique URIs for each community. It also provides a way to qualify terms by associating them with URIs. For example, 'CoreSample' class under MinExOnt ontology is a term having namespace or URI like http://www.gsu.edu/ontologies/MinExOnt#CoreSample.

Node (Vertex): A record consisting of one or more fields that are linked to other nodes or vertices. (Corcho et al., 2006). All concepts, in other words 'classes' in the ontology are represented in nodes. Section 5.3.3 shows UML diagrams, including nodes.

Object: It is a part of RDF triple sentence (Subject-Predicate-Object) (Allemang and Hendler, 2008). 'Technican prepares Sample' is an example of triple sentence and 'Sample' is an object in this sentence.

Ontology: It is a clearly, openly described concepts or terms and their relations with a machine readable structure (Gruber, 1993). It is an explicit description of a specific topic or domain. Ontology is created in machine readable languages of RDF, XML and OWL.

Predicate: The identifier for the thing that specifies properties of the entities in the subjects (Allemang and Hendler, 2008). For example, in the triple sentence of 'Technican prepares Sample', 'prepares' represents a predicate.

Property: It is an attribute of instance and describes the concepts in ontology. It can be Object Property, making relations between instances of different classes to each other and connection resource to resource or Datatype Property, making relations between instances of classes and RDF literals and connection resource to datatype value (Allemang and Hendler, 2008).

Relation: Type of association between concepts of the domain. The ways in which classes and individuals can be related to one another (Hoekstra, 2009). For example, in the triple sentence of 'Technican prepares Sample', there is a relation between subject and object with the help of predicate.

Range: A concept or datatype object and a second argument of the relation (Corcho et al., 2006). For example, 'Exploration Company drills Drillhole' in this sentence, 'Drillhole' is a range of this triple.

RDF: It stands for Resource Description Framework and is a flexible way to design and represent metadata on the web (Beckett, 2004).

RDF Triple: The basic building block for RDF. (Hoekstra, 2009). All resources (subjects, predicates, or objects) on the Semantic Web are identified using unique Uniform Resource Identifiers (URIs). For example, 'Assay studiedBy ExplorationGeologist' is a RDF triple sentence in which 'Assay' is a subject, 'studiedBy' is a predicate and 'ExplorationGeologist' is a object of this RDF sentence.

Semantic Web: is a special form of ontology on the web and allows machines process the knowledge on world wide web, connect and interpret it to help humans for interpretation. It is also called as "web of data". This term is produced by Tim Berbers-Lee (http://en.wikipedia.org/wiki/Semantic_Web).

Subclass: A class that is derived from another class. For example, 'Sedimentary Rock' is a subclass of 'Rock'.

Subject: The identifier or first component of a RDF triple statement (Allemang and Hendler, 2008). For example, 'Technician prepares Sample' is an example of triple sentence and 'Technician' is a subject in this sentence.

Subsumption: ('is-a'), the relationship between classes and subclasses or generalization-specialization relation (Noy and McGuinness (2001). A subsumption is used to show a connection between class and subclass. For example, 'SurfaceSample' is a subclass of 'Sample' and the connection between them is generated with 'is-a' connection.

UML Diagram: Unified Modeling Language diagram, a structure diagram showing classes, their attributes and the relationships between classes (see section 5.3.3).

Unidirectional relationship: One way relationship between the two nodes either from A to B or from B to A. For example, the sentence of 'GravitySuvey hasMeasuredParameter Density' in the ontology has one relationship from 'GravitySurvey' to 'Density'.

CHAPTER 3: METHODOLOGY

Ontology design and development in semantic works must be supported by software engineering techniques (Brusa et al., 2006). These methods may be variable for different implementations and provide different results after each technique. This chapter gives a main idea about the methods used for design, development and visualization of ontology.

The Protégé editor, which is an ontology integrated development environment, is used to develop the ontology in this research. Protégé is free and open-source ontology editor used by system developers and domain experts to develop knowledge-based systems (Horridge et al., 2007). It was developed by Stanford Medical Informatics at the Stanford University School of Medicine (http://protege.stanford.edu/) with collaboration from several other agencies and is an ontology editor as well as an open source Java tool that provides an extensible architecture for the creation of customized knowledge-based applications.

Protégé provides loading and saving ontologies based on Semantic Web languages like OWL (Web Ontology Language) and RDF (Resource Description Framework), defining logical class characteristics, and editing and visualizing classes and properties. They are kind of computer languages representing specific knowledge and used to create ontologies. According to Berners-Lee, Semantic Web supported by World Wide Web Consortium (W3C) standard is a web of data managed by directly or indirectly machines (Berners-Lee and Kagal, 2008). It can be considered as a special form of ontology.

Ontology languages are formal languages that are used to construct ontologies in computer science and allow the knowledge encoding about specific domains. There are a number of languages for ontologies, both proprietary and standard-based. As a language for the World

Wide Web, XML is easy to parse, its syntax is well defined and it is human and machine

readable. They allow users to define their own tags and attributes, define data structures, extract

data from documents and develop applications which test the structural validity of XML

document. It also has a system schema that can be used to define input parameters and

constraints (Mello and Xu, 2006). Figure 3.1 shows an example of XML Schema diagram for

Aquifer (Babaie and Babaei, 2005). Aquifer example shows input parameters and their

properties as an XML Schema.
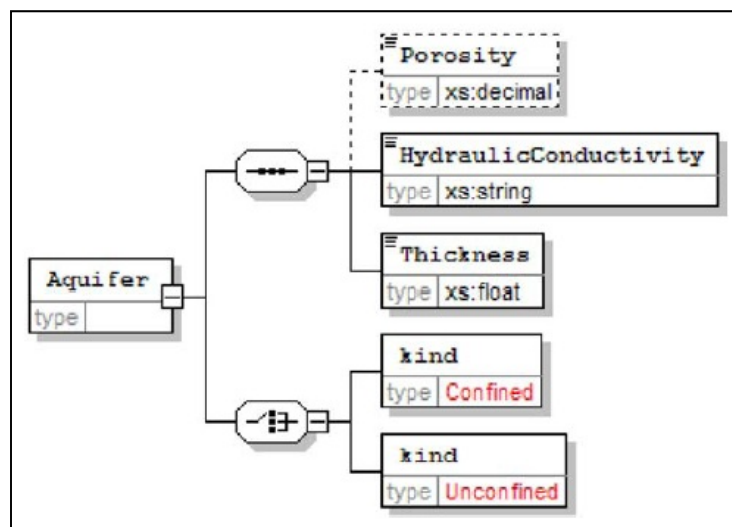
Figure 3.1. XML Schema diagram for Aquifer. Each connection shows input parameters and their properties with their types (decimal, string, float).

RDF data model is developed by the W3C for the creation of metadata describing

resources on the web (Beckett, 2004). According to Heflin and Hendler (2000), 'RDF has aim to

specify semantics for data based on the XML format in a standardized, interoperable manner and

to define a mechanism for describing resources that makes no assumption about a particular

application domain or the structure of a document containing the information'. It is written in

XML and designed to be read and understood by machines. The basic constituent of the RDF

data model is triple, which has a subject-predicate-object structure. Each part of the triple is

referred to (i.e., named) the URI (Uniform Resource Identifier), which provides universal

identifier to name these resources. The subject of the triple is a real-world object or abstract

concept. The object can be either an object or a literal or XML Schema data type such as string

and integer. The predicate is the property or relation that relates the subject and object resources.

Predicates define specific aspects, characteristics, attributes or relations used to describe a

resource. The object of the triple assigns a value for the property of triple's subject (resources)

(Klyne and Carroll, 2004). For example, the domain statement: '*Exploration geologist logs core*'

is given by the 'ExplorationGeologist logs Core' RDF triple, in which 'ExplorationGeologist' is

the subject, 'logs' is the predicate, and 'Core' is the object. The 'logs' property makes a

relationship between the subject, which is 'ExplorationGeologist' and object, which is 'Core'.

RDF is not enough to make a relationship among concepts. That's why RDF Schema has

an important role on that point. The RDFS data model allows defining the relationships between

properties and other entities like resources. It also provides main elements for ontology

development to create sharable, controlled and extensible vocabularies. These main elements for

classes in RDFS are *rdfs:class, rdfs:resource and rdf:property,* and for properties are

rdfs:domain, rdfs:range, rdf:type, rdfs subclassOf, rdfs:subPropertyOf, rdfs:label, rdfs:comment

and *rdfs:seeAlso, isDefinedBy.* (http://www.w3.org/TR/REC-rdf-syntax/)*.*

OWL, which stands for Web Ontology Language, is a language for Web knowledge

processing and mainly focused in this research. It is designed to process Web information and

easily read by machine. Moreover, it is a W3C standard, written in XML and built on the top of

RDF. RDF and OWL show some similarity, but OWL is more advanced and stronger. Since it is

written in XML, information in OWL can be transformed in different systems (W3C OWL

Working Group, 2009). Although XML, RDF and RDFs are the basic elements in Semantic

Web, OWL is more expressive because of its ability to describe knowledge of domain and to represent machine readable content on the Web languages (Deliiska, 2007).

Protégé 4.2 beta (new version of Protégé) software supported by OWL is used to develop the Mineral Exploration domain ontology in this thesis. In Protégé it is easy to create hierarchies of classes and properties, and make a relationship among them. Since Protégé is a widely used open source ontology development editor, it can be easily shared and extended with various contributions by other developers (http://protege.stanford.edu/).

As an IBM product, Rational Rhapsody provides collaborative design and development for systems engineers and software developers creating real-time or embedded systems and software based on UML (Unified Modeling Language) (Rational Rhapsody Developer). This proprietary modeling software is not open source for personal use. For this thesis, Microsoft Office Visio 2010, which supports UML, is used to create class diagrams of the ontology.

Knoodl, which is a Distributed Information Management System, is used to visualize the OWL classes and their properties instead of the graphs in Protégé. Combining semantic technologies with traditional information management technology, Knoodl contains tools for creating, managing, analyzing, and visualizing RDF/OWL descriptions, and features support collaboration in all stages of these activities (http://www.knoodl.com/).

In summary, Protégé editor is used to develop the domain ontology in OWL. The design of the ontology is done in Microsoft Visio applying UML diagrams of classes, properties and relationships in a hierarchical perspective. Knoodl-OntVis is used to visualize the class structure and relations. Different sources including Marjoribanks (1997) and Robert (2010) are used to get better knowledge along with the author's previous experience about the domain, which is about mineral exploration activity.

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CHAPTER 4: MINERAL EXPLORATION ACTIVITIES

Mineral exploration activity involves scientific process of locating valuable mineral, which has a commercial value. Mineral deposits of commercial value are called ore bodies. The goal of mineral exploration is to prove the existence of an ore body that can be mined at a profit Marjoribanks (1997).

Mineral exploration processes occur in stages, with early stages focusing on gathering surface data that are easier to acquire, and later stages focusing on gathering subsurface data, which requires drilling data, detailed geophysical survey data, and metallurgical analysis. These stages represent main steps for mineral exploration to get a commercial value of an ore body.

4.1. General steps taken during mineral exploration

Exploration activities play an important role in locating and defining a particular economically mineable mineral commodity (ore) in a mineral province. There are important factors in the economic recovery of minerals, which must be considered in order to get a valuable ore deposit. According to Evans (1995), the principal steps in the exploration for an ore body are the followings:

- ➢ mineral exploration: to discover ore body
- ➢ feasibility study: to prove its commercial viability
- ➢ mine development: establishment of the entire infrastructure
- ➢ mining: extraction of ore from the ground

➢ mineral processing (ore dressing): milling of the ore, separation of ore minerals from gangue, separation of the ore minerals into concentrates, e.g. copper concentrate; separation and refinement of industrial mineral products

➢ smelting: recovering metals from the mineral concentrates

➢ refining: purifying the metal

➢ marketing: shipping the product (or metal concentrate if not smelted and refined at the mine) to the buyer, e.g. custom smelter, manufacture

According to Marjoribanks (1997), prospect exploration involves advancing through a progressive series of definable exploration stages. These stages are defined and summarized relative to the stages defined by Evans (1995). Although the steps are defined and expressed with different terms and ways, they are generally almost the same. According to Marjoribanks (1997), the stages in prospecting exploration are:

➢ prospect generation

➢ target generation

➢ target drilling

➢ resource evaluation

➢ resource definition

➢ feasibility studies

➢ mining

Through these exploration stages, not all prospects may reach a mine. Most of them may be discarded at a certain stage. The continuity of exploration processes is shown in Figure 4.1.

The curves show how, for any given exploration program, the number of prospects decreases in an exponential way through the various exploration stages (Marjoribanks, 1997). It shows the importance of 'Mineral Exploration' in mining industry.
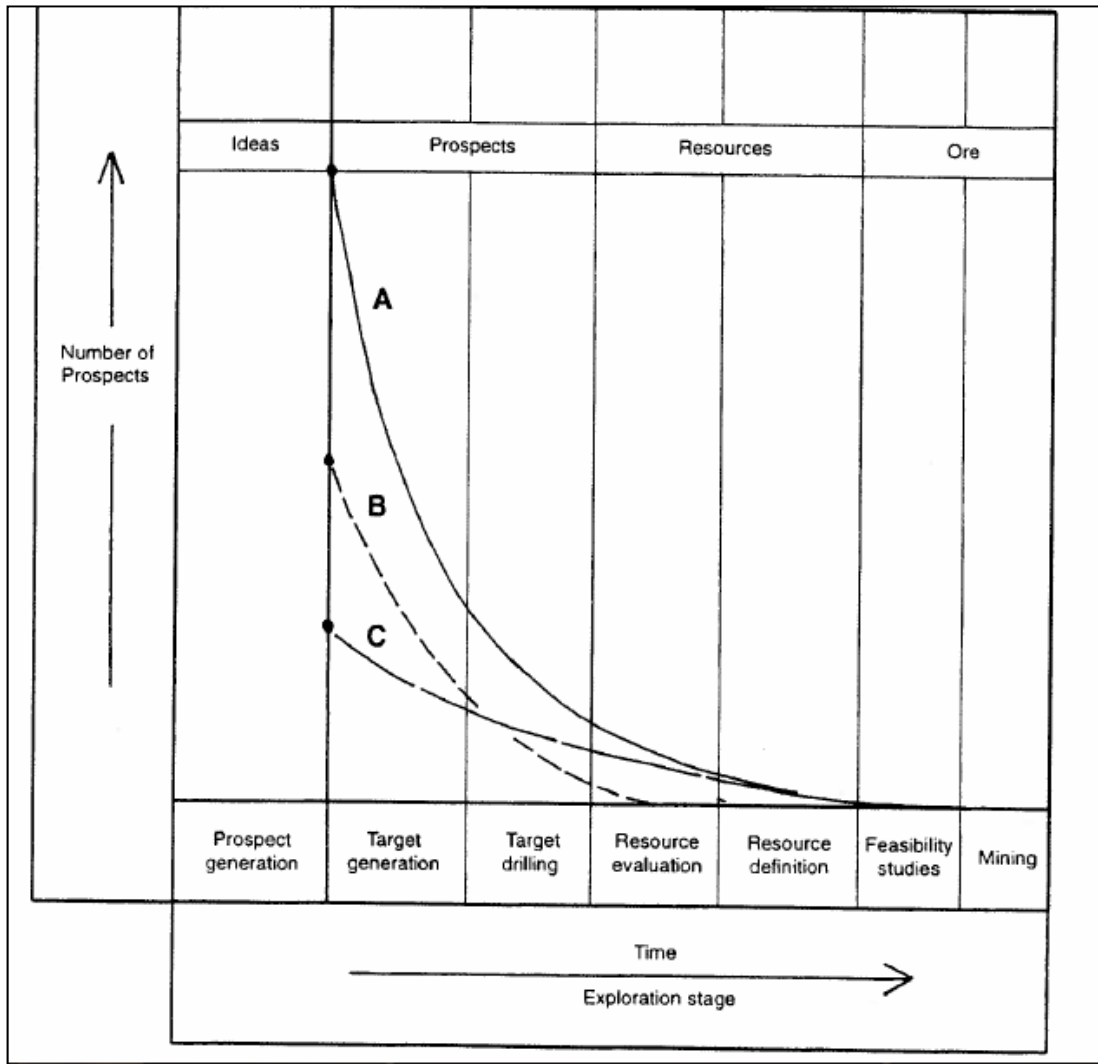
Figure 4.1. The exploration or prospect wastage curve (Marjoribanks, 1997)

4.2. Main steps taken during mineral exploration

Based on literature research and author's 5-year experience in a mining company, the process of mineral exploration can be subdivided into the following six main steps based on the references of Evans (1995), Marjoribanks (1997) and Moon et al. (2006):

- ➢ area selection
- ➢ target generation
- ➢ target drilling
- ➢ resource evaluation
- ➢ resource definition
- ➢ extraction or mining

4.2.1. Area selection

Area selection is the main step of mineral exploration activities to be worked on detailed and important to generate new targets for the mineral exploration prospects. Dealing with general literature survey and reviewing available digital data result in the selection of worthy areas. It also applies different techniques, like basin modeling, structural geology, geochronology, petrology, and geophysical and geochemical disciplines to make assumptions and find clues between the known ore deposits and their physical forms (Evans, 1995). This work provides geologist to see specific points from a general point of view. Selection of the most prospective area in a mineral field, geological region helps in making it not only possible to find ore deposits, but also to find them easily, cheaply and quickly. Therefore, deciding a target for the prospect

that the company is interested in is most significant stage in mineral exploration since it shows from where to be started to explore commercial value.

4.2.2. Target generation

Target generation involves certain stages, such as mapping, geochemical survey, geophysical survey, and remote sensing. Mapping includes development of the geological, topographical (base), geochemical, geophysical, and structural maps. Geological map focuses on identifying and mapping outcrops, describing mineralization and alteration zones, and making geological cross sections. In other words, it relies on the identification of rocks and minerals and the understanding of the environment in which they form. It aims to find what rock types occur at or close to the surface and how these rock types are related to each other, e.g., by defining their boundaries, ages, and structure. Topographical map, which is a base map, depicts the topographical features (contour, hill, stream, etc.). Geochemical map includes surface sample locations and results, including analyses of rock, silt, and soil samples. Geophysical map depicts the geology and results obtained from geophysical survey. Structural map shows the orientation data (strike, dip, type, etc.) of bedding planes, faults, folds, joints and other structural features (Marjoribanks, 1997). They are all gathered to be used for the interpretation in mineral exploration studies.

Geochemical survey is a kind of sampling method in mineral exploration and results in 'Assay' after laboratory works. Exploration geochemistry has evolved from its early origins using the chemistry of the environment surrounding a deposit in order to locate it (Evans, 1995). A wide variety of geological material including rock, sediment, soil, water can be chemically analyzed in laboratory for this survey. In mineral exploration studies, geochemical methods

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involve the geochemical analysis of geological materials, including rock, soil, and stream sediment or silt sediment. In addition to these surface samples, any materials obtained from drilling can be analyzed for the evaluation. The results of sampling may reveal patterns that point to the location of an ore deposit, which may be present either underground or at the surface (Marjoribanks, 1997). This survey provides physical results to be worked on for the further interpretation and is used for identifying geochemical anomalies, which are used for geochemical mapping.

Geophysical survey focuses on measuring physical characteristics (e.g., magnetism, density, conductivity) of rocks at or near the Earth's surface and uses surface methods to measure these properties to designate a potential ore body. The measured values are then used to compare with the values and models of known ore deposits (Marjoribanks, 1997). The results obtained from this survey are gathered together to make a geophysical anomaly maps, which is a good way for evaluation.

Remote Sensing is the collection of information about an object or area without being in physical contact with it. According to the Evans (1195), 'data gathering systems used in remote sensing are photographs obtained from manned space flights or airborne cameras, and electronic scanner or sensors such as multispectral scanners in satellites or airplanes and TV cameras, all of which record data digitally'. Aerial photography and satellites allow people to work with modern techniques. Aerial photography is used to sense the amount (quantity) of mineral in a particular area. The mineral exploration company collects information such as tracks, roads, fences, and habitation, as well as maps of outcrops, regolith, and vegetation cover across a region. Landsat image (satellite imagery) is used both for the visible light spectrum over mineral exploration

properties, but also spectra, which are beyond the visible (Marjoribanks, 1997). It is a modern, direct way of detecting minerals and their alteration.

4.2.3. Target drilling

Target drilling is the process whereby rigs or some operated tools are used to make boreholes to intercept an ore body. It can be done by contractors with more experienced operators. This method is used to obtain very detailed information about rock types, mineral content, and rock fabric, and the relationships between rock layers close to the surface and those at depth (Marjoribanks, 1997). Then, subsurface geology in a particular area is evaluated after the results are obtained. That indicates if the potentially economic resources are present or not.

In general, the purpose of drilling is to: determine the absence or presence of ore bodies, veins, and other type of mineral deposit, define the volume of and depth to the ore body; estimate reserve of ore body reservoir. Then, ore deposit is discovered before it is decided to be mined.

4.2.4. Resource evaluation

It is an evaluation of tonnage (volume) and grade (concentration or weight percent) of the ore body. The volume is determined by using drill data to outline the deposit in the subsurface, and by using geometric models to calculate the volume. The grade is the average concentration determined from numerous assays of drill samples. The purpose of the resource evaluation is to understand the possibility to expand the known size of the deposit and mineralization (Eggert, 2010). In this way, the economic standards of an ore body are obtained, which is needed for the next step. This step should give an information or idea about proceeding of mineral exploration activities. Resources at this work are determined during exploration and do not provide certain

results of grade and tonnage. In order to get an exact size, quality of the commercial mineral, 'reserve definition', which is next step of mineral exploration studies, is used.

4.2.5. Reserve definition

Reserve definition is important to transform a mineral resource into economic asset, which is an ore reserve and find the answer if it is valuable or not. 'Reserve' is more intensive, technical, and well characterized term with its exact quality and size relative to 'Resource'. Also, reserve estimation may be changed over time because of the assessments during and after the mining. The main purpose of this stage is the making decision on the techniques just before extraction as a result of the results. It includes technical, economic evaluation, geotechnical assessment, and engineering studies of the rocks surrounding the deposit to determine the potential parameters of proposed open pit or underground mining methods (Eggert, 2010). At the end of this process, a feasibility study is published, and the ore deposit is supposed either uneconomic or economic. At this stage, a decision is made whether to mine the mineral deposit from the surface, called as 'open-pit mining', or by tunneling, called as underground mining (Marjoribanks, 1997). Then, everything gets ready for mining to get a sustainable profit.

4.2.6. Extraction (Mining)

The main purpose of mineral exploration activities is to find valuable minerals to be mined or extract and to get a profitable and beneficial sale of mineral commodities. Extraction is the last stage of mineral exploration activities and mining engineers have a crucial role at that point to extract the commercial mineral from the ground. It also includes plan, design and construction of the facilities in which valuable mineral is processed (Eggert, 2010). Along with

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the decision whether the mineral is mined with surface or subsurface mining, more detailed studies are done at this stage. After mining, metallurgical processes start up for transformation of the valuable mineral into the product which can be sold.

CHAPTER 5: MINERAL EXPLORATION DOMAIN ONTOLOGY

5.1. Domain ontology workflow

Figure 5.1 represents the workflow for the Mineral Exploration domain ontology project. The study starts with the determination of the specific domain for ontology, which is in this study is Mineral Exploration. Since it is too broad subject, two well-known parts of this domain, which are Target Generation and Target Drilling are focused and discussed in more detail throughout this thesis. The next step is generating a naming style for the ontology, which is explained in section 5.3.1. It is used to define the terms of the RDF triple statements which are used in the next step. Writing a general description of the Mineral Exploration domain is another part of this study (see section 5.3.2). In this step, all rules about naming style are applied to the RDF sentences generating the whole ontology. The UML diagrams are then created in order to systematically show the relationships between the subject and object classes (see section 5.3.3). The last part of this thesis describes the ontology development process with Protégé, and visualization of the OWL ontology with Knoodl.

Determine scope/specific domain for ontology	'Mineral Exploration'
Specify well-known parts on the domain	'Target Generation' and 'Target Drilling'
Generate naming style for domain concept	See section 5.3.1
Write general description of the domain	See section 5.3.2
Create UML diagrams	See section 5.3.3
Ontology development with Protégé	See section 6
OWL Visualization with Knoodl - OntVis	See section 7

Figure 5.1. Domain ontology workflow for the thesis project.

5.2. The role of the Mineral Exploration domain

Economic geology is a field that helps us to understand Earth's natural resources, such as minerals, petroleum, and coal. Exploration geology, or mineral exploration, is a sub-discipline of economic geology. Figure 5.2 shows part of the Geology class hierarchy using OWLViz. According to this hierarchy, Hydrology, Structural Geology, Economic Geology, Environmental Geology and Engineering Geology are subclasses of Applied Geology, is a subclass of Geology. The subsumptive relationship between classes and subclasses is shown with an 'is-a' connector, which is a relation that points from a specialized class to the more general class. According to Noy and McGuinness (2001), a subclass represents a concept that represents a class which is a 'kind of' a supereclass above it in the hierarchy. For example, the Silicate subclass is a kind of the Mineral class. Mineral is the superclass of the Silicate class.
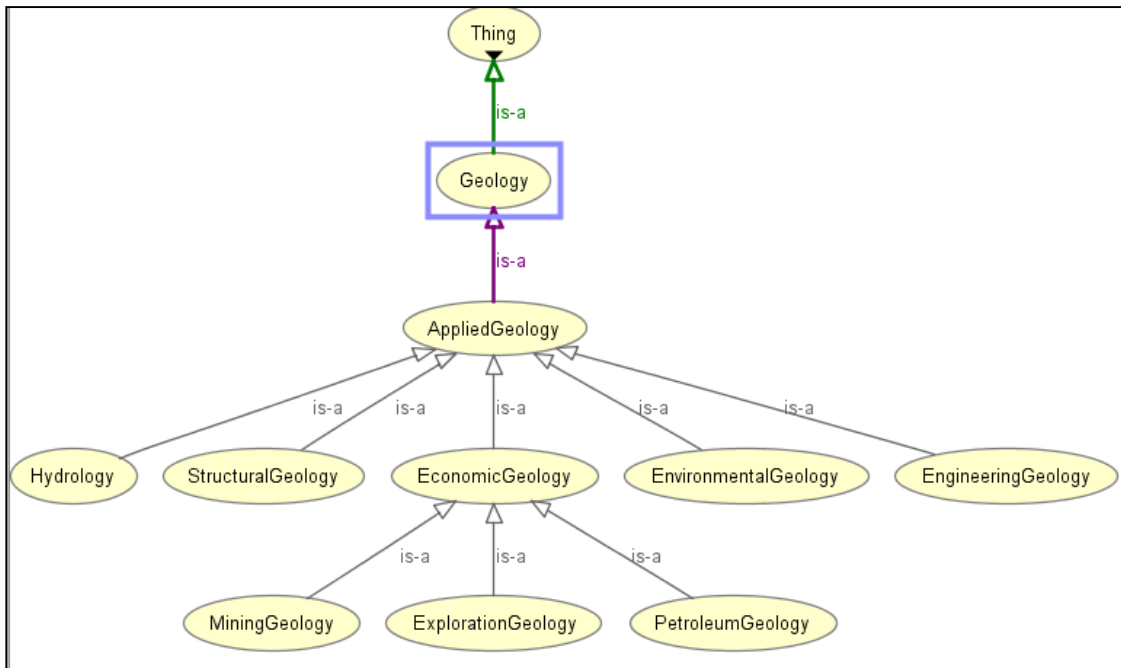
Figure 5.2. Visualization of 'Exploration Geology' as a subclass of 'Applied Geology' using OWLViz. The arrows (is-a), which are subsumption show generalization and specification relation between classes and subclasses represented within the ellipsoids

Figure 5.2 also shows the class hierarchy that represents the broad aspects of this project. The specific focus of this thesis project is on the Exploration Geology class, which will be modeled in the following sections. In the Protégé 4.2 beta editor, in which the ontology is built, the initial OWL project is given the following URI: http://www.semanticweb.org/ontologies/2011/10/ExplorationGeology.owl, which stands for Mineral Exploration ontology. All classes and subclasses of the MineralExploration ontology are defined under the owl:Thing, which is the superclass of everything.

Mineral Exploration is a broad field, and for the scope of this thesis project, only part of it was modeled, which includes the area selection, target generation, target drilling, resource evaluation, and resource definition stages. Figure 5.3 shows the OWLViz class hierarchy for the classes and subclasses of the MineralExplorationStage class.
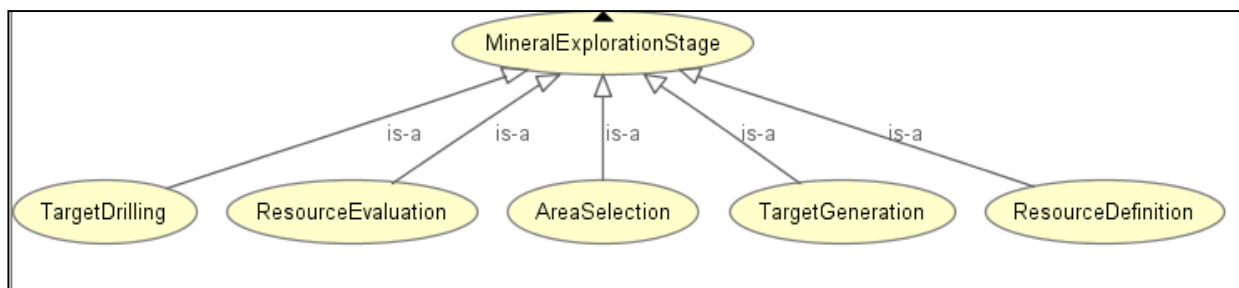
Figure 5.3. OWLViz class hierarchy showing the subclasses of the MineralExplorationStage class.

5.3. Mineral Exploration domain ontology

In this study, Mineral Exploration is the domain name for the ontology which is built in this thesis project. The Target generation and target drilling are the two stages which are defined in the ontology. These stages are carried out once a prospect has been identified or an area selection has been done.

5.3.1. Naming style for domain concepts

The rules for the naming style for the Mineral Exploration domain are given in Table 5.1.

Table 5.1. The naming style for domain concepts.

Triple parts	Type	Type	Font	Letter Style	Example
Subject	Class	Simple	Arial	first letter is in upper case	Employee
		Compound		upper CamelCase	ExplorationCompany
Predicate	Property	Simple	Arial	lower case	describes
		Compund		lower camelCase	hasPart, doneBy
Object	Class	Simple	Arial	first letter is in upper case	Employee
		Compound		upper CamelCase	ExplorationCompany
	Attribute	Simple	Arial-italic	lower case	*easting*
		Compound		lower camelCase	*holeID, startDate*

The subject part of the RDF statement is always a class, and can be either simple or compound. If it is simple, its first letter is only capitalized, e.g., Employee, Sample. If it is a compound class, it is given in the upper CamelCase style, in which the first letter of each word is written in the upper case, e.g., ExplorationCompany, TargetGeneration. The predicate is a property, and can be either simple or compound. If it is a simple name, it is given in the lower case style, e.g., describes, specifies. If it is a compound name, it is given in the lower

camelCase, in which the first letter of the first word is in the lower case but the beginning of all other words in the compound name are in the upper case, for example, hasPart, doneBy, hasEmployee. The object is either a class or an attribute (datatype) and can be either simple or compound. If the object is a simple class, it is given in Arial font and only its first letter is capitalized, e.g., Employee, Sample. If the object is a compound class, it is given in Arial font and upper CamelCase style, e.g., ExplorationCompany, TargetGeneration. If the object is a simple attribute, it is given in Arial-Italic font and lower case letter style, e.g., *easting, elevation.* If the object is a compound attribute, it is given in Arial-Italic font and lower camelCase letter style, e.g., *holeID, startDate.*

Each RDF triple statement is made up of a subject, predicate, and an object. Subject and object are resources, and predicate (property) connects these resources together. All these relationships will be described in more detail in the ontology development section. The following table shows some examples of the RDF triple statements of the ontology (Table 5.2).

Table 5.2. Examples for RDF triple statements of the MineralExploration ontology.

Subject	Predicate	Object
ExplorationGeologist	dealsWith	Mapping
SurfaceLithology	describes	Rock
ExplorationCompany	has	Employee
Employee	worksFor	ExplorationCompany
MineralExploration	performedBy	ExplorationCompany
Sample	sampledBy	ExplorationGeologist
Technician	prepares	CoreSamples

The relationship between subject and object can be either unidirectional or bidirectional. Table 5.3 gives examples regarding these kinds of relationships between subjects and objects. According to the Table 5.3, while number 1 and 2 represent bidirectional relationships, number 3 and 4 show unidirectional relationships.

Table 5.3. Examples of bidirectional (#1 - 2) and unidirectional properties (# 3 - 4).

#	Subject	Predicate	Object
1	ExplorationGeologist	logs	Core
	Core	loggedBy	ExplorationGeologist
2	Laboratory	analyzes	Sample
	Sample	analyzedBy	Laboratory
3	GravitySurvey	hasMeasuredParameter	Density
4	CoreSample	takenFrom	Core

5.3.2. *General description of the* **MineralExploration** *domain*

Mineral exploration is a process to get a valuable profit from a mine, or to take place as part of a strategy to locate and define a particular economically mineable mineral (Marjoribanks, 1997). According to the general point of view about mineral exploration, there are five steps to complete mineral exploration studies. In this section, activities in the mineral exploration domain are given in RDF triple statements. For example, MineralExploration has MineralExplorationStages, which are AreaSelection, TargetGeneration, TargetDrilling, ResourceEvaluation and ResourceDefinition. In a factored out fashion, the RDF triples of these facts are: MineralExploration (hasAreaSelection, hasTargetGeneration,

hasTargetDrilling, hasResoruceEvaluation, hasReserveDefinition). These are the main

steps taken during mineral exploration studies and each one has a detailed workflow. The

TargetGeneration also has several TargetGenerationStages which are Mapping,

GeochemicalSurvey, GeophysicalSurvey, and RemoteSensing. In short hand, these are

more formally stated as: TargetGeneration has (GeochemicalSurvey,

hasGeophysicalSurvey, hasMapping, hasRemoteSensing) (Figure 5.5). AreaSelection is

the first step which is taken to start and explore new targets with potential for valuable minerals.

Since this step is assumed to be already done for this project, it is not discussed in detail. More

information about this step is mentioned at Section 4.2.1.

MineralExploration is performedBy an ExplorationCompany, having specific

companyName, companyAddress, and *companyPhone*. ExplorationCompany has many

Employees, having *employeeID, employeeName, employeeStatus*, and *employeeSalary*

(or Employee worksFor ExplorationCompany). ExplorationGeologist, who is an Employee

in the company, dealsWith Mapping. (or Mapping is doneBy ExplorationGeologist). Map is

a productOf Mapping and has different kinds, which are GeologicalMap, BaseMap or

TopographicalMap, GeochemicalMap, StructuralMap, and GeophysicalMap.

GeologicalMap is important for identifying outcrops and describing lithology and

mineralization. It aims to find what rock types occur at or close to the surface and how these rock

types are related to each other, e.g., by defining their boundaries, age, and structure.

GeologicalMap has SurfaceLithology and SurfaceAlteration. SurfaceLithology and

DHLithology (DownholeLithology or SubSurfaceLithology) are Lithology which describes

Rock and is determinedBy ExplorationGeologist. Rock has types, which are IgneousRock,

SedimentaryRock and MetamorphicRock. SurfaceAlteration and DHAlteration

(DownholeAlteration) are Alteration and describe Mineralization. GeophysicalMap is utilizedFor GeophysicalSurvey. GeochemicalMap is usedFor GeochemicalSurvey. StructuralMap has GeologicalStructure, which can be BeddingPlane, Fault, Joint, or Fold. Each one has specific p*rojectID, easting, northing, type, strike,* and *dip* (Figure 5.6).

GeochemicalSurvey is a kind of sampling and used for finding geochemical anomalies, which are used in geochemical mapping. Geochemical methods involve the collection and geochemical analysis of geological materials, including rock, soil, and stream sediment (silt sediment). GeochemicalMap has SurfaceSample, which is a Sample (having specific *projectID* and *sampleType*), and can be RockSample, SoilSample, SiltSample (=StreamSample) and is sampledBy ExplorationGeologist, preparedBy Technician, and analyzedBy Laboratory, and then resultsIn (=leadsTo) Assay, studiedBy ExplorationGeologist. RockSample has specific *rSID, rSEasting, rSNorthing, rSSampler,* and *rSComment.* SoilSample has specific *sSID, sSEasting, sSNorthing, sSSampler*, and *sSComment.* SiltSample has specific s*tSID, stSEasting, stSNorthing, stSSampler, stSComment.* SurfaceAssay, which is an Assay (information about geochemical analyses) has specific *projectID, labID, sSampleID, sAssayID, sEasting, sNorthing, sAssay*, and *sResults* (for Au, Ag, Cu, Mo etc). SurfaceEvaluation needs SurfaceAssay to evaluate surface geochemical data (Figure 5.7).

Geophysicist, who is an Employee, manages GeophysicalSurvey of TargetGeneration under MineralExplorationStages (GeophysicalSurvey is managedBy Geophysicist). This survey is important for interpretation and must be utilizedFor GeophysicalMap to make them more understandable and clear. GravitySurvey,

MagneticSurvey, ElectricalSurvey, ElectromagneticSurvey, and RadiometricSurveys are

types of GeophysicalSurvey. Density is a MeasuredParameter for GravitySurvey

(GravitySurvey has MeasuredParameter Density) and Gravimeter is a tool to measure a

Density (GravitySurvey hasTool Gravimeter). MagneticSusceptibility and Remanence

are MeasuredParameter for MagneticSurvey (MagneticSurvey has MeasuredParameter

MagneticSusceptibility) and MagneticSurvey hasTool Magnetometer. ResistivitySurvey,

InducedPolarizationSurvey (IPSurvey), and SelfPotentialSurvey (SPSurvey) are types of

ElectricalSurvey. Resistivity and Chargeability are MeasuredParameters for

ElectricalSurvey (ElectricalSurvey has measuredParameter Resistivity and

Chargeability). Conductivity is a MeasuredParameter of ElectromagneticSurvey.

(ElectromagneticSurvey has MeasuredParameter Conductivity). Radiation is a

MeasuredParameter of RadiometricSurvey (RadiometricSurvey

hasMeasuredParameter Radiation) (Figure 5.8).

RemoteSensing as a part of TargetGeneration of MineralExplorationStages,

having either AerialPhotography or SatelliteImagery, and is evaluatedBy

ExplorationGeologist. It is the collection of information about an object or area without being

in physical contact with it. It is also used for AreaSelection step at the beginning of the mineral

exploration studies (Figure 5.9).

TargetDrilling is used to obtain very detailed information about rock types, mineral

content, and rock fabric, and the relationships between rock layers close to the surface and those

at depth. It has two types: DiamondDrilling and RCDrilling. ExplorationCompany drills

Drillhole (or Borehole or Collar). Each Drillhole has specific *holeID, projectID, easting,*

northing, latitude, longitude, elevation (RL), azimuth, dip, depth, startDate, endDate, and DrillType. Drillhole has DHSample (DownholeSample), which is a Sample and can be either ChipSample or CoreSample. Each DHSample has *holeID, projectID, coreID, dHSampleID, dHSFrom and dHSTo*. ExplorationGeologist samples Sample. CoreSample which is takenFrom a Core is sampledBy ExplorationGeologist. Core, having specific *holeID, projectID, coreID, coreFrom, coreTo*, and *coreSampler,* is also loggedBy ExplorationGeologist (ExplorationGeologist logs Core). Then, Technician prepares CoreSample which is analyzedBy Laboratory. Each Laboratory has specific *labID, labName, labLocation, labSampleID*, and *labSampleType*. The Laboratory analyzes DHSample (CoreSample or ChipSample), which resultsIn DHAssay (DHGeochemicalResults or Analyzes) and DHAssay is studiedBy ExplorationGeologist. Each DHAssay has also specific *holeID, projectID, labID, dHSampleID*, and results for Au, Ag, Cu, Mo etc. DHSample also leadsTo DHAlteration and DHLithology. DHAlteration has specific *holeID, projectID, coreID, altFrom, altTo, altName, and altCode*. DHLithology has specific *holeID, projectID, coreID, lithFrom, lithTo, lithName, and lithCode.* DHLithology describes a Rock and Mineral. Each Rock has *rockName and rockType*. Each Mineral has *mineralName and mineralType*. IgneousRock, SedimentaryRock and MetamorphicRock are Rock (Figure 5.10).

SubSurfaceEvaluation needs DHAssay (SubSurfaceAssay), DHLithology, and DHAlteration. SurfaceEvaluation needs SurfaceAssay, SurfaceLithology, SurfaceAlteration, and Map.

ExplorationGeologist works on Drillhole, DHAssay, DHLithology, and DHAlteration. It means that ExplorationGeologist investigates data by plotting, doing statistics, making diagrams, and interpreting the results, which are used to find information about subsurface ore body.

5.3.3. UML diagrams for MineralExploration domain

In order to design the general information about MineralExploration domain, UML diagrams are created to explain all classes and relationships among themselves comprehensively. The statements described in the previous section are visualized in the following UML class diagrams and their relationships (associations).

Figure 5.4 shows all the class hierarchy in the MineralExploration domain without naming the relationships, which makes it difficult to understand the type of the relationship among them. The relationships are therefore given for smaller parts of the hierarchy in other diagrams such as Figures 5.5 Figure 5.5 through 5.10. Each figure is also described in section 5.3.2. Figure 5.6, Figure 5.7, Figure 5.8, Figure 5.9, and Figure 5.10 have explanations about the legend, and provide information about the connections.
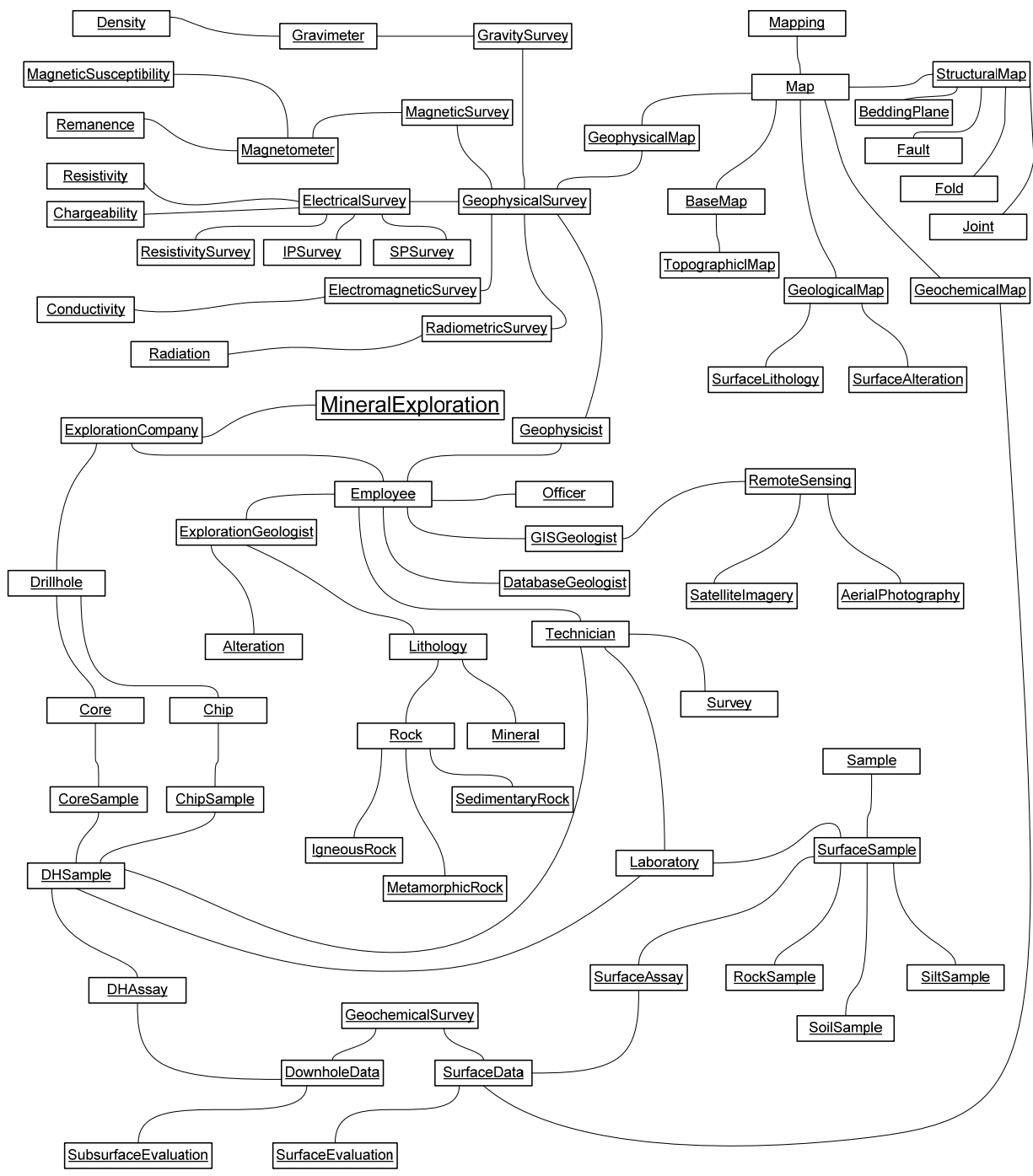
Figure 5.4. Class hierarchy in the MineralExploraion domain. Each box represents a class, and the edge or arc between two classes shows the relationship between the classes.
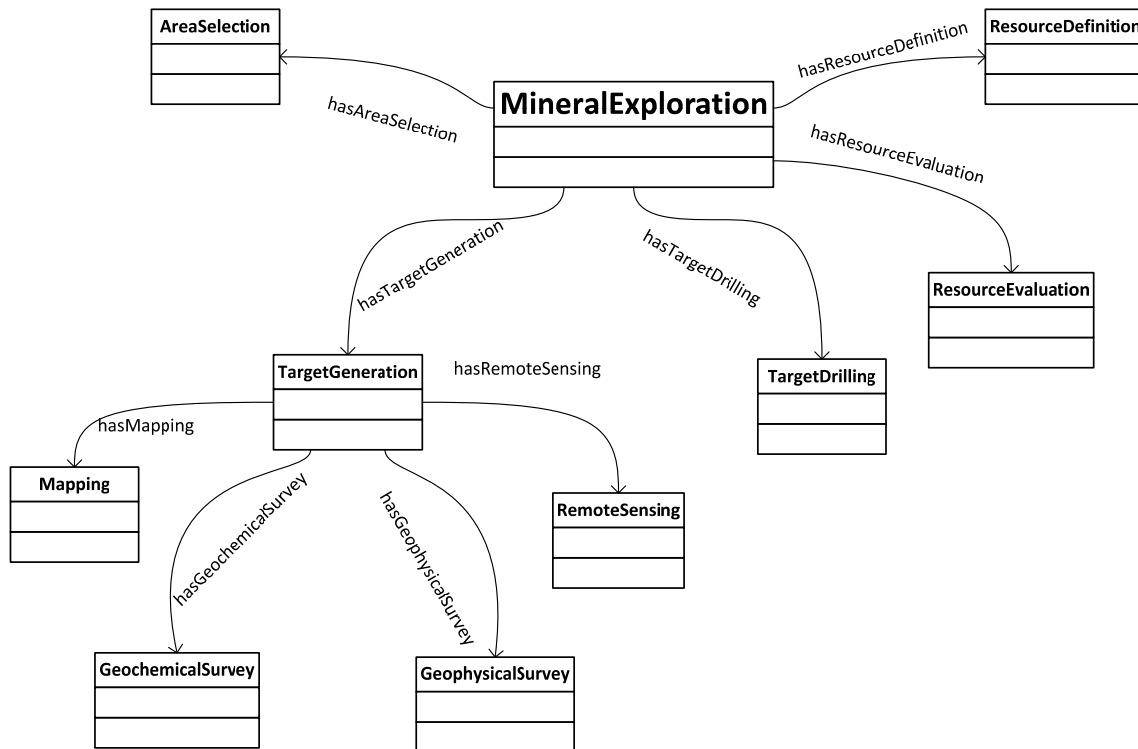
Figure 5.5. Partitive (meronomic) hierarchy in the MineralExploration domain. Each box is a class is related to the MineralExploration class. The edges or arcs without arrow are bidirectional relations. The label, which is closer to the node, is used as a property for the RDF triple, e.g., hasTargetDrilling connector, which is subproperty of hasMineralExplorationStages is closer to the MineralExploration class than the TargetDrilling class. The triple is therefore read as 'MineralExploration hasTargetDrilling TargetDrilling'.
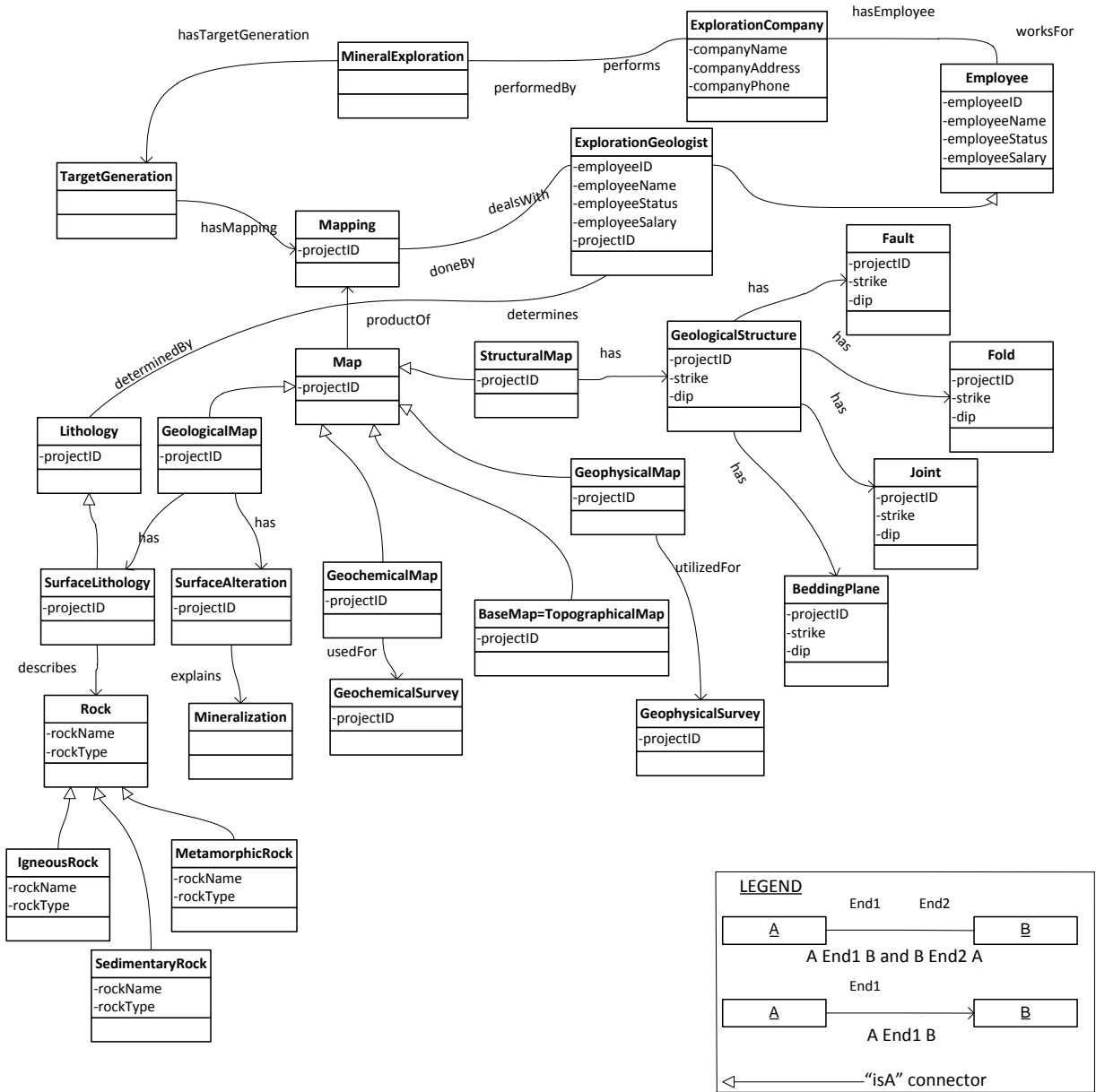
Figure 5.6. UML diagram showing the Mapping as a part of TargetGeneration class. The rectangle labeled as A or B in the legend is a node (vertex) and represents a class. The labels End1 and End2 on the line connecting A to B, in the legend, represent properties. The relationships between the two nodes are shown with an edge or arc. Bidirectional properties (arcs) do not have an arrow. The label, which is closer to the node, is used as a property for the RDF triple, for example, if End1 is closer to A than B, the sentence is read as 'A End1 B'. Unidirectional relations have a one-way arrow. The subsumptive 'isA' connector relates a subclass to its superclass, and is indicated with an open arrow head that points to the superclass. If the direction of this connector starts with node A through node B, it is read as 'A is a B' and means A is a subclass of B. Each class has a set of attributes under the class name.

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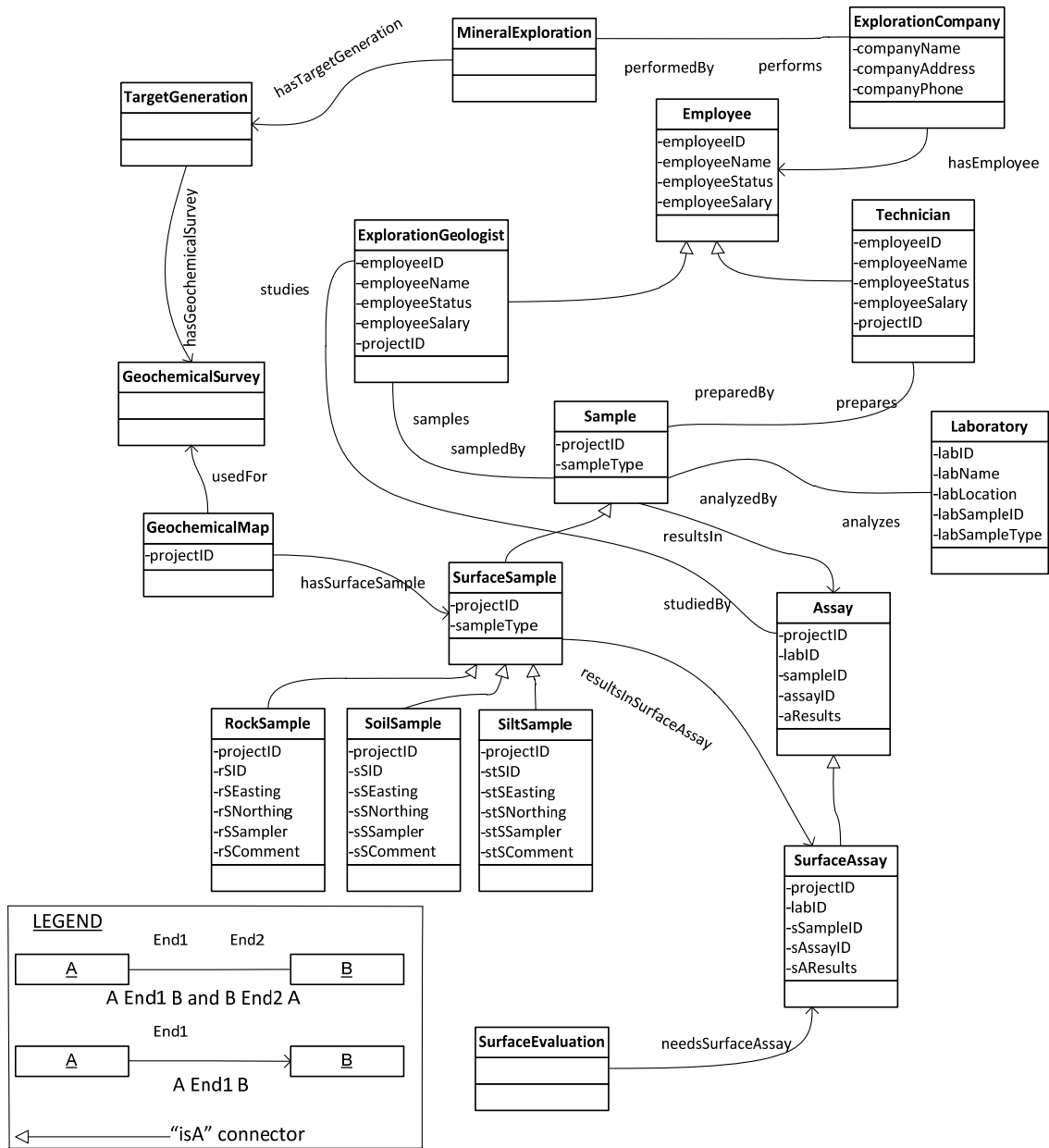
Figure 5.7. UML diagram for GeochemicalSurvey as a part of TargetGeneration. See Figure 5.6 for the explanation of the symbols in the legend.
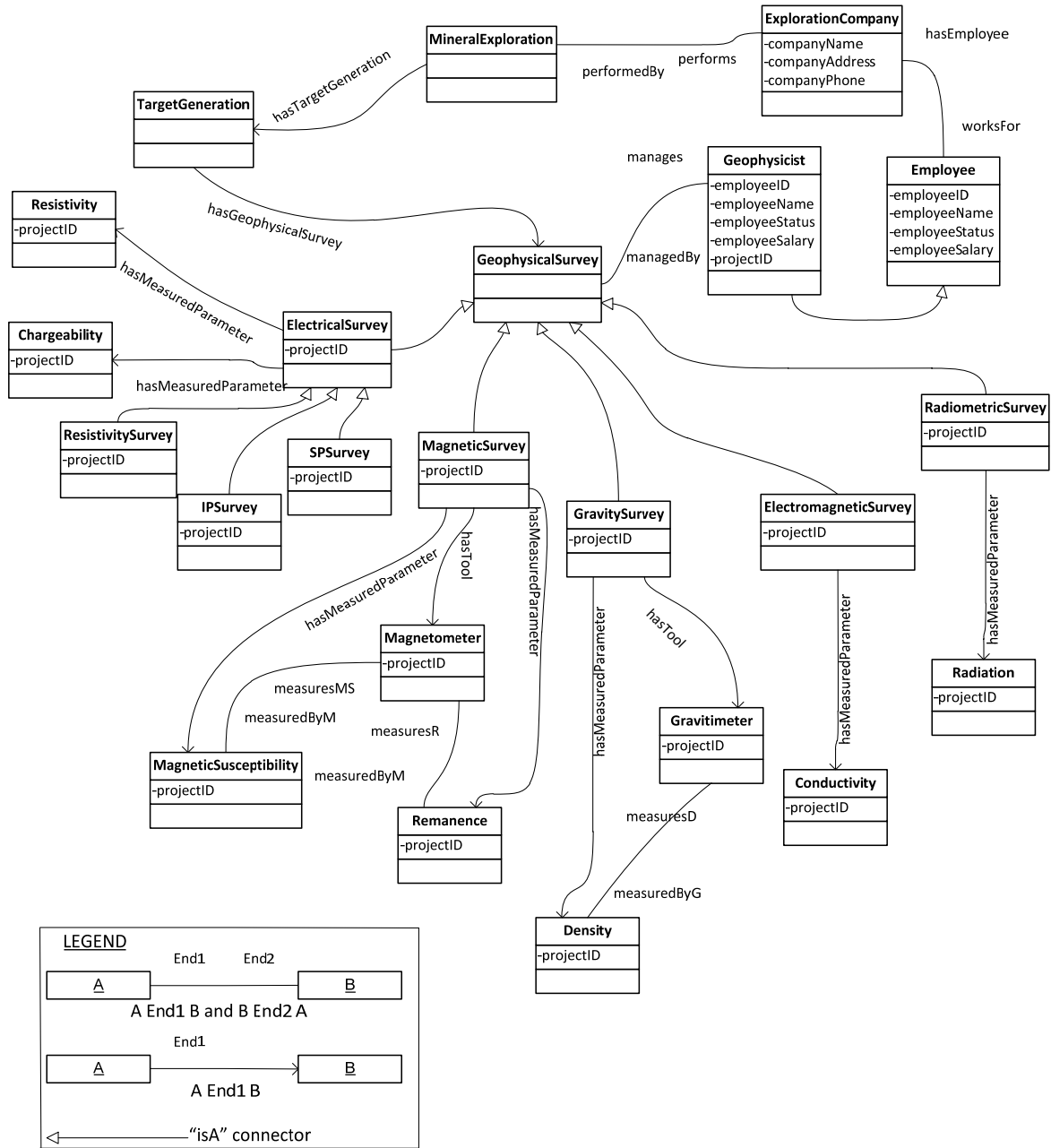
Figure 5.8. UML diagram for GeophysicalSurvey as a part of TargetGeneration. See Figure 5.6 for the explanation of the symbols in the legend.
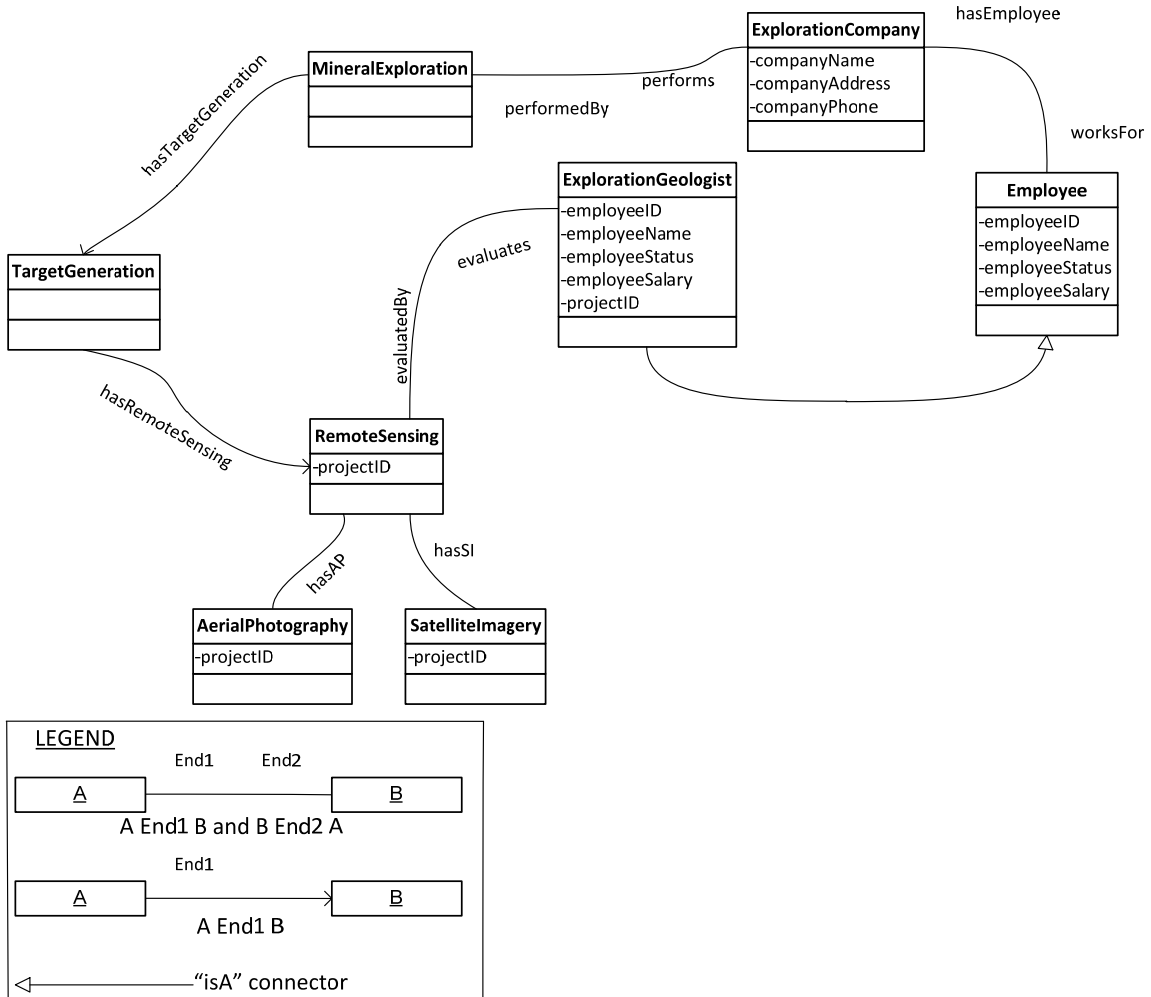
Figure 5.9. UML diagram for RemoteSensing as a part of TargetGeneration. See Figure 5.6 for the explanation of the symbols in the legend.
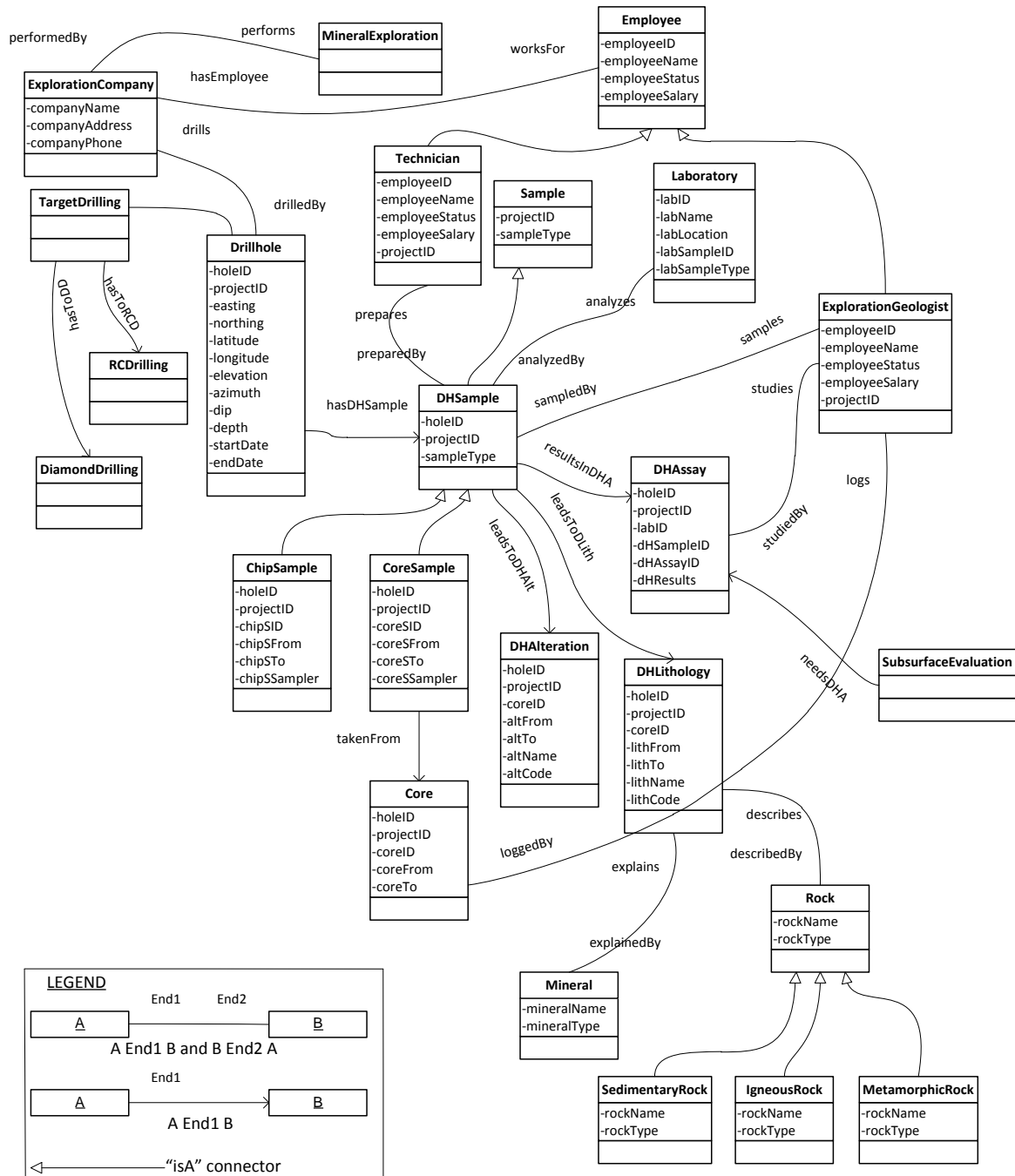
Figure 5.10. UML diagram for TargetDrilling as a part of MineralExploration. See Figure 5.6 for the explanation of the symbols in the legend.

CHAPTER 6: ONTOLOGY DEVELOPMENT WITH PROTÉGÉ

This section describes the next stage of the domain ontology workflow, i.e., ontology development with Protégé, which comes after the UML diagrams are completed as defined in the previous chapter (Figure 5.1). During this stage, the semantics of the classes and properties are defined in OWL code. Visualization of the ontology is done with Knoodl, which is discussed in Chapter 7 (OWL Visualization with Knoodl-OntVis).

Information about Protégé ontology editor can be found in Chapter 3 (Methodology). The user guide for Protégé (Horridge, 2011) provides a general background about a software usage.

6.1. Building the Mineral Exploration Ontology

Protégé 4.2 beta, which is the last version of the software, is used to develop the Mineral Exploration domain ontology. It is downloaded from the Protégé website at: http://protege.stanford.edu/download/protege/4.2/installanywhere/Web_Installers/. The next step, after Protégé 4.2 beta is set up, is to create a new OWL ontology name in Protégé. The name of the ontology for this study is 'MinExOnt', which stands for 'Mineral Exploration Ontology'. The active Ontology tab, which is the first screen when the ontology starts up, provides information about the ontology to be specified. This tab in Protégé has several main parts which include Ontology IRI and Ontology Version IRI. Ontology IRI (Internationalized Resource Identifiers - a component of URI) should be used in order to identify the domain ontology and specify the location where the ontology is stored. Ontology Version IRI is used to identify the version of the ontology. Ontology IRI: http://www.gsu.edu/ontologies/MinExOnt and Ontology

Version IRI: http://www.gsu.edu/ontologies/MinExOnt/1.0 were selected for this project. The

screen shot of the Active Ontology tab is shown in Figure 6.1.
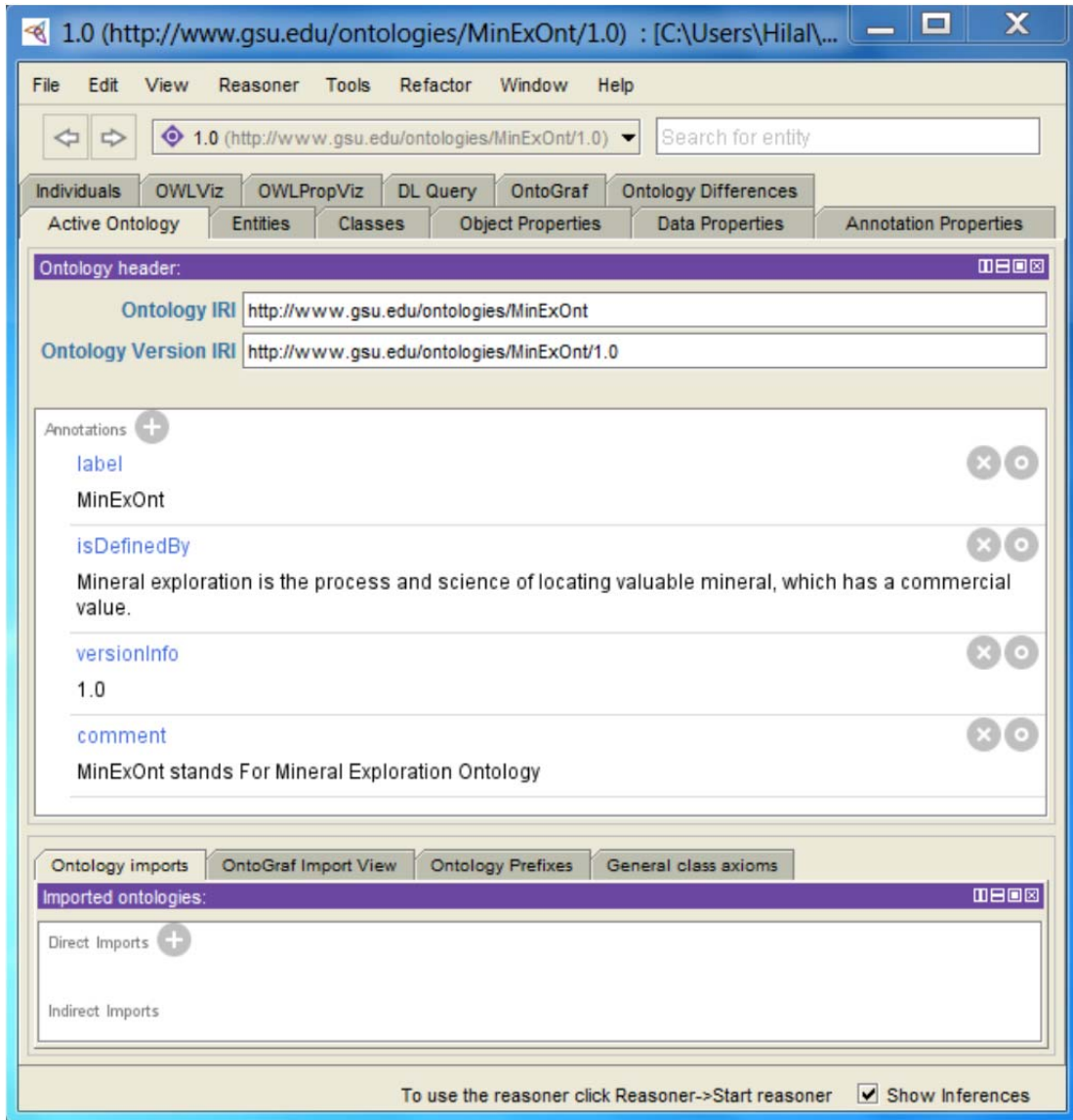
Figure 6.1. Screenshot of the 'Active Ontology' tab in Protégé to create ontology name and its annotations.

Ontology annotations are used to add detailed information about the ontology. After

clicking the 'annotations' button just below the ontology header, the 'Create Annotation'

window appears. The annotations are listed as 'backwardCompatibleWith', 'comment',

'deprecated', 'incompatibleWith', 'isDefinedBy', 'label', 'priorVersion', 'seeAlso',

'versionInfo'. In order to give information for each category, the box under the 'Value' in

Figure 6.2 can be filled. Some of the annotations, which give a general definition for this domain

ontology, such as ontology version information, comments, and label were used for the

MinExOnt ontology (Figure 6.2).
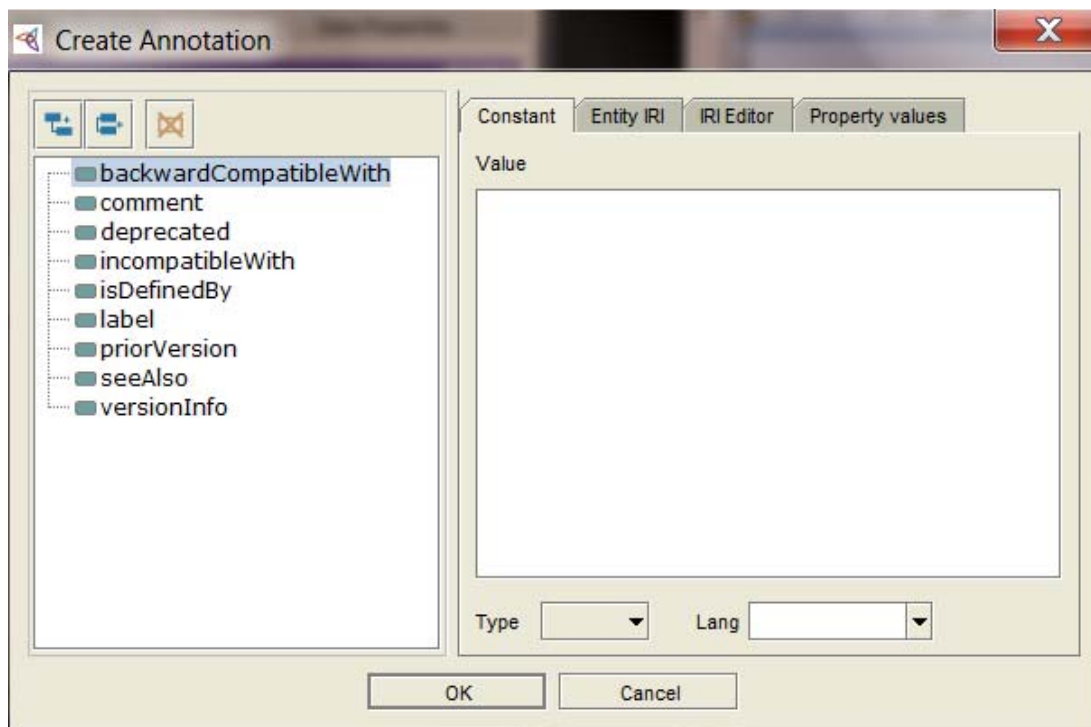
Figure 6.2. Screenshot of ontology annotations in Protégé to add extra information about the ontology.

6.2. Classes

The first and main component of an ontology is the set of classes that define all the concepts in the domain. All the terms defined in the UML class diagrams (Section 5.3.3) are added and named under the 'Class hierarchy' below the 'Classes' tab as shown in Figure 6.3. The icons just below the 'Class hierarchy' are used for adding subclass, sibling class and deleting class respectively.
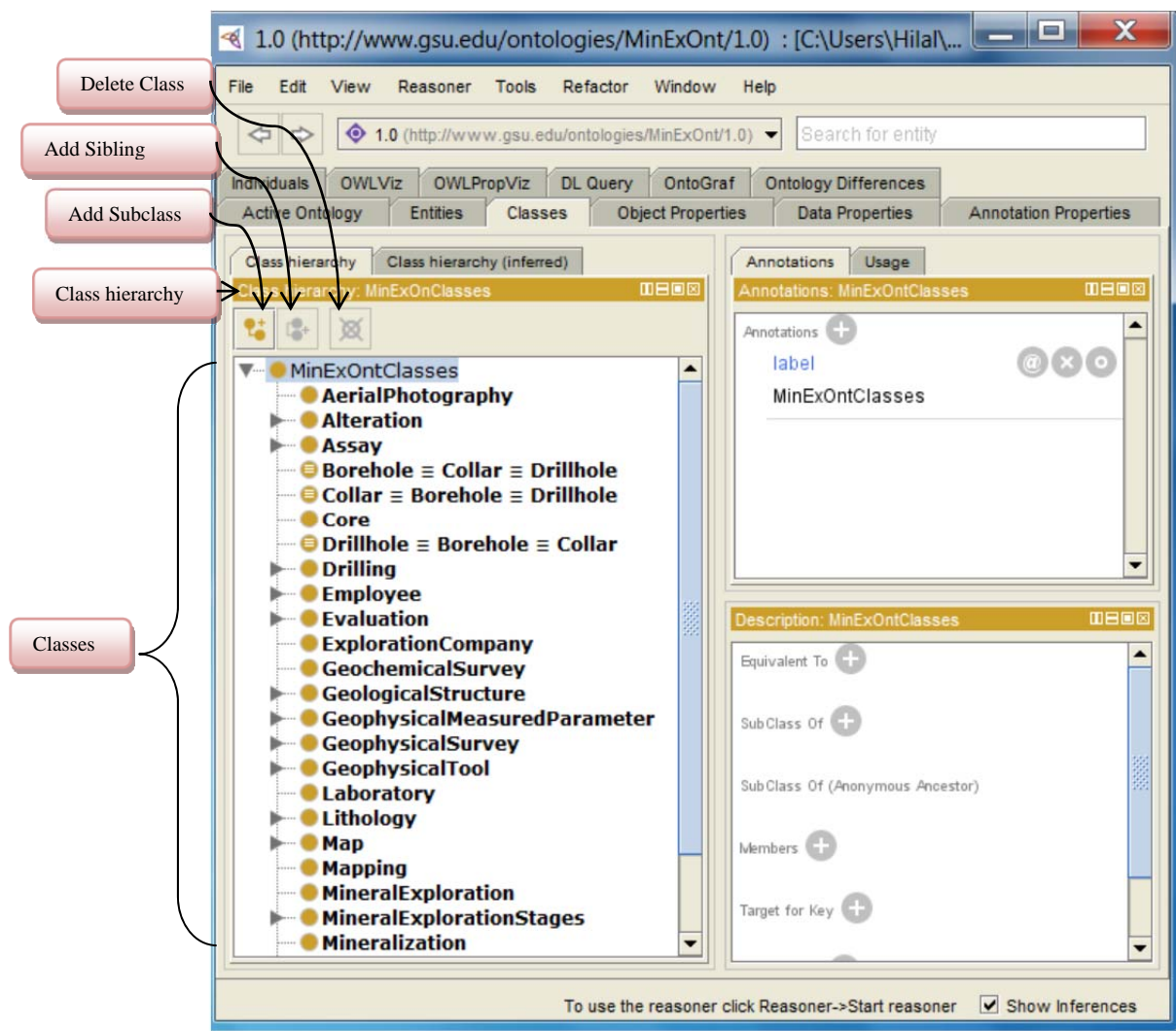
Figure 6.3. Screenshot of the 'Classes' tab in Protégé to add and edit classes.

The 'Thing' class under 'Class Hierarchy' is a superclass for all classes and a class representing the set containing all individuals. Each class added to this part is a subclass of a 'Thing'. 'Thing' can be changed with a different name using label annotation under the 'Annotations' tab. In this project, 'Thing' is replaced with 'MinExOntClasses' as shown in Figure 6.4
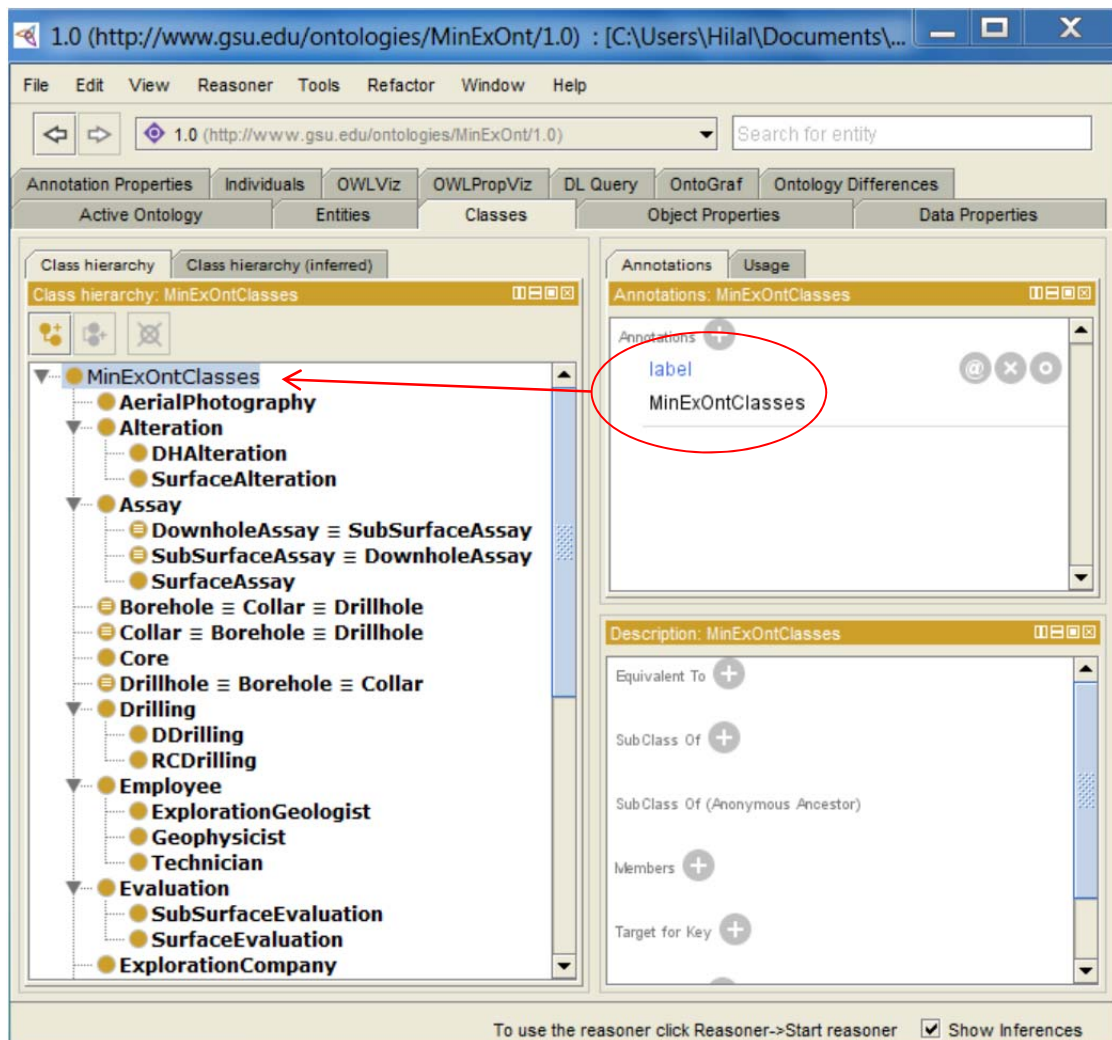
Figure 6.4. Screenshot of the 'Classes' tab in Protégé, showing the 'MinExOntClasses' as the topmost superclass instead of the 'Thing' class.

Ontology contains many classes and their various subclasses, which are built in a hierarchy, which is also known as taxonomy. The classes are also interpreted as sets that contain individuals. Although the individuals are not discussed in this study, the subclasses and superclasses are used, as shown in Figure 6.5. For instance, Map is a class and has six subclasses, which are BaseMap, GeologicalMap, GeochemicalMap, GeophysicalMap, StructuralMap and TopographicMap. In order to assign these subclasses under the Map class, 'Add Subclass' icon is used and each subclass is added separately under the Map class (Figure 6.3 and 6.5).
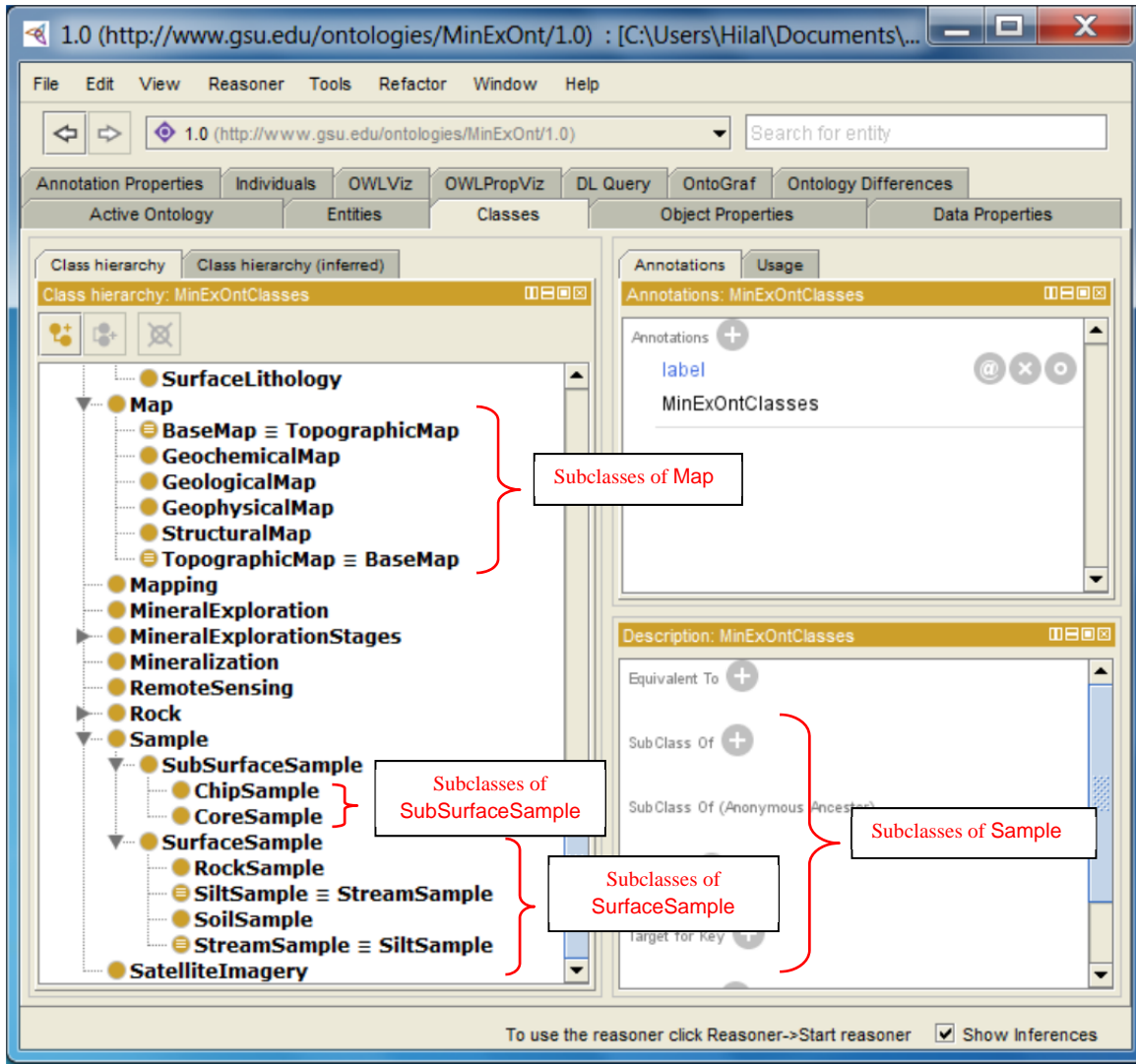
Figure 6.5. Screenshot of the 'Classes' tab in Protégé showing the Map class and its subclasses.

All the subclasses are defined with the same procedure. For example, IgneousRock, MetamorphicRock and SedimentaryRock are subclasses of a Rock. The hierarchical view of classes in Protégé allows us to visualize the class hierarchy. As it is seen in Figure 6.5, while SubSurfaceSample and SurfaceSample are subclasses of the Sample class, they have their own different subclasses. RockSample, SiltSample and SoilSample are subclasses of a SurfaceSample, which is a subclass of a Sample. ChipSample and CoreSample are

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subclasses of a SubSurfaceSample, which is also a subclass of the Sample class. This way, the hierarchy among classes is built following the relationships defined in the UML diagrams.

The left side of the window on the 'Classes' tab shows the domain and range for the object properties under the 'Object Properties' tab. The top right side of this window has 'Annotations', which is the default for all concepts in the ontology and same as the one mentioned for 'Active Ontology' tab. The 'label' annotation for all classes and properties, and the 'comment' annotation for some of the classes are added as annotations (Figure 6.6). The reason why 'label' are added for all of the classes will be mentioned in the following chapter about OWL Visualization with Knoodl.

Figure 6.6 shows how to add extra information to a class using the 'Annotation' tab. In this figure, Rock, which is one of the classes under the 'Thing' class, is used to explain the 'Annotation' list. Different information can be added and edited later. In the following example, extra information about a Rock is added to the 'comment' box, for example: '*Rock is a naturally occurring solid aggregate of minerals*'.
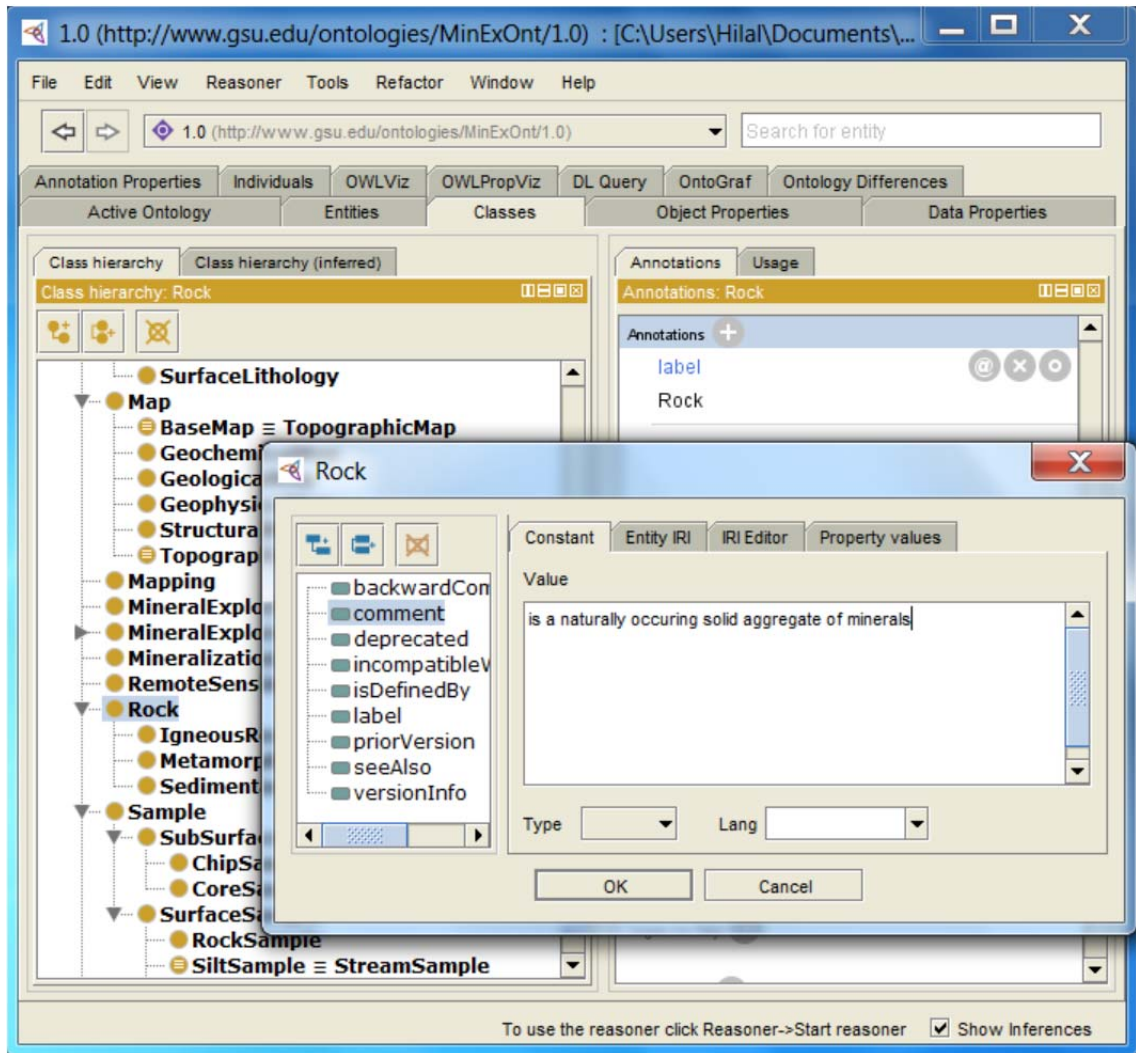
Figure 6.6. Screenshot of 'Annotation' in Protégé, showing the Rock class and its annotations such as 'label' and ' comment'.

The 'Description' tab, located at the bottom right side corner of the window, has several properties, including 'Equivalent To', 'SubClass Of', 'SubClass Of (Anonymous Ancestor)', 'Members', 'Target for Key', 'Disjoint with'. The plus icon next to each description can be used to add description for each of them. For instance, 'BaseMap' class is set to be equivalent to the TopographicMap' class, using the 'Equivalent To' description (Figure 6.7). Since BaseMap is an active class in the 'Class Hierarchy' on the left, everything under 'Description' is related to

this active class. In addition to the 'Equivalent To' description, 'SubClass Of' can be used automatically since it is determined with the help of the 'Class Hierarchy' tab. Instead of using 'Add Subclass' button under 'Class hierarchy', the 'Equivalent To' under description part can be used in order to add subclasses.
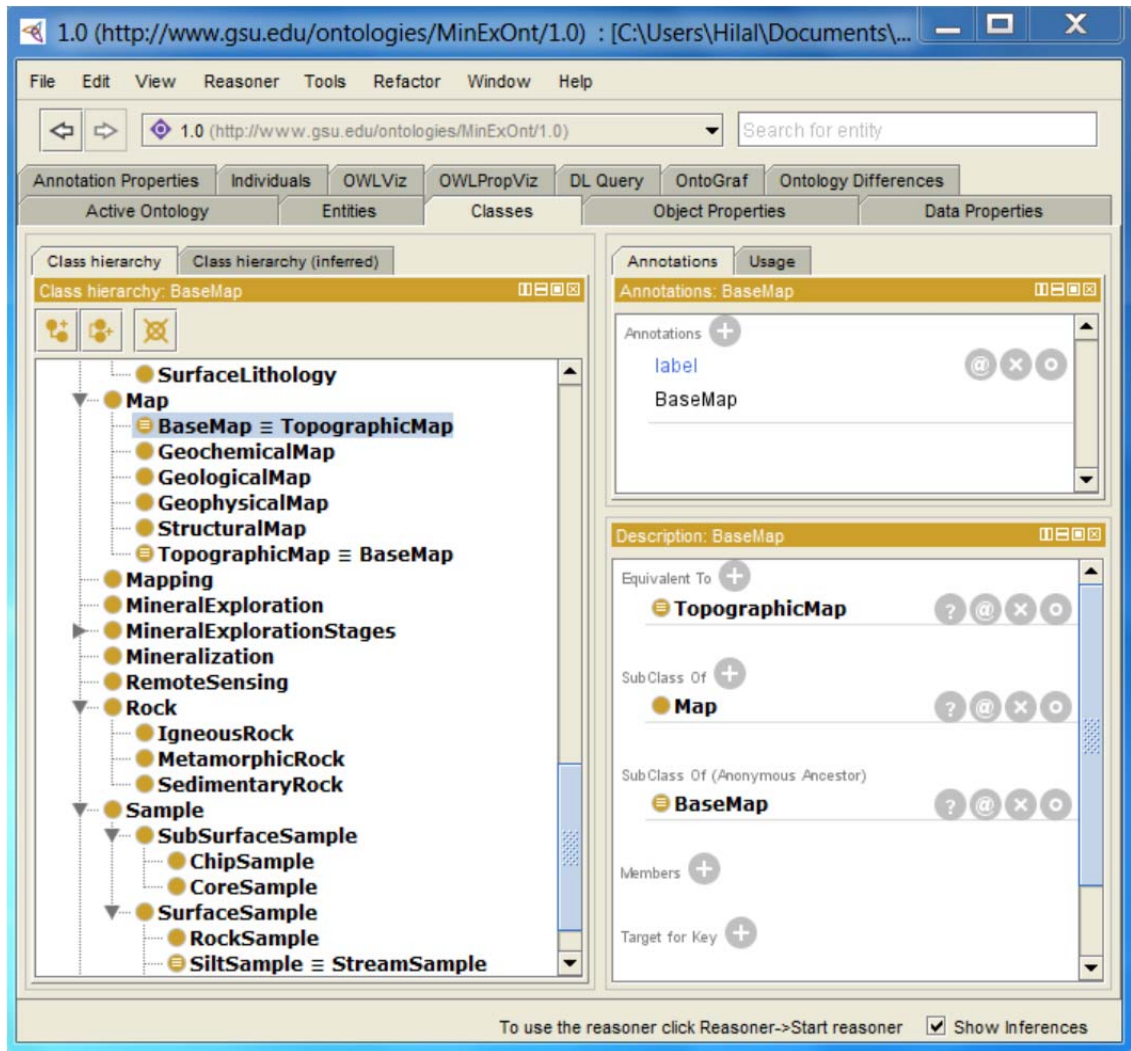
Figure 6.7. Screenshot of the 'Classes' tab in Protégé showing the BaseMap and TopographicMap classes as equivalent.

The taxonomy (class hierarchy) for 'MinExOnt' ontology is shown in Figure 6.8, which allows us to visualize the whole ontology which includes around 85 classes. Since the list of the classes is so long, they are separated into four segments as it is shown in Figure 6.8. All classes in the MinExOnt ontology are defined directly in this project, and existing ontologies from other sources are not imported into this project.
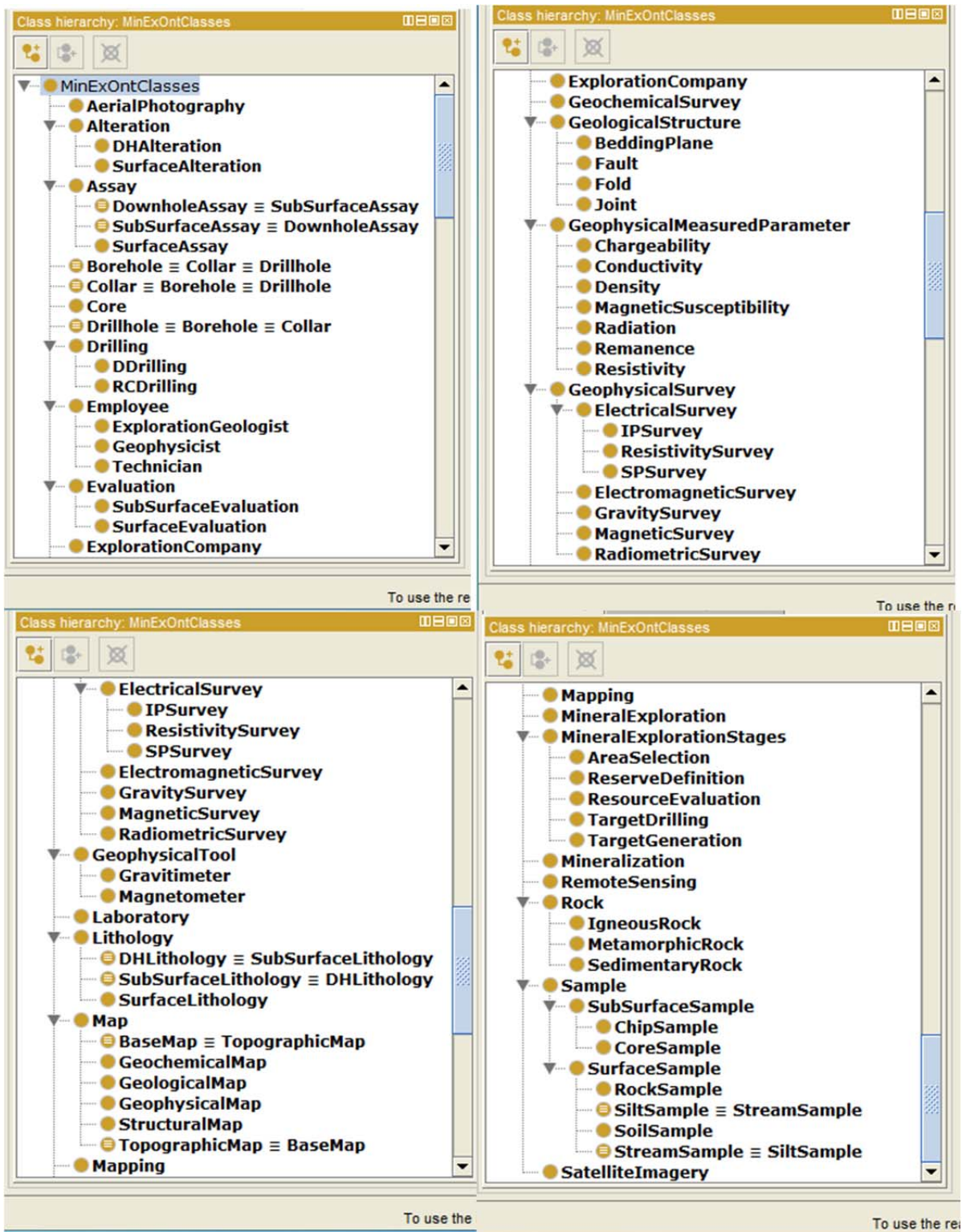
Figure 6.8. Screenshot of the MinExOnt class taxonomy in Protégé showing 'Class Hierarchy' and the list of classes in the MinExOnt Ontology.

6.3. Object properties

Although there are two major types of properties (datatype and object properties) in OWL, only object properties are used in this study. Object properties represent the relations among classes. In other words, they are the relationships between two classes or two individuals. Protégé has the 'Object Properties' tab just next to the 'Classes' tab. The procedure for adding a sub-property and sibling property and deleting a property is almost similar to that mentioned for the 'Classes' tab. The view of this tab is shown in Figure 6.9.
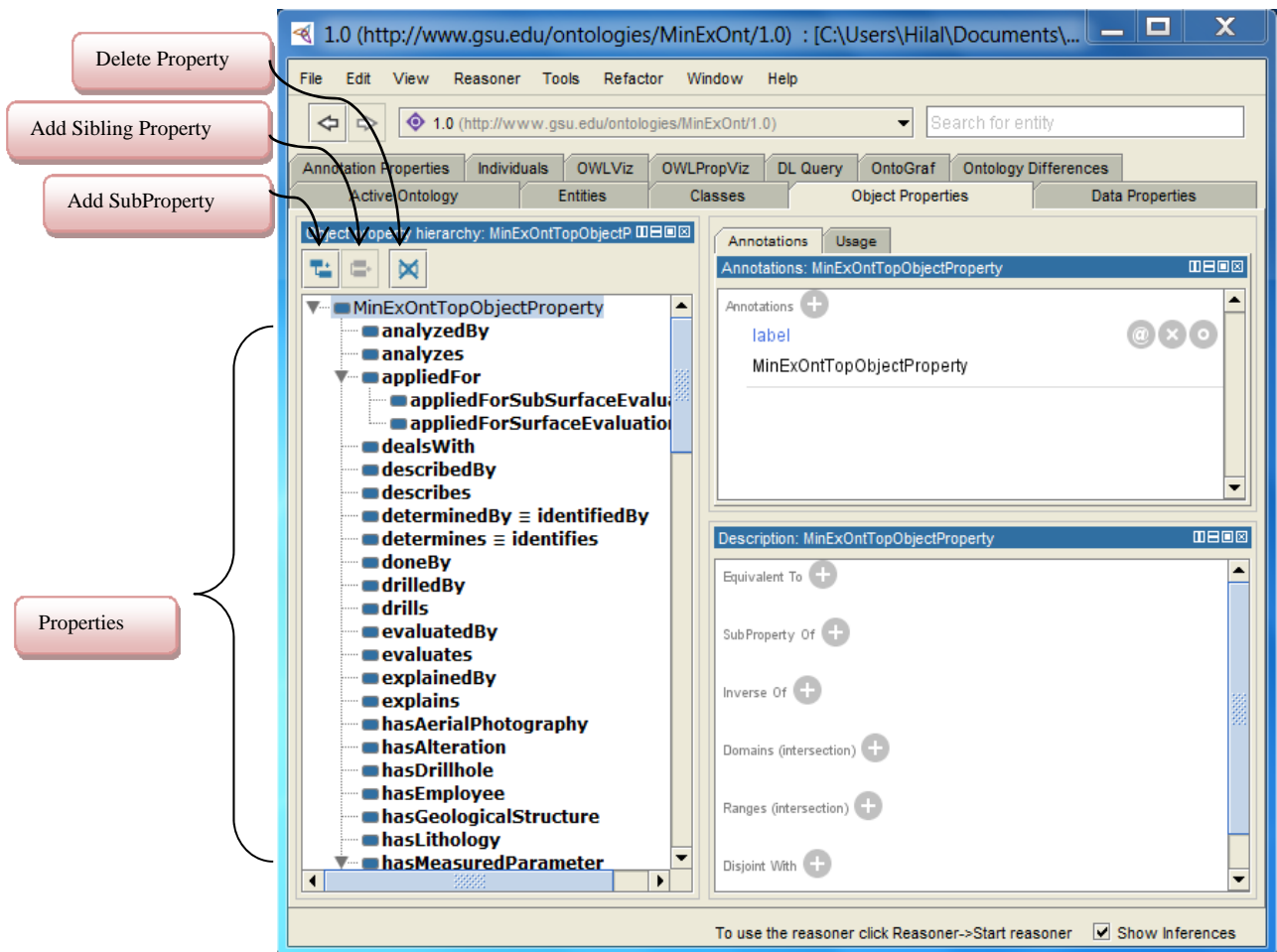
Figure 6.9. Screenshot of the 'Object properties' tab in Protégé showing properties defined under MinExOntTopObjectProperty in the ontology.

Similar to the 'Thing' superclass, which was substituted with the name of the ontology, the 'TopObjectProperty' is replaced by the 'MinExOntTopObjectProperty' as the top object property in this ontology (Figure 6.9).

In this study, various the 'hasX' naming style is used for the object properties, where X is substituted with meaningful names (e.g., hasAlteration, hasEmployee) (Figure 6.10). The property-subproperty hierarchy was used to make the set of properties more clear, and understandable. For instance, hasMeasuredParameter is used as a top property for the ones below it (Figure 6.9). Since more than one parameter is used for geophysical processes in this study, the others except the one on the top are the subproperties of hasMeasuredParameter as shown in Figure 6.10. These subproperties are listed as hasMPChargeability, hasMPConductivity, hasMPDensity, hasMPMagneticSusceptibility, hasMPRadiation, hasMPRemanence, and hasMPResistivity.
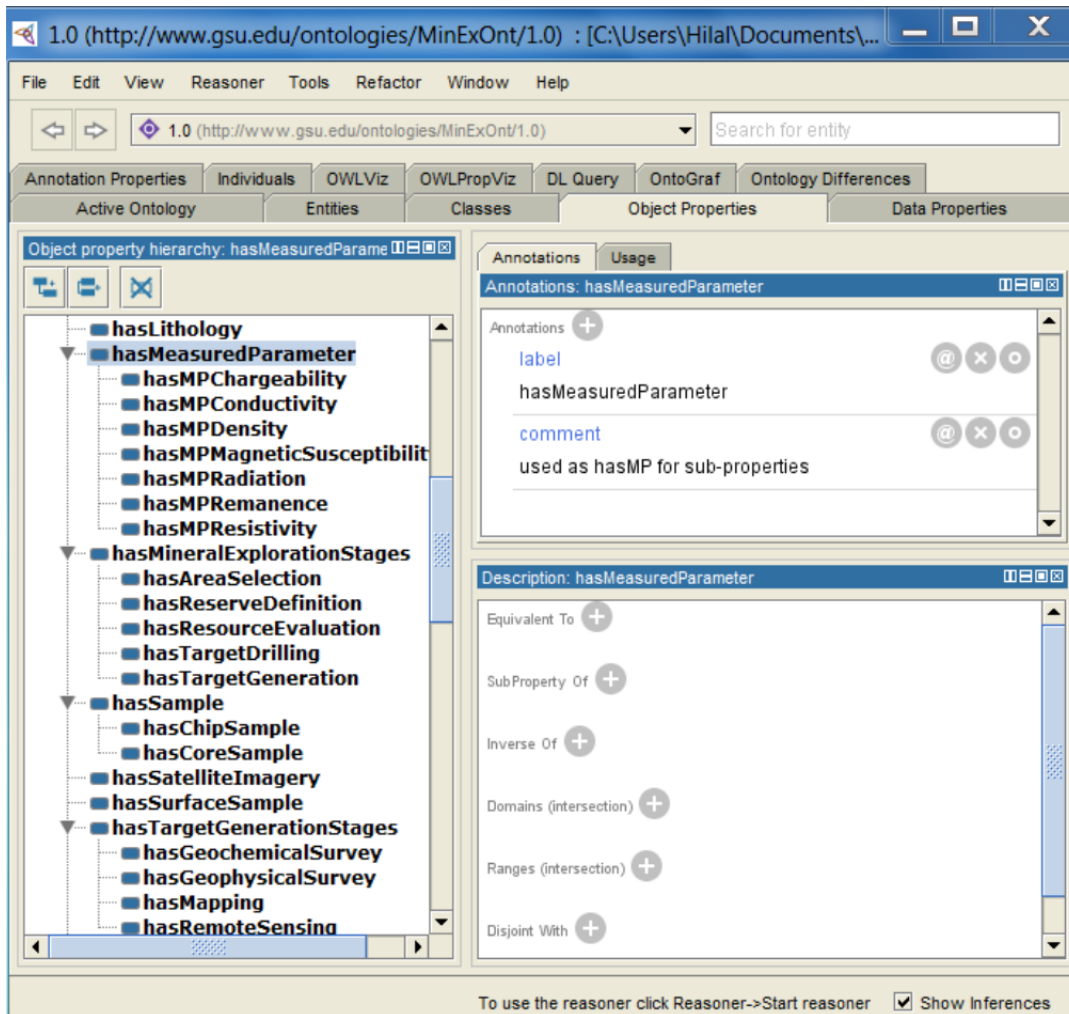
Figure 6.10. Screenshot of the 'Object Properties' tab in Protégé, showing the subproperties of few of the properties.

The most important role of the 'Object Properties' tab is to define the domain and range

for the properties. For instance, the logs object property has the ExplorationGeologist class as a

domain and the Core class as the range (Figure 6.11). This way, the RDF triple would read as

'ExplorationGeologist logs Core' in which ExplorationGeologist is the subject, logs is the

predicate, and Core is the object of the triple. In addition, the reverse sentence can be created by

using 'Inverse Of' under 'Description' just on the right side. For example, the loggedBy object

property is assigned as an inverse property of the logs property, which reads as: 'Core

loggedBy ExplorationGeologist'. The following screenshot has different examples about the

use of the 'Inverse Of', property, e.g., for the manages-managedBy, performs-performedBy,

prepares-preparedBy sets of properties.
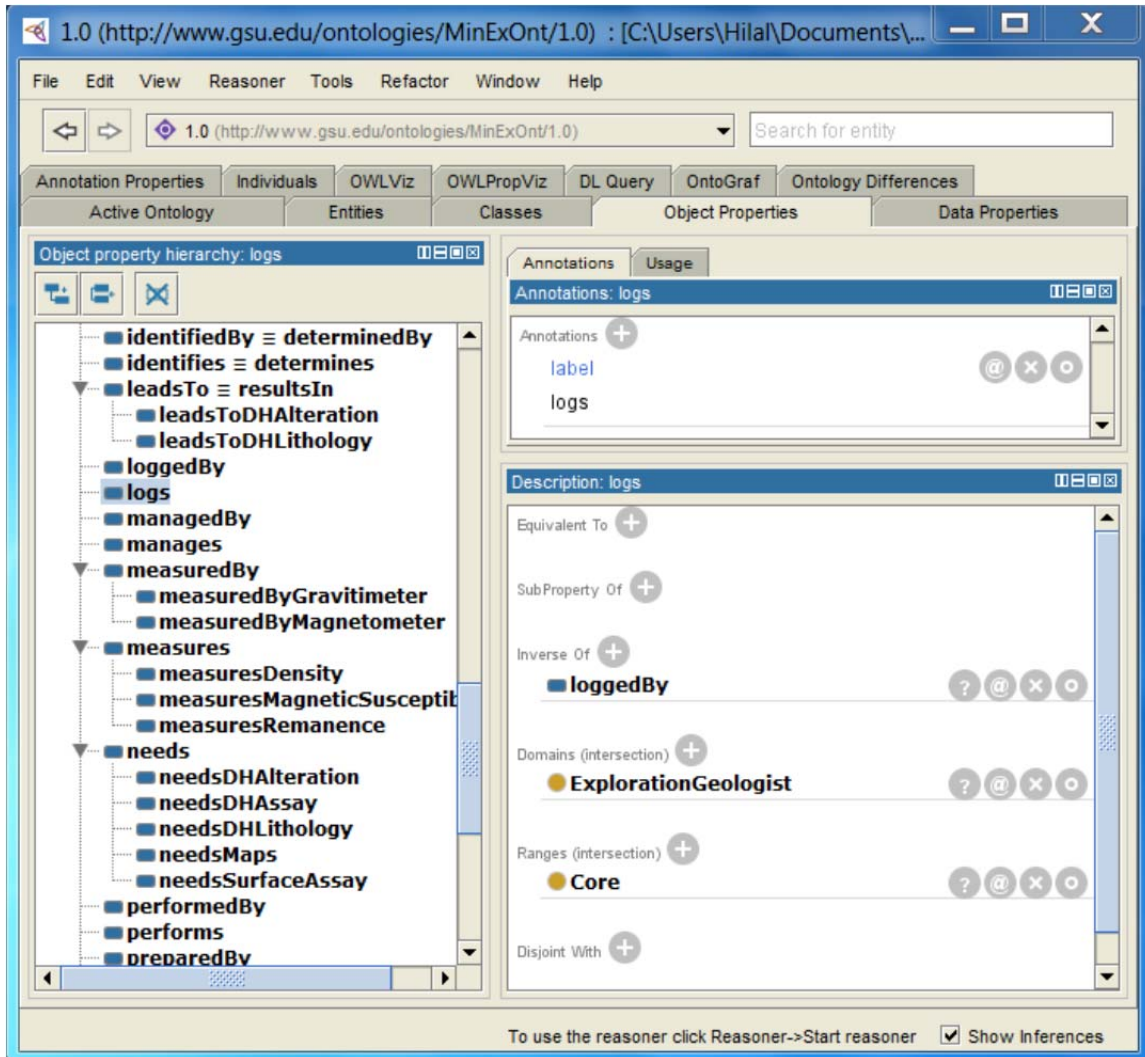
Figure 6.11. Screenshot of the 'Object Properties' tab in Protégé, showing the logs property as an object property with its ExplorationGeologist domain, and Core range, and its loggedBy inverse property.

In addition to the 'Inverse Of' property, the equivalent property can be assigned under

'Description' tab. The hardest thing for this study was finding good and meaningful object

properties among relations based on domain knowledge. Same property may be needed to define different relationships. However, if the same object property is used for different property domains and ranges, the result would not be acceptable based on requirements. For instance, in the relationship 'A – X – B', X is the property with A as domain and B as range. If X is also used for another relationship, as in 'C – X – D', the meaning of the relation may not be the same as that in the 'A – X – B' relation. The problem is that it is not clear which of two domain classes (A or C) connects to which of the range classes (B or D). It can be easily understood when the classes are visualized in the graph. A and C connect to same property, which is X and this property connects to B and D. Using properties with alternate names such as use or utilize, or specifying differently named properties under the same top property, for example, measuredByGravimeter and measuredByMagnetometer, will help to resolve the issue. For instance, applying the same uses property in the following two triple sentences: GeochemicalSurvey uses GeochemicalMap and GeophysicalSurvey uses GeophysicalMap leads to confusion, which can be removed by using the utilizes property for the second sentence instead of the uses property. Figure 6.12 shows one example for the use of the 'Equivalent To' property to make the uses and utilizes object properties equivalent. It also shows the usedFor inverse object property. In this thesis, the property restriction, which is another option to resolve the issue,is not used. Additional information about an object property can easily be addedusing the plus sign next to the 'Equivalent To' and 'Inverse Of' under the 'Description' tab.
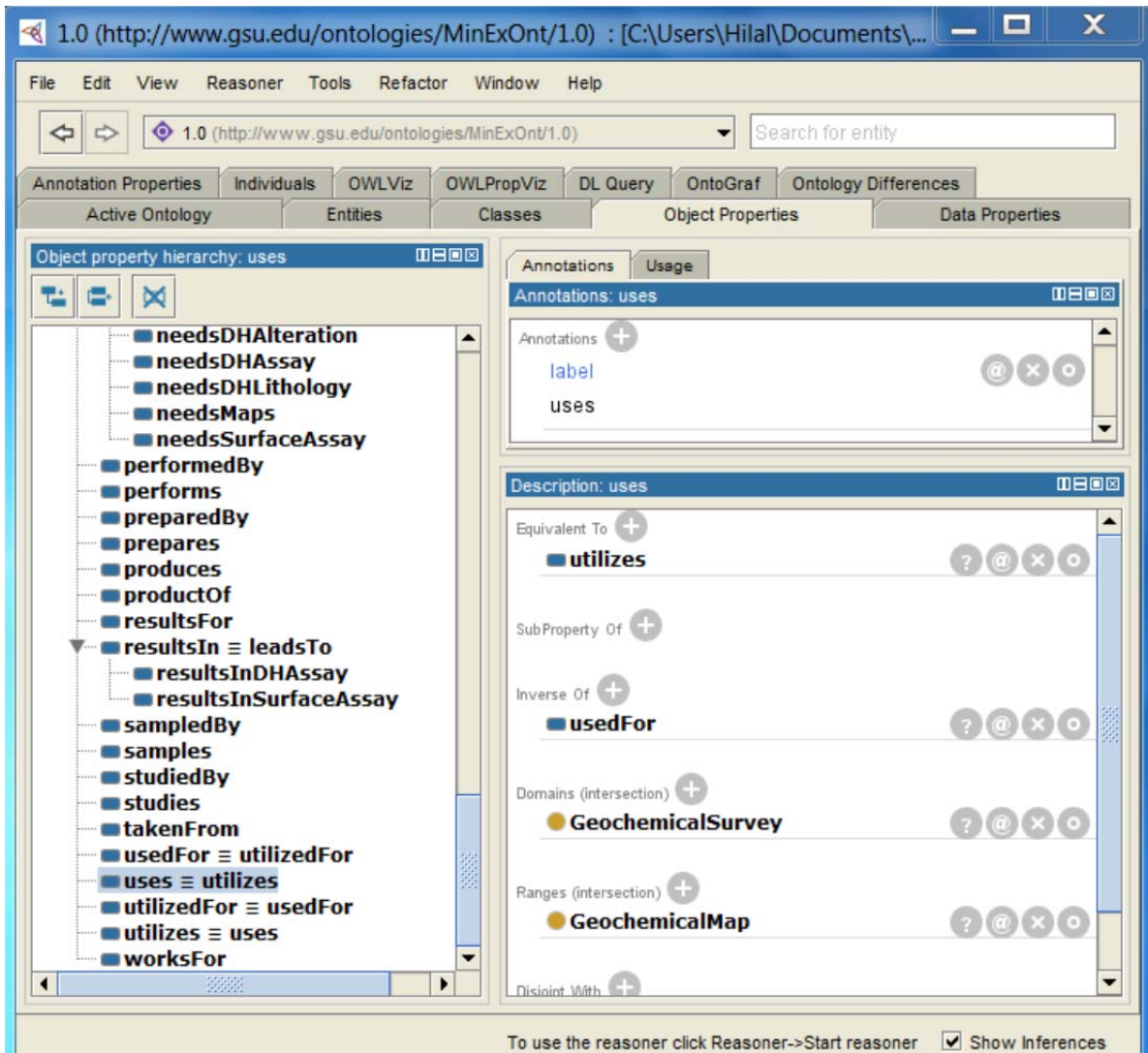
Figure 6.12. Screenshot of the 'Object Properties' tab in Protégé, showing the 'Equivalent To', and 'Inverse Of' properties, and the domain and range for the `uses` object property.

Figure 6.13 shows all the properties and subproperties (about 90 object properties) in alphabetic order under 'MinExOntTopObjectProperty' used for this domain ontology. These are shown in three sections in order to show all of them on one page.
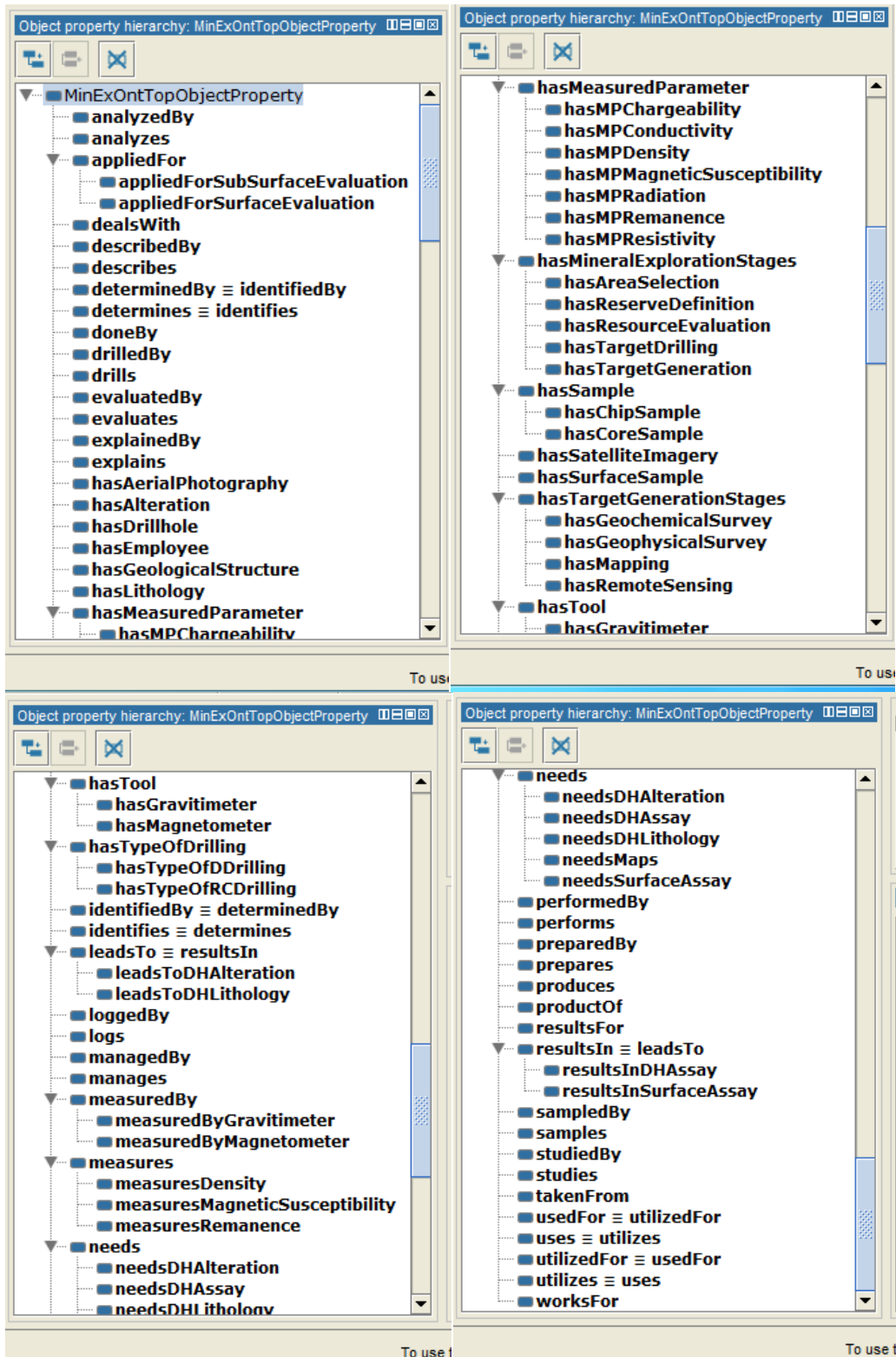
Figure 6.13. Screenshot of the taxonomy for the 'MinExOnt' object properties in Protégé, showing all the named properties under the top MinExOntTopObjectProperty object property.

6.4. OWL visualization with Protégé

Protégé 4.2 beta has two visualization options to choose. One of them is OWLViz, which enables viewing of the class hierarchies in OWL ontology in the editor. Another one is OntoGraf, which provides support for interactive navigation of the relationships in OWL ontologies. Except for these visualization options, two more visualization plug-ins can be used to represent classes and their relations. OntoViz is not compatible with Protégé 4.2 beta version yet, but it is compatible with Protégé 3.4, which is an older version. The OWLPropViz plug-in is compatible with Protégé 4.0 but has some issues, for example, after proper downloading, it did not work for this project. The issue is a subject of discussion under Protégé.

While some of these visualization plug-ins supports only the 'is-a' relationship, others show all types of relationships. The following sections give information about some of these OWL visualization plug-in which were used in this study. The efficient way of OWL visualization is discussed in the following chapter (Chapter 7: OWL Visualization by Knoodl - OntVis).

6.4.1. OWLViz

The OWLViz plug-in only allows the generalization-specialization, class hierarchies in OWL ontology to be viewed. However, relations other than 'is-a' cannot be displayed with this visualization tool. Figure 6.14 represents a screenshot of OWLViz for the Map class under MinExOntClasses. This view provides a better understanding of the relations between classes and subclasses.
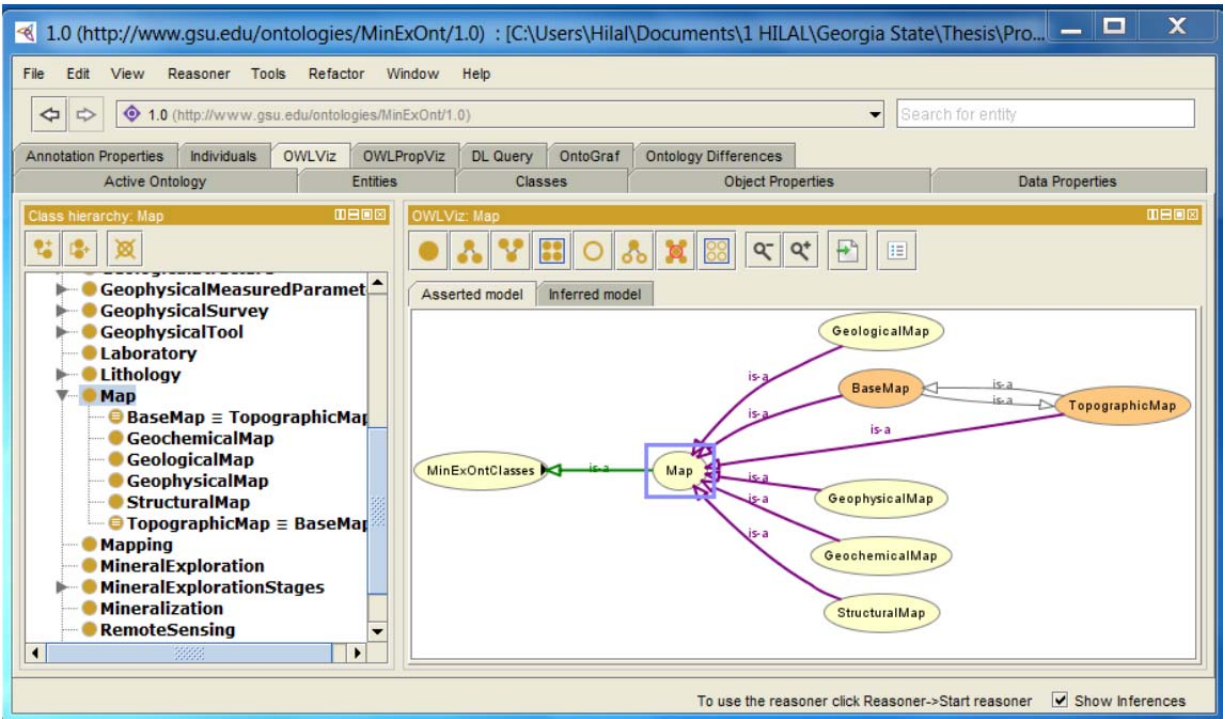
Figure 6.14. Screenshot of the 'OWLViz' tab in Protégé, the class structure under the Map class.

According to Figure 6.14, BaseMap, GeochemicalMap, GeologicalMap, GeophysicalMap, and StructuralMap are subclasses of Map. In the OWLViz plug-in all classes, except for the classes equivalent classes, are shown with a light yellow colored ellipsoid. Equivalent classes are shown with a light orange colored ellipsoid. Each open arrow, representing the is-a relationship, starts from a specialized class, and points to a general class.

Another example can be given for the Sample class under the MinExOntClasses class. Figure 6.15 depicts two levels of class hierarchy under the Sample sample.
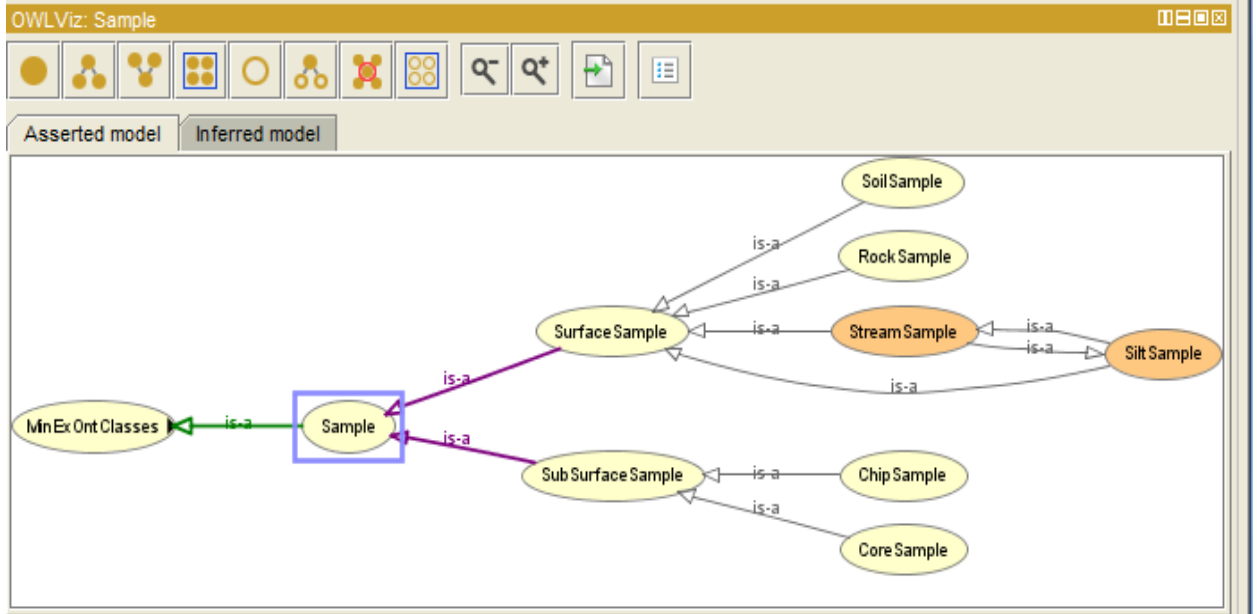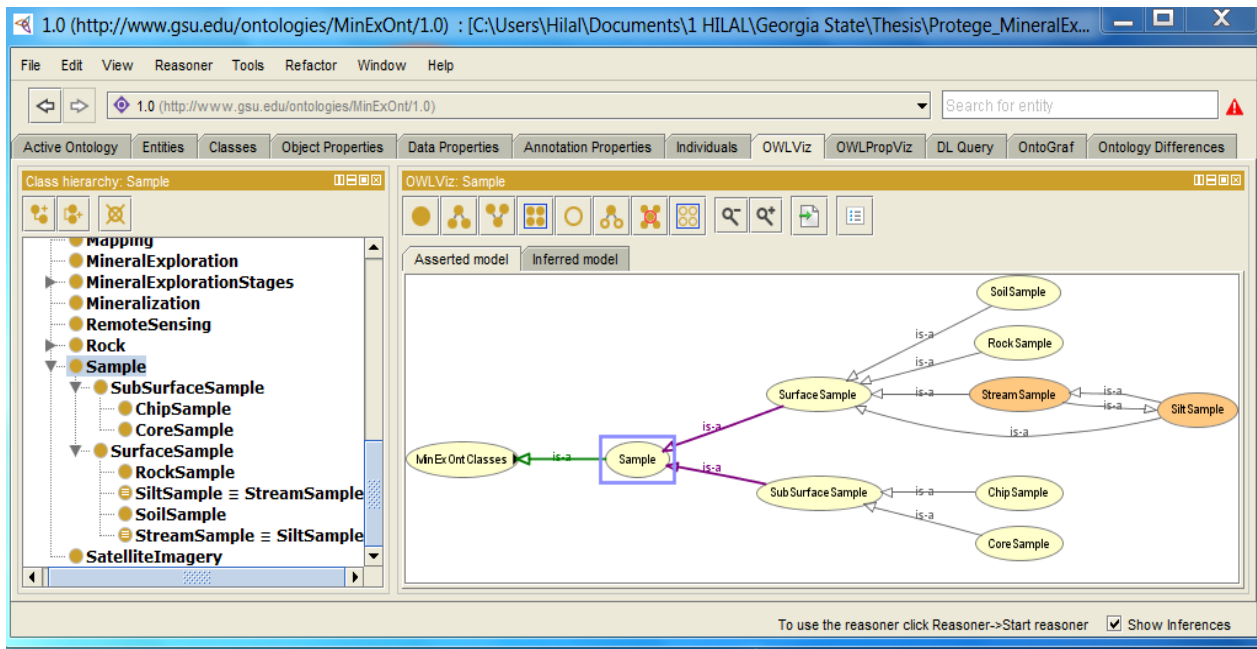
Figure 6.15. Screenshot of the 'OWLViz' tab in Protégé, showing the class structure under the Sample class.

All classes under the 'MinExOntClasses' class in OWLViz are shown in Figure 6.16.

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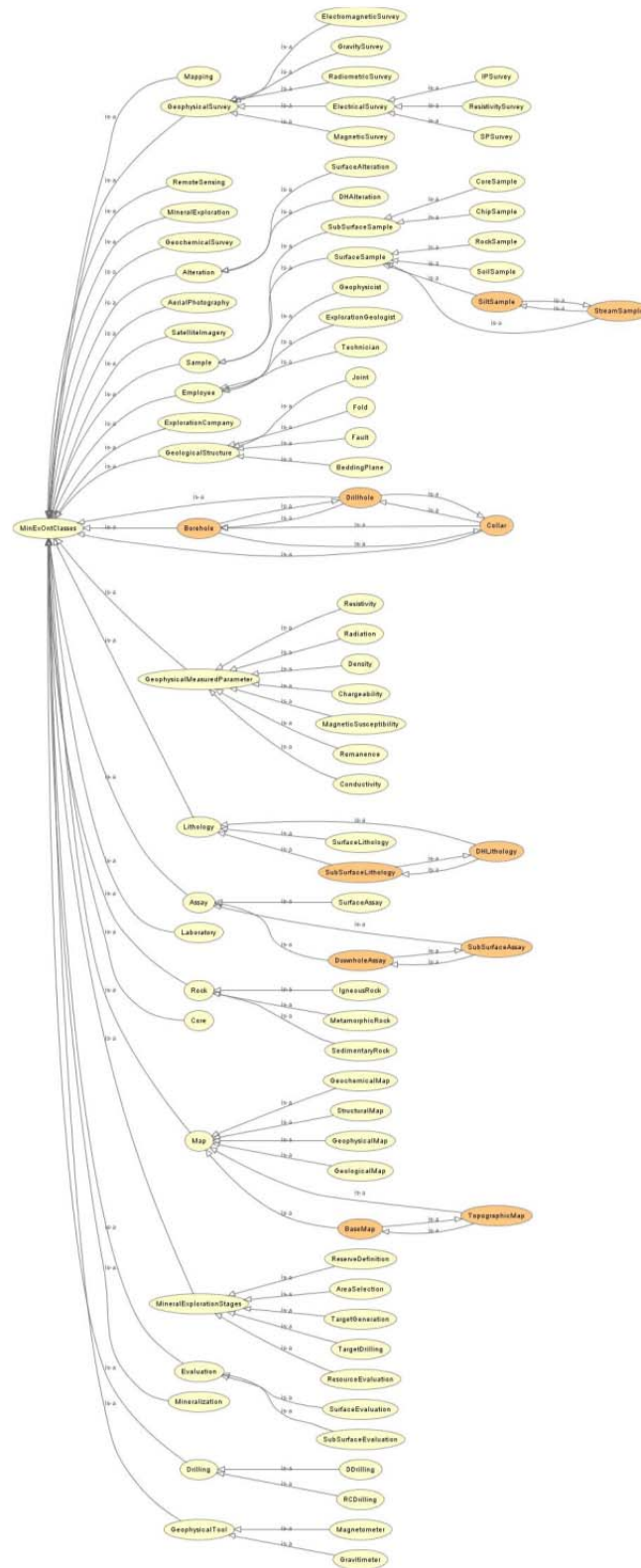
Figure 6.16. Screenshot of 'OWLViz' tab in Protégé, showing the class hierarchy of all the classes in the MinExOnt Ontology.

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6.4.2. OntoGraf

OntoGraf can show other relations in addition to the 'is-a' relationship. It provides automatically organized structure with interactive relationships among classes. The domain and range for each property are shown with colorful arcs, which are labeled in the Arc Types legend just next to the OntoGrap window (Figure 6.17). Figure 6.17 gives an example of OntoGraf's visualization capability. In such a vife, the Sample class is set as a central point relative to the other classes which are related to it (Figure 6.17). The Arc Types legend of the OntoGraf makes visualization of a class hierarchy very useful.
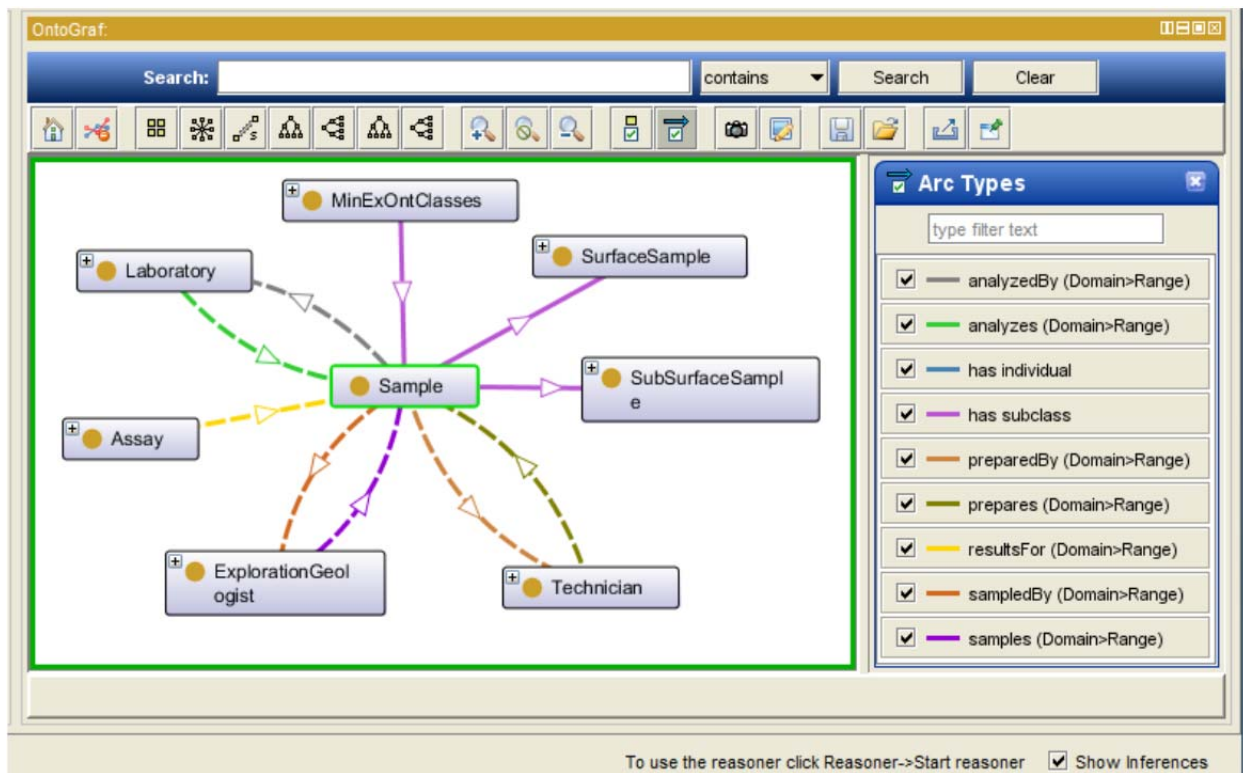
Figure 6.17. Screenshot of 'OntoGraf' tab in Protégé, showing all kinds of relations between the Sample class and its related classes

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The following relations are displayed in Figure 6.17 ('is-a' relations are not listed):

✓ Sample hasSubClass SurfaceSample

✓ Sample hasSubClass SubSurfaceSample

✓ Sample analyzedBy Laboratory

✓ Laboratory analyzes Sample

✓ Sample preparedBy Technician

✓ Technician prepares Sample

✓ Sample sampledBy ExplorationGeologist

✓ ExplorationGeologist samples Sample

✓ Sampling relatedTo Sample

Showing all those relations in one diagram is helpful for the visualization of the whole ontology. However, since the arcs are not labeled on the graph, it is hard to read and match all properties with classes.

6.5. OWL Reasoner

OWL ontologies are described by OWL DL (Description Logic), which can be processed and checked with different reasoners. The most important purpose for reasoners is to test and check if one class is a subclass of another class. An inferred class hierarchy is produced at the

end of this process from the asserted class hierarchy. Moreover, it also allows checking if one class has instances or not. Reasoners provide other support such as consistency check, like identifying subsumption relations among classes, and classification check (Horridge et al., 2007). In general, they are a kind of tool used for ontology processing. This process is achieved by the 'Reasoner' menu item under Protégé editor.

Figure 6.18 shows the view before selecting a 'none' for the reasoner menu item. The asserted class hierarchy and inferred class hierarchy are shown before the reasoner process. At that point, there is nothing under inferred class hierarchy since the reasoner has not been started yet.
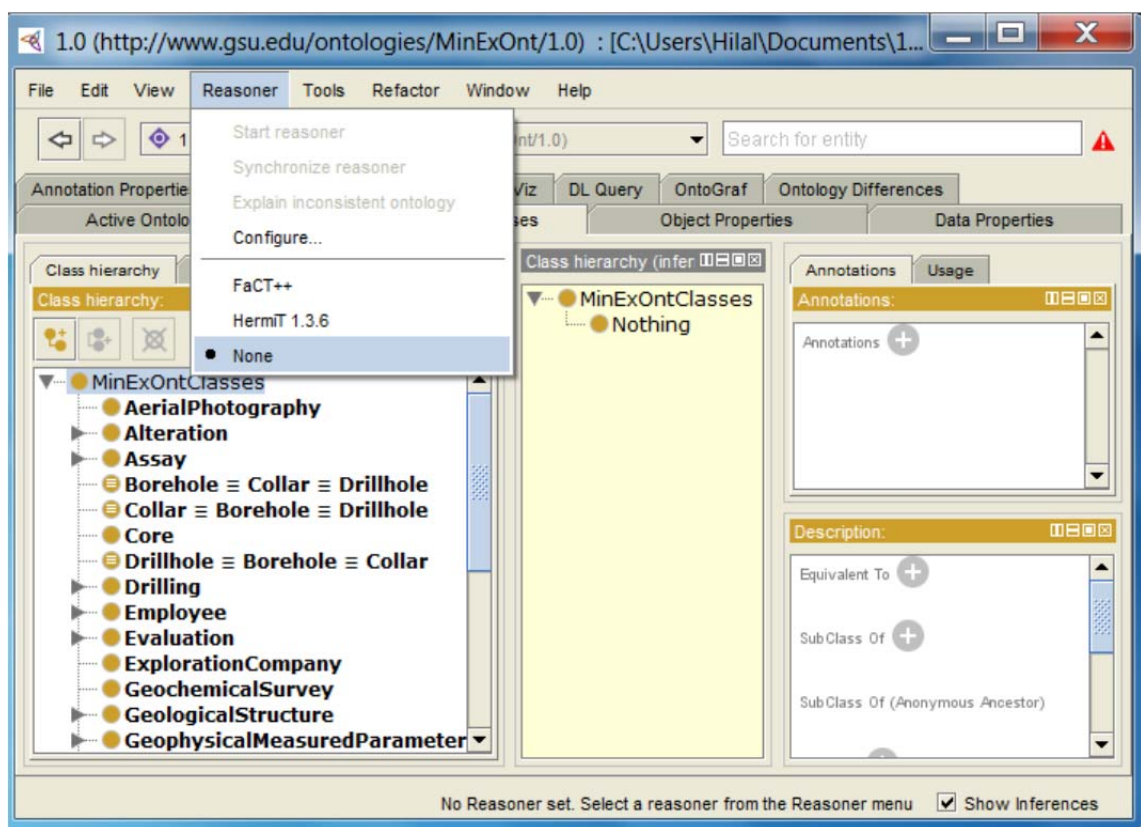
Figure 6.18. Screenshot of Protégé when no reasoned is selected.

Protégé 4.1 beta has already FaCT++ and HermiT 1.3.6 reasoners pre-installed under 'Reasoner' menu item as it is shown in Figure 18. They are reasoners for ontologies written using OWL and used for whether or not the ontology is consistent. Although they are used for same purposes and open source, they have some differences regarding with implementation and algorithm. While HermiT is an OWL DL reasoner with implemented in Java, FaCT++ is an OWL DL reasoned with implemented in C++ (http://www.w3.org/2007/OWL/wiki/Implementations).

After each reasoner is run, same inferred class hierarchies are obtained as the asserted hierarchy shown in the left panel of Figure 6.19.
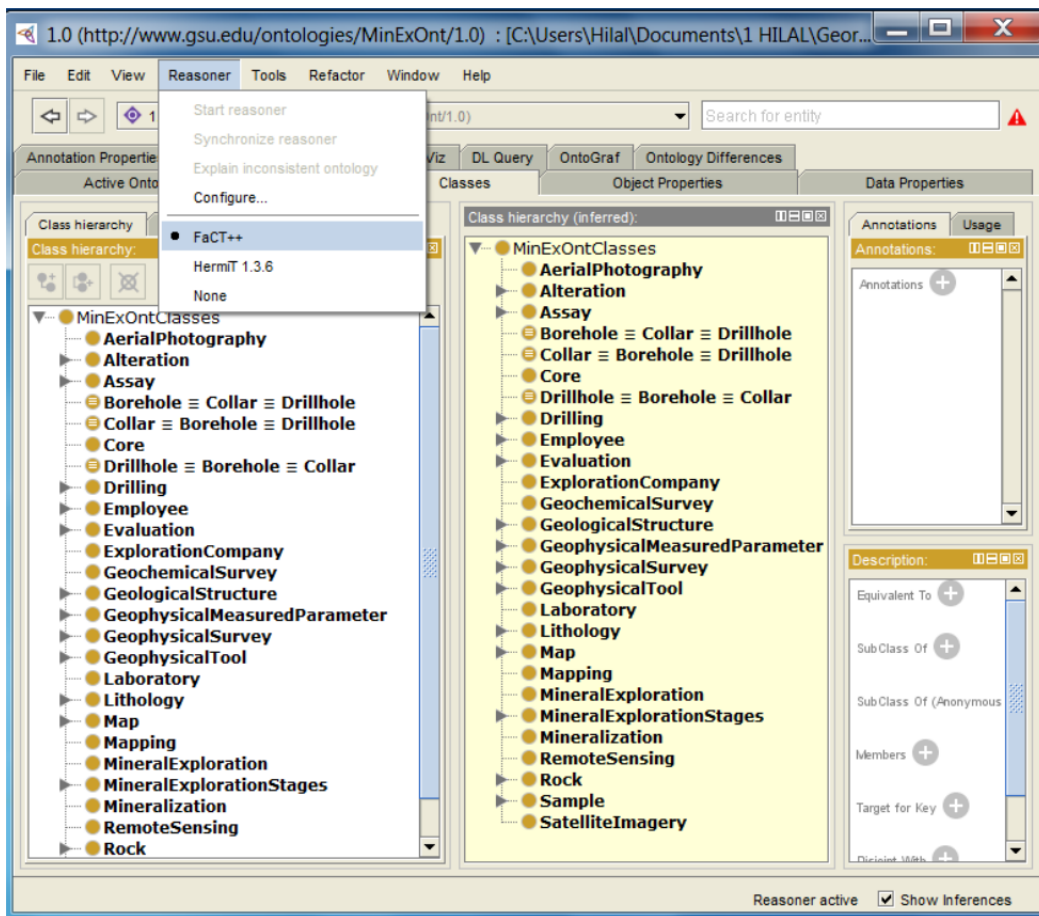
Figure 6.19. Screenshot of 'Reasoner' in Protégé showing the asserted and inferred class hierarchies of the ontology after FaCT++ and Hermit 1.3.6 reasoners are used.

CHAPTER 7: OWL VISUALIZATION BY KNOODL - ONTVIS

Knoodl is an open and free tool for creating, managing, analyzing, and visualizing RDF/OWL descriptions. The general information about this online software is given under the 'Methodology' section. There are various ontologies under the community sessions of the Knoodl software. After the registration step, and a login, creating a new community is the next step to start using Knoodl (Figure 7.1). The community name is called 'Geosciences' and the description includes information about what people can find under this community page.

Figure 7.1. Screenshot of a Knoodl page showing a new community creation.

The community may have many tabs as shown in Figure 7.2. However, just 'Ontologies' part, which maintains the ontologies under this community is examined and used for this project.
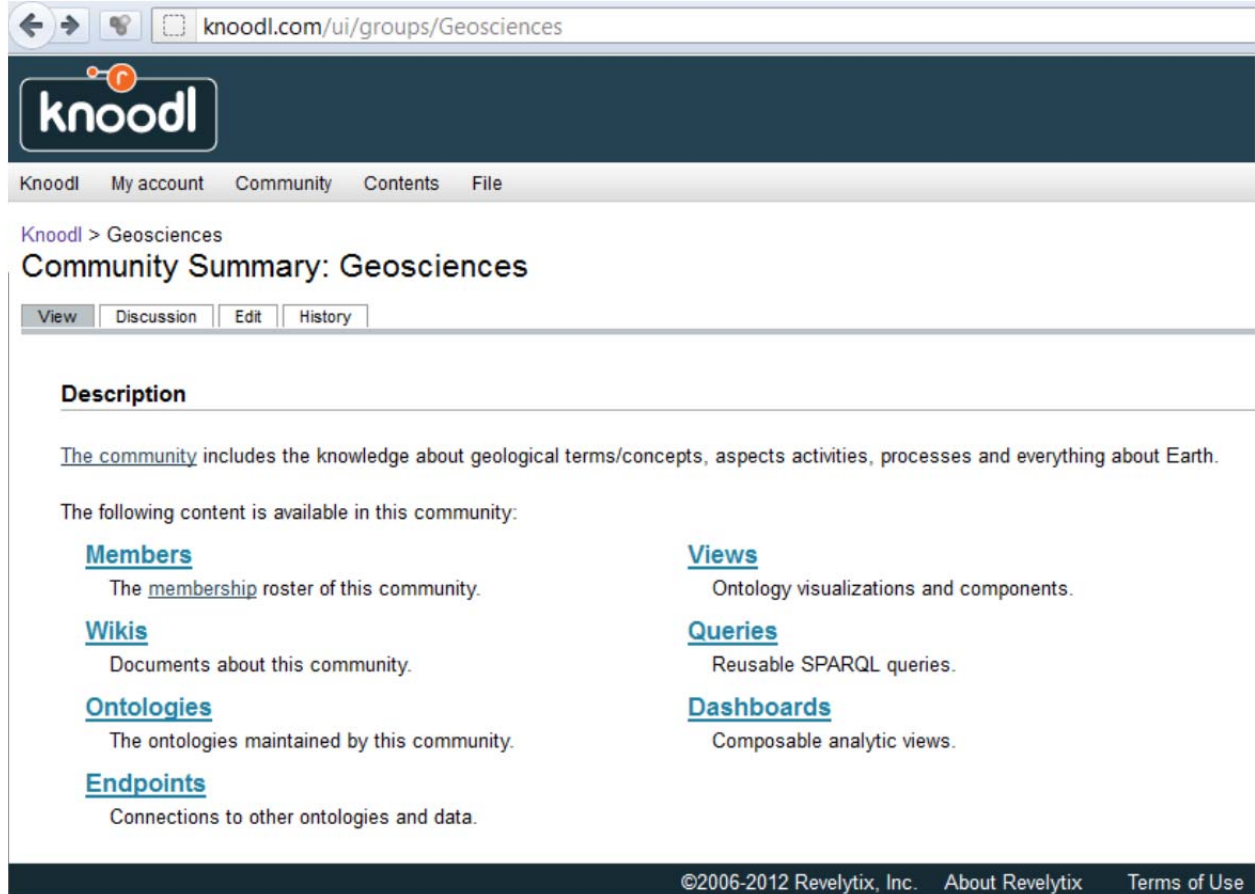
Figure 7.2. Screenshot of a Knoodl page showing tabs under a community.

The next step is uploading the ontology that is already created in Protégé. The MinExOnt

domain ontology, generated by Protégé is used and uploaded to the site to visualize the class

structure and relations. Knoodl requires the ontology to be in the RDF/XML format instead of an

OWL/XML format. Because the 'MinExOnt' domain ontology is saved in Protégé with

OWL/XML format, it was saved as an RDF/XML format in order to use it under the Knoodl tool

(Figure 7.3).
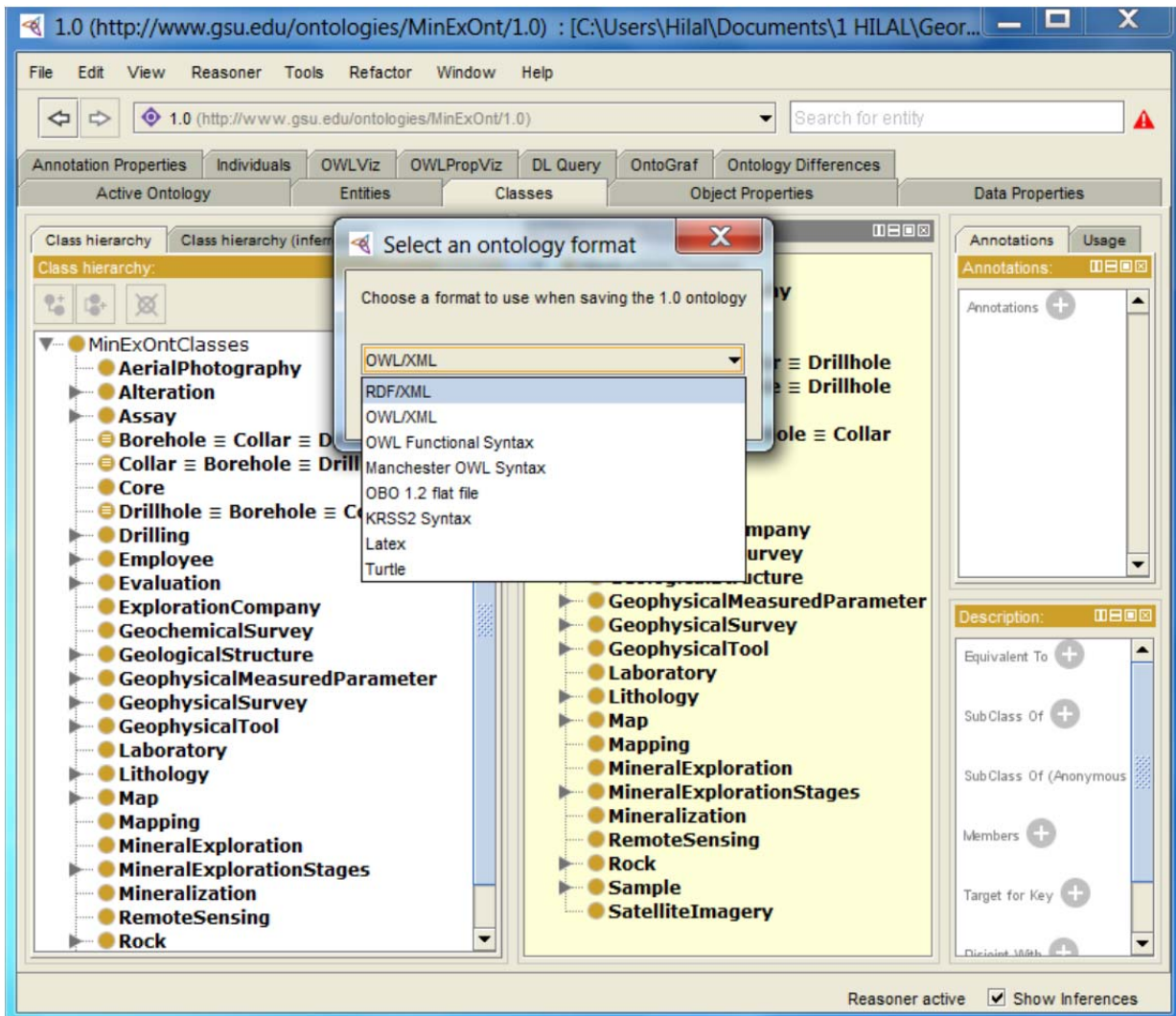
Figure 7.3. Screenshot of the Protégé editor showing the selection of an ontology format.

Under the 'Ontologies' tab in Knoodl (Knoodl>Geosciences), the ontology can be imported using the 'Import a vocabulary' option as shown in Figure 7.4. An ontology saved as an RDF/XML format is uploaded as 'Source filename'. The Vocabulary name is 'MinExOnt' and the vocabulary version is 1.0, as is identified in Protégé.
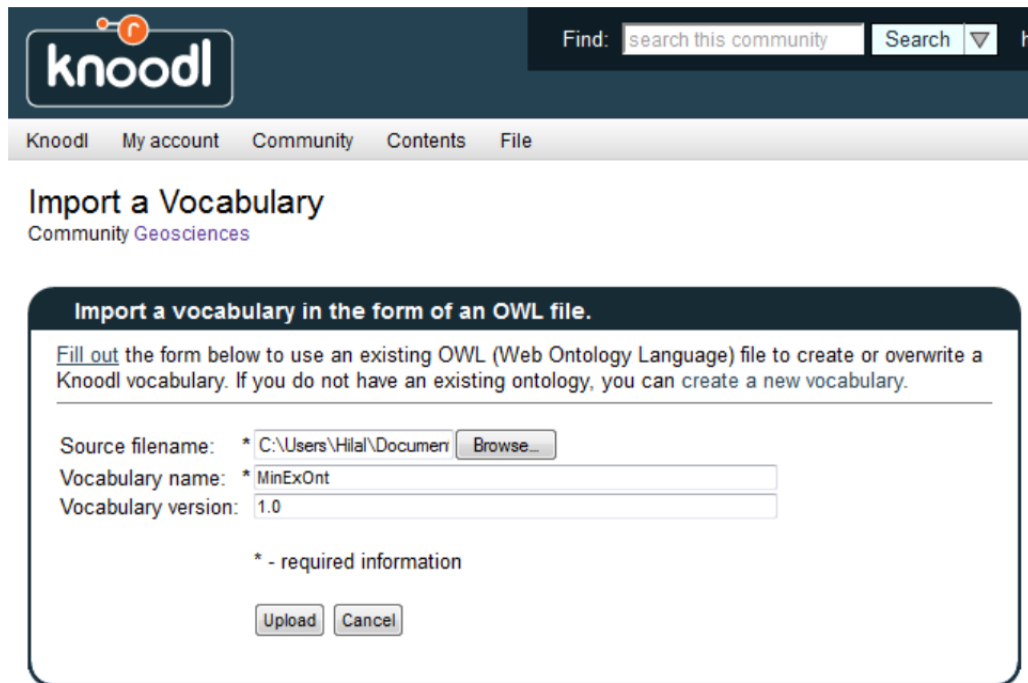
Figure 7.4. Screenshot of the Knoodl page showing 'Import a Vocabulary' tab.

After the uploading process, the domain ontology is ready to use in Knoodl. The general view looks like Protégé as it is displayed in Figure 7.5. 'Classes' and 'Properties' tabs with their annotations and their URIs are located on the left side of this figure. 'View', 'Graph', 'RDF', 'Discussion', 'Edit', 'History' tabs are on the right hand side of the window.
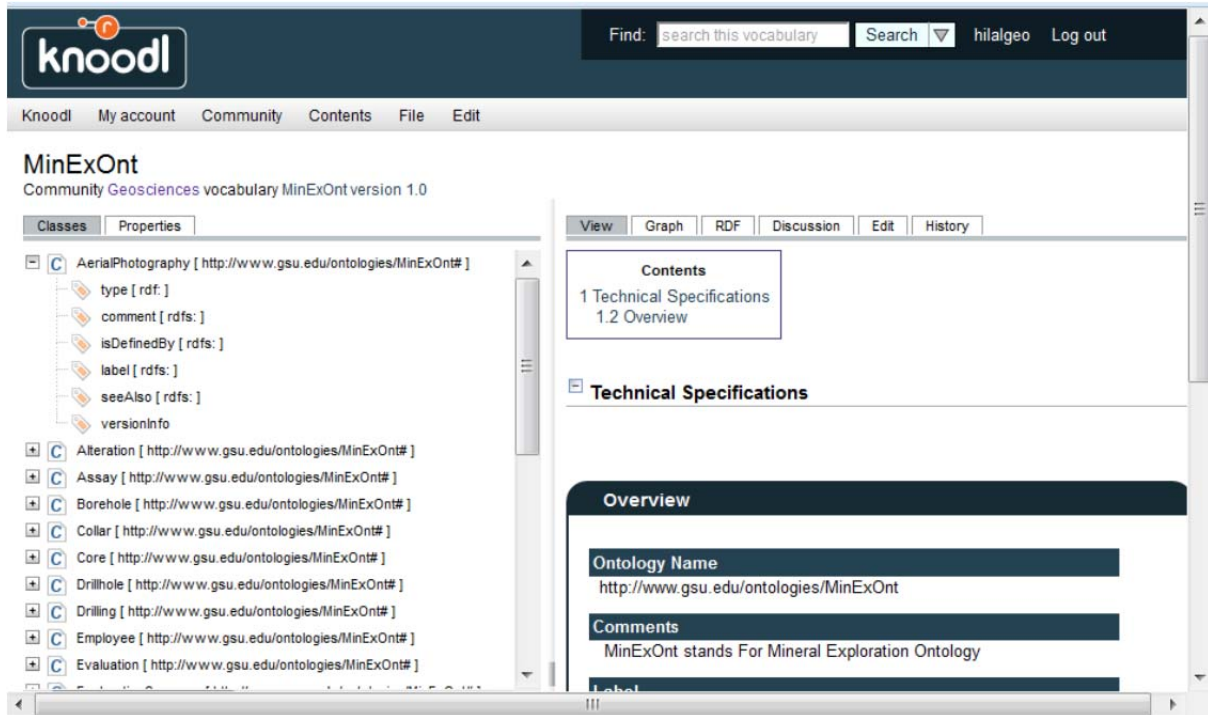
Figure 7.5. Screenshot of the Knoodl page showing a general view after uploading the ontology.

Figure 7.6 shows the contents of the 'Overview' tab, which includes information about the contents, which are listed as 'Ontology Name', 'Comments', 'Label', 'Defined By', 'Version Information', and 'Dependencies'. They are all uploaded from the ontology which was created in Protégé.

Figure 7.6. Screenshot of the Knoodl page showing the content under the 'Overview' tab.

OntVis is an application of Knoodl for visualizing an ontology. The 'Graph' tab is used in order to visualize the ontology. OntVis starts up with 'Graph' tab in Knoodl (Figure 7.7).
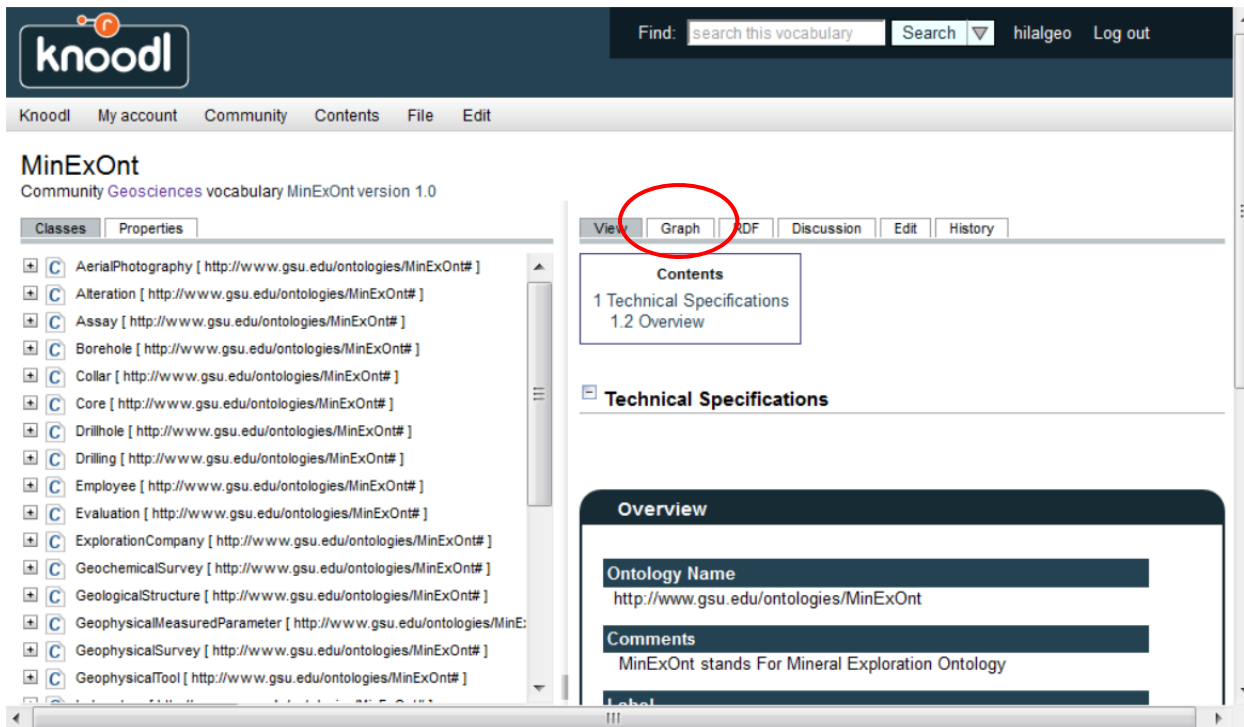
Figure 7.7. Screenshot of the Knoodl page showing the 'Graph' option in order to get visualization.

The 'Graph' page starts up with the blank page until classes and properties are picked up from the left side of the window. The only way to view classes and properties in the 'Graph' tab is dragging class or property onto the 'Graph' section. The general legend for the diagrams created in OntVis is shown in Figure 7.8. It gives a general explanation about the boxes and symbols used in OntoVis to visualize the ontology structure.
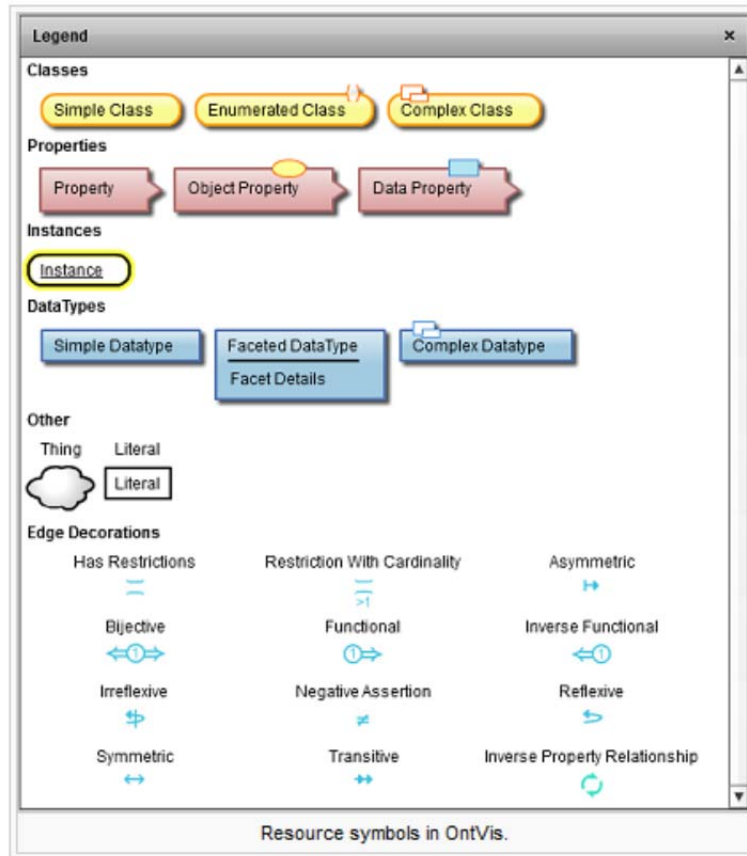
Figure 7.8. Screenshot of the OntVis legend for 'Graph' diagram.

The rest of this chapter provides various examples, including classes and properties from the MinExOnt ontology. Classes and properties can be viewed separately in the visualization. If the classes are dragged onto the 'Graph' tab, the related classes, annotations and properties can be shown as it is seen for a Sample class example in Figure 7.9 and Figure 7.10. Each class or property has three extra information which can be turned on or off by clicking next to the labels (Figure 7.9). Figure 7.10 shows the subclasses of the Sample class with their detailed information.
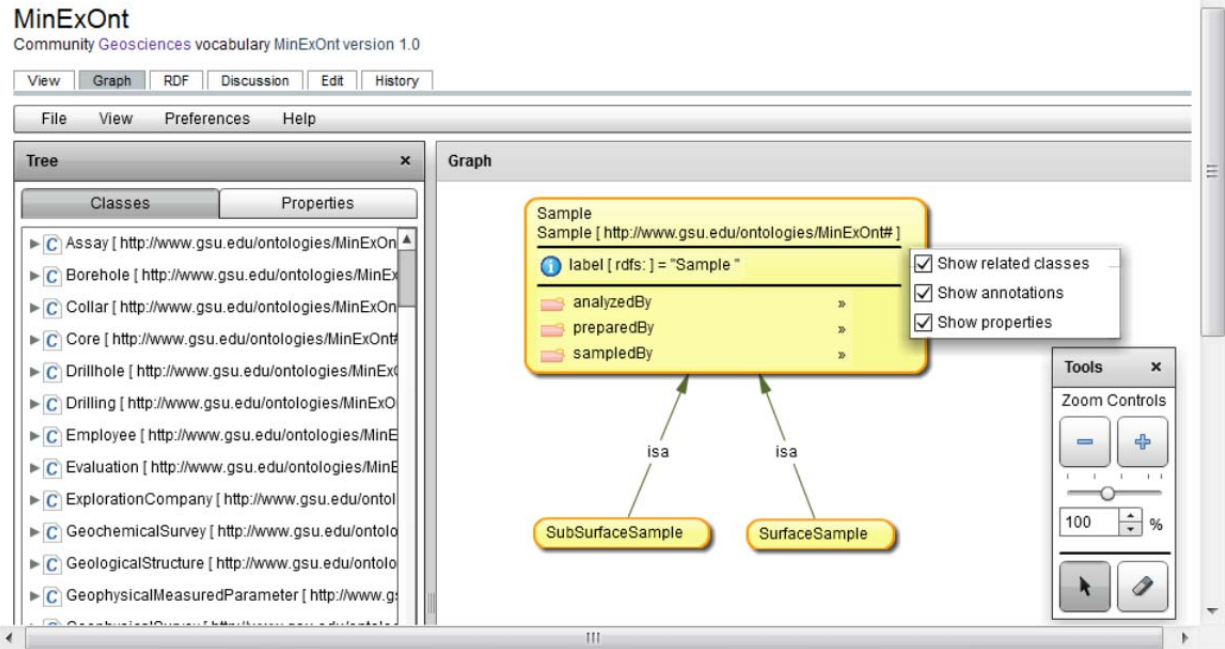
Figure 7.9. Screenshot of OntVis for the Sample class.
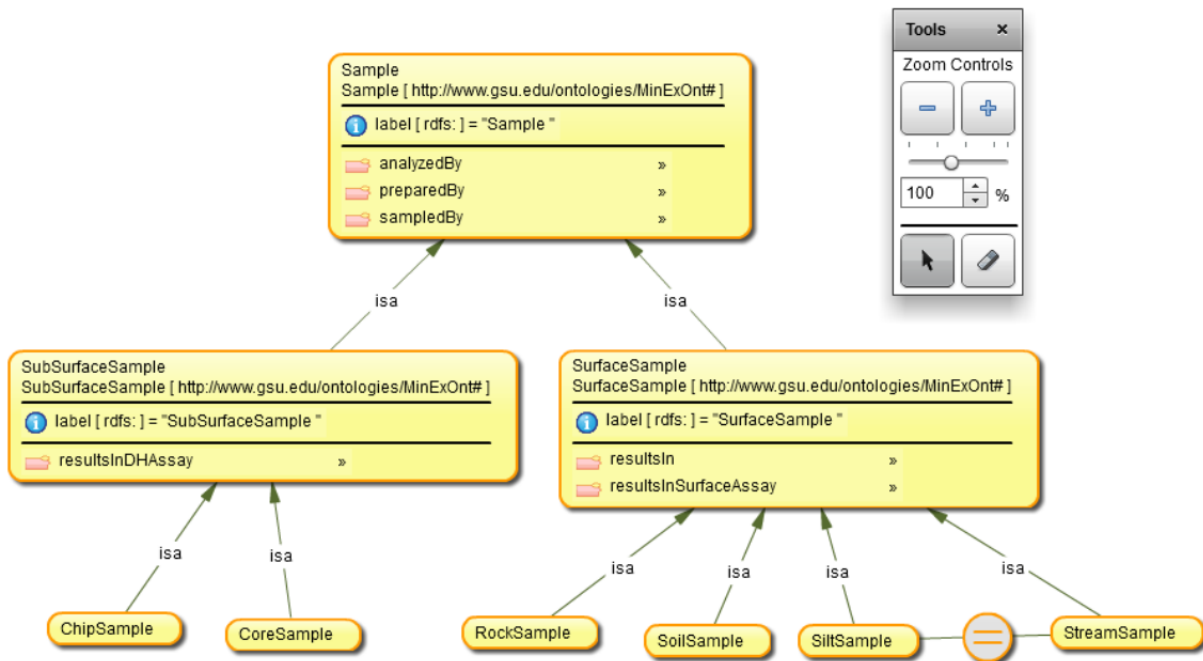
Figure 7.10. Screenshot of OntVis for the Sample class.

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If labels are not assigned to properties and classes in Protégé, OntVis would represent the properties and classes with their URIs in their boxes. As it is mentioned in the previous chapter, the labels are added for all classes and properties in Protégé for this project because of the OntVis requirements. The classes and properties in the boxes are linked to the label annotation for each class and property if they exist. Figure 7.11 represents one example for the case when labels are not assigned for classes and properties in Protégé, and the in 'Graph' is shown with URIs.. Since the URIs for each class and property are too long for display, it is hard to work under the 'Graph' tab to visualize the ontology. To remove this problem help was saught from the support center of Knoodl (knoodl-support@revelytix.com), which provided useful information about OntVis usage and extra knowledge that cannot be found online.
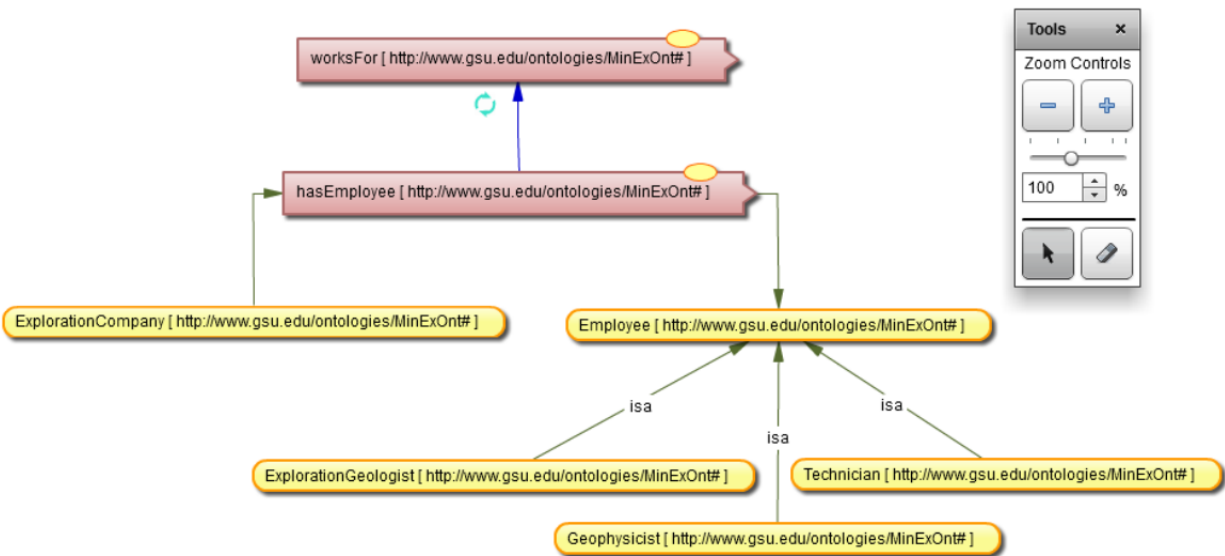
Figure 7.11. Screenshot of OntVis showing the URI for classes and properties without label annotation.

If the labels already exist in the ontology, the properties and classes are shown with only their namespaces without URIs as it is seen in Figure 7.12. All subclasses and the relations among them with annotation can be displayed by clicking the options available at the top corner of each box (Figure 7.13).
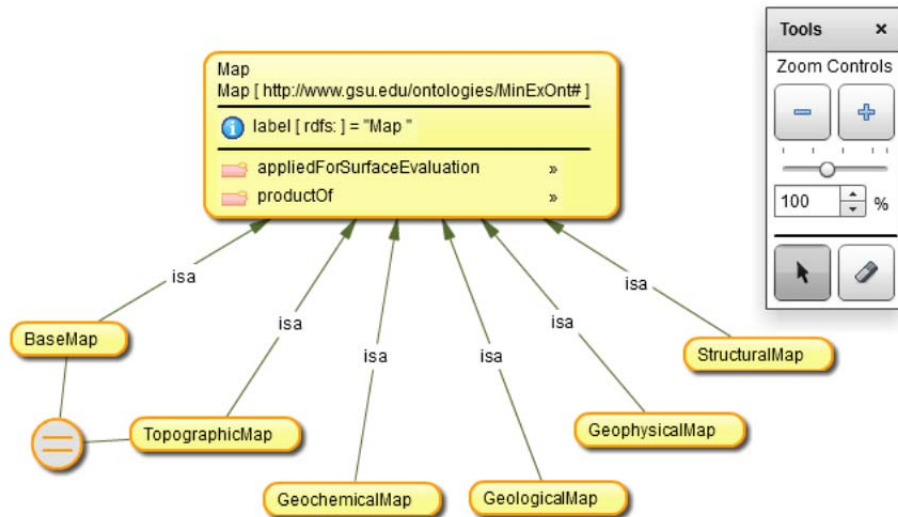
Figure 7.12. Screenshot of OntVis for the Map class with label annotations.
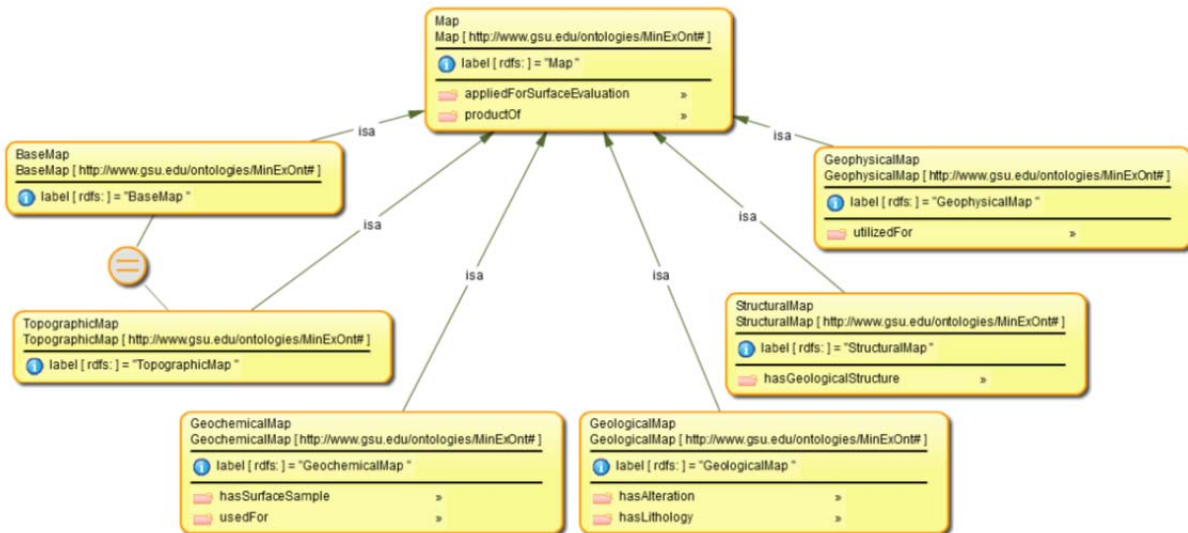
Figure 7.13. Screenshot of OntVis for the Map class with additional information displayed.

The property visualization in OntVis is better and more useful than class visualization since it is possible to represent the domains and ranges for the properties. The object properties are grouped in alphabetical order ('ana..ide' and 'ide…wor') as shown in Figure 7.14.
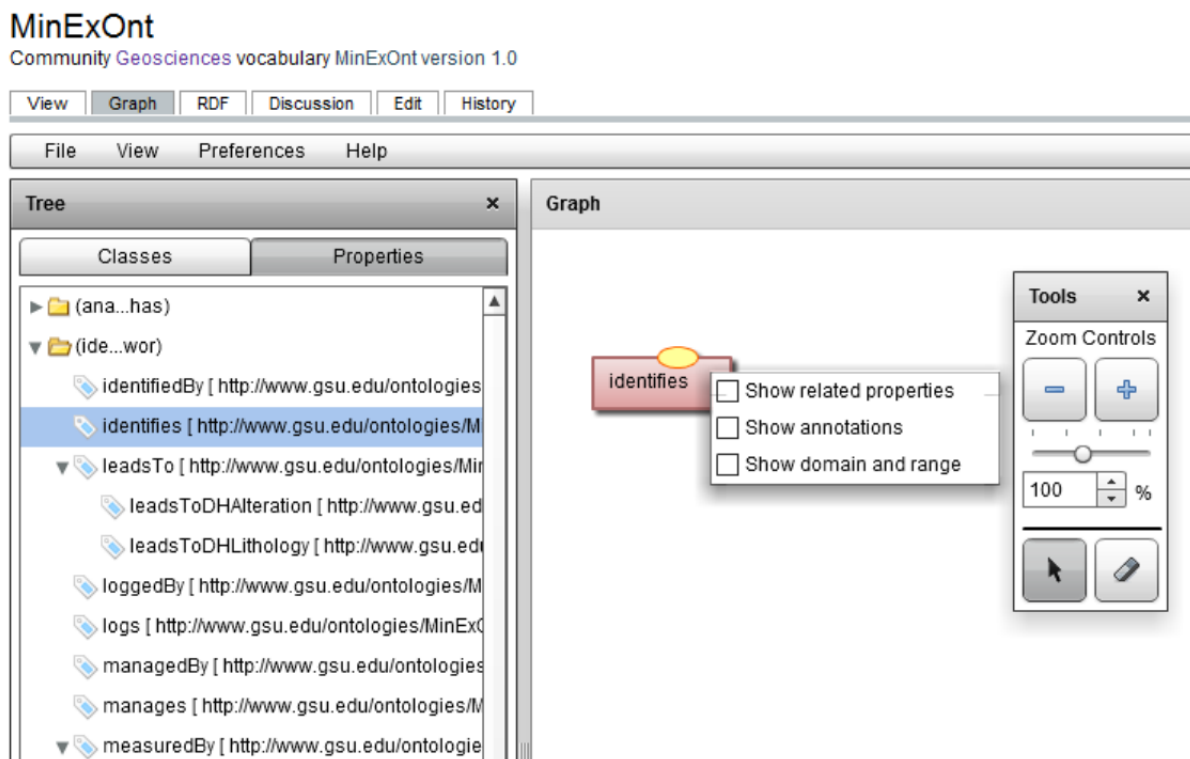
Figure 7.14. Screenshot of OntVis showing the 'Property Tree' on the left and the 'Graph' window on the right.

Figure 7.15 shows an example for the analyzedBy property in the MinExOnt ontology. The explanations of each box and the symbol in the diagrams can be found in Figure 7.8, which contains the general legend of OntVis. Pink rectangular box with a small yellow ellipsoid at the top line represents an object property. Object properties have extra information, which can be hidden or unhidden with a click just on the top right corner. The options include (Figure 7.15): 'Show related properties', 'Show annotations', and 'Show domain and range'. These allow the

user to view the desired diagram. Three screenshots representing those processes are shown in the figures below.
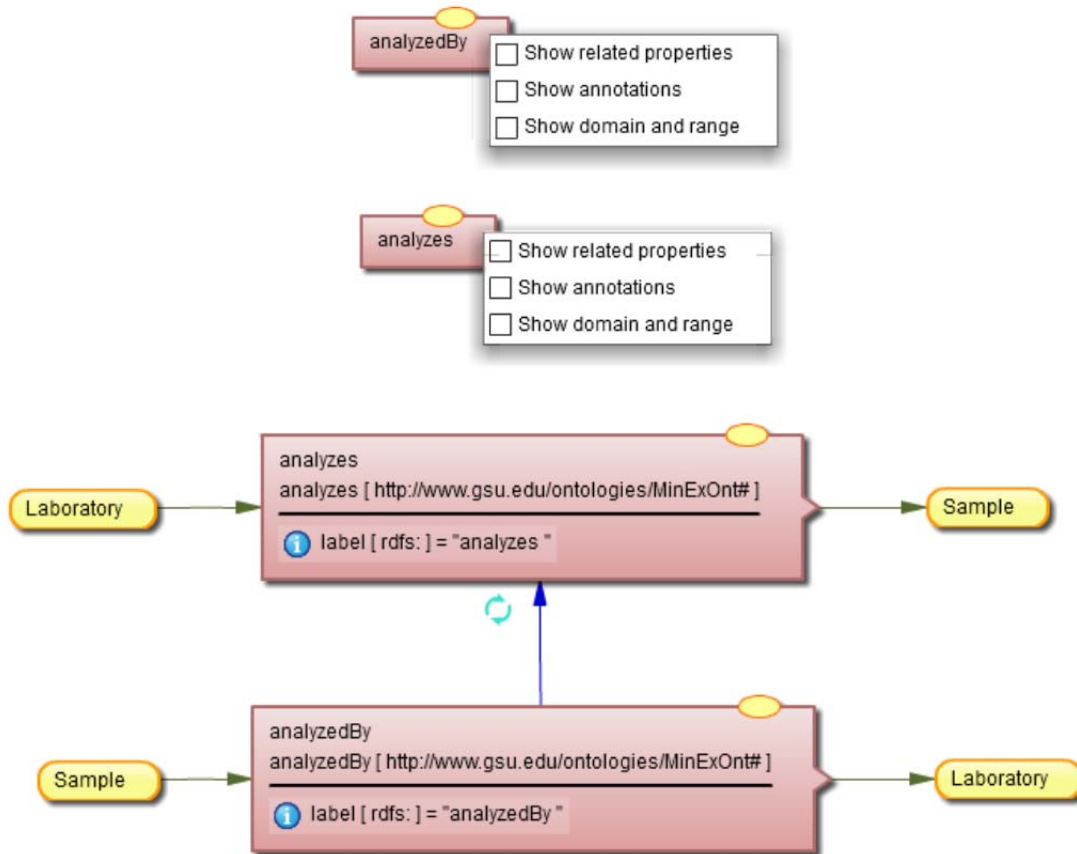
Figure 7.15. Screenshot of OntVis for the analyzedBy property and its domain and range. The related analyzes property and its annotations are also displayed.

Properties are like control points for the Graph window and the classes can be extended with extra information, such as related properties, classes, and annotations. Figure 7.16 gives an example showing the domains and ranges, and the relationships between properties, inverse of properties, and class hierarchy if it exists.
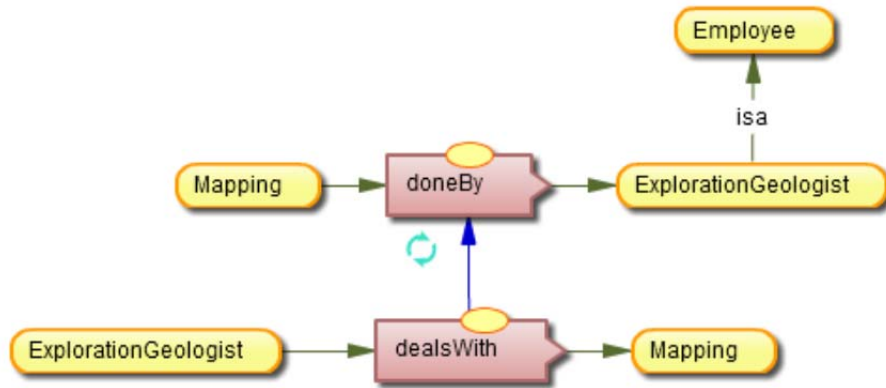
Figure 7.16. Screenshot of OntVis showing the domain and range of the dealsWith property and its related property.

As shown in Figure 7.17, the diagrams based on properties show all the information not only for properties but also for their domain and range classes, making the visualization more useful than the class visualization diagrams. Building of the diagram starts with dragging the samples property, which has the ExplorationGeologist class as domain and Sample class as range. The related classes for each class and the related properties, domains and ranges for each property can be shown. Figure 7.17 shows the ExplorationGeologist class as a subclass of another class (Employee), the relations for the samples property, and the subclasses of the Sample class.
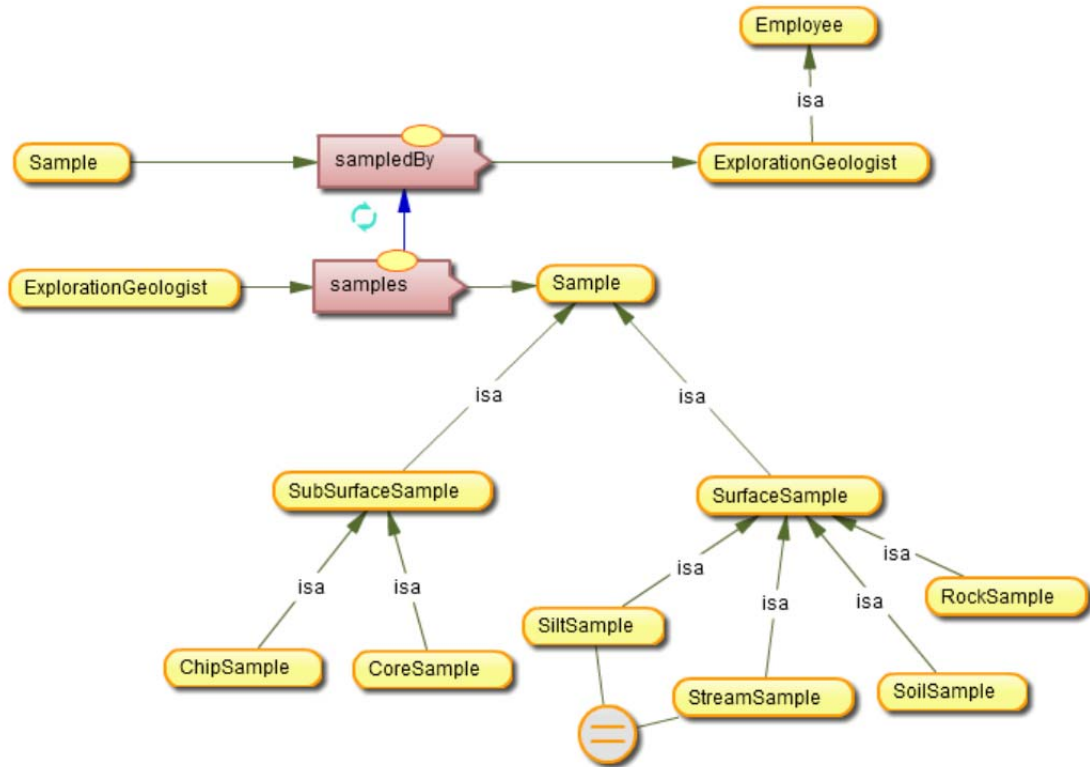
Figure 7.17. Screenshot of OntVis showing the samples property and extension of its property, and subclasses of the Sample class.

OWL visualization is quite important and necessary for the ontology development, and allows the relations between classes to be more readily seen and understood.

CHAPTER 8: CONCLUSION AND FUTURE WORK

8.1. Conclusion

This thesis research project discusses how to design and develop domain ontology for the mineral exploration field. The ontology formalizes specific consensual semantics of the knowledge of this field with Web Ontology Language (OWL). Different tools were applied to model, build, and visualize the ontology. The workflow to generate the ontology is stated and explained in each step, and includes: determining the scope for the ontology, focusing on some parts in the domain, generating naming styles, writing general descriptions of the domain, creating UML diagrams, developing ontology in Protégé, and generating OWL visualization in Knoodl. The information regarding ontology development workflow helps people to understand how ontology is created, and provides a guidance to be followed in order to get the best from the results.

The Semantic Web technologies enable mineral exploration geologists to formally specify their knowledge for machine processing and data integration. Generating a common vocabulary for mineral exploration geology eliminates the use of heterogeneous terms among exploration geologists. Moreover, the vocabulary can be useful for different areas in geology and provide a taxonomy which can be reused, for example as database schema. The stages used for mineral exploration activities include various vocabularies, which can be used, extended, or modified by other developers in the future.

The 'MinExOnt' domain ontology may be accessed on the Web, and be used for storing RDF data about different aspects of mineral exploration in a related knowledge base. The

ontology can support publishing and retrieving structured data sets originating from different, distributed sources on the Web. This allows effective data integration,discovery, access, and use by both humans and machines (software agents).

The quality of ontology depends on the developer's knowledge of the subject, and on how well it represents the domain knowledge. According to Noy and McGuinnes (2001) *'There is no one correct way to model a domain – there are always viable alternatives. The best solution almost always depends on the application that you have in mind and the extensions that you anticipate'*. It is expected that the mineral exploration ontology will grow as technology improves and more people apply it.

8.2. Future work

The following topics can be pursued as a continuation of this thesis research in the future:

- ➢ MinExOnt is a valuable source of information for researchers dealing with mineral exploration; therefore, it can be reused andextended with further detailed and new information, and integrated with other existing geological ontologies.
- ➢ The ontology generated in this research represents (models) the knowledge of the domain expert. Thus, another domain expert mayconsider and analyze the domain from a different perspective which depends on how much or what kind of knowledge he/she has.
- ➢ OWL object and data properties used for this domain ontology can be enriched through the use of property characteristics. Few features including inverse and equivalent properties are used in the study. They can be improved with other

variable characteristics, such as functional, inverse functional, transitive, symmetric, asymmetric, reflexive, and irreflexive, to build a more meaningful knowledge model.

➢ The MinExOnt ontology can be instantiated with real values from the mineral exploration domain and mining companies.

➢ MinExOnt can be published on the web. The MinExOnt can be linked to other related ontologies, for example in the Linked Open Data Cloud. This will enable the domain knowledge to grow and extend faster.

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APPENDIX A: OWL code

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    <!ENTITY xml "http://www.w3.org/XML/1998/namespace" >
    <!ENTITY rdfs "http://www.w3.org/2000/01/rdf-schema#" >
    <!ENTITY rdf "http://www.w3.org/1999/02/22-rdf-syntax-ns#" >
]>


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     xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
     xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
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     versionIRI="http://www.gsu.edu/ontologies/MinExOnt/1.0">
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Ontology</Literal>
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   <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Assay"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#GeologicalStructure"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SubSurfaceLithology"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Lithology"/>
```

```
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SubSurfaceSample"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Sample"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SubsurfaceEvaluation"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Evaluation"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceAlteration"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Alteration"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceAssay"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Assay"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceEvaluation"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Evaluation"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceLithology"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Lithology"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceSample"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Sample"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#TargetDrilling"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#MineralExplorationStages"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#TargetGeneration"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#MineralExplorationStages"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Technician"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Employee"/>
    </SubClassOf>
    <SubClassOf>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#TopographicMap"/>
        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Map"/>
    </SubClassOf>
```

```xml
<EquivalentObjectProperties>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#determinedBy"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#identifiedBy"/>
</EquivalentObjectProperties>
<EquivalentObjectProperties>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#determines"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#identifies"/>
</EquivalentObjectProperties>
<EquivalentObjectProperties>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#leadsTo"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#resultsIn"/>
</EquivalentObjectProperties>
<EquivalentObjectProperties>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#usedFor"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#utilizedFor"/>
</EquivalentObjectProperties>
<EquivalentObjectProperties>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#uses"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#utilizes"/>
</EquivalentObjectProperties>
<SubObjectPropertyOf>
  <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedForSubSurfaceEvaluation"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedFor"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
  <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedForSurfaceEvaluation"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedFor"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasAreaSelection"/>
  <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMineralExplorationStages"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasChipSample"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasSample"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasCoreSample"/>
  <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasSample"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
```

```xml
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasGeochemicalSurvey"/>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetGenerationStages"/>
  </SubObjectPropertyOf>
  <SubObjectPropertyOf>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasGeophysicalSurvey"/>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetGenerationStages"/>
  </SubObjectPropertyOf>
  <SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasGravitimeter"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTool"/>
  </SubObjectPropertyOf>
  <SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPChargeability"/>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter"/>
  </SubObjectPropertyOf>
  <SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPConductivity"/>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter"/>
  </SubObjectPropertyOf>
  <SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPDensity"/>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter"/>
  </SubObjectPropertyOf>
  <SubObjectPropertyOf>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPMagneticSusceptibility"/>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter"/>
  </SubObjectPropertyOf>
  <SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPRadiation"/>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter"/>
  </SubObjectPropertyOf>
  <SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPRemanence"/>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter"/>
```

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```xml
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPResistivity"/>
      <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter"/>
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMagnetometer"/>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTool"/>
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMapping"/>
      <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetGenerationStages"/>
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasRemoteSensing"/>
      <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetGenerationStages"/>
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasReserveDefinition"/>
      <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMineralExplorationStages"/>
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasResourceEvaluation"/>
      <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMineralExplorationStages"/>
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetDrilling"/>
      <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMineralExplorationStages"/>
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetGeneration"/>
      <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMineralExplorationStages"/>
    </SubObjectPropertyOf>
    <SubObjectPropertyOf>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTypeOfDDrilling"/>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTypeOfDrilling"/>
    </SubObjectPropertyOf>
```

```xml
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTypeOfRCDrilling"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTypeOfDrilling"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#leadsToDHAlteration"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#leadsTo"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#leadsToDHLithology"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#leadsTo"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#measuredByGravitimeter"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measuredBy"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#measuredByMagnetometer"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measuredBy"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measuresDensity"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measures"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#measuresMagneticSusceptibility"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measures"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measuresRemanence"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measures"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needsDHAlteration"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needs"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needsDHAssay"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needs"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needsDHLithology"/>
```

```
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needs"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needsMaps"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needs"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needsSurfaceAssay"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#needs"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#resultsInDHAssay"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#resultsIn"/>
</SubObjectPropertyOf>
<SubObjectPropertyOf>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#resultsInSurfaceAssay"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#resultsIn"/>
</SubObjectPropertyOf>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#analyzes"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#analyzedBy"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#dealsWith"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#doneBy"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#describedBy"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#describes"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#determinedBy"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#determines"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#drilledBy"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#drills"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#evaluatedBy"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#evaluates"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#explains"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#explainedBy"/>
```

```
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#worksFor"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasEmployee"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#identifiedBy"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#identifies"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#logs"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#loggedBy"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#manages"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#managedBy"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measuredBy"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#measures"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#performedBy"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#performs"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#prepares"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#preparedBy"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#productOf"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#produces"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="#resultsFor"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#resultsIn"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#samples"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#sampledBy"/>
</InverseObjectProperties>
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#studiedBy"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#studies"/>
</InverseObjectProperties>
```

```
<InverseObjectProperties>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#usedFor"/>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#uses"/>
</InverseObjectProperties>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#analyzedBy"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Sample"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#analyzes"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Laboratory"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedForSubSurfaceEvaluation"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#DHAlteration"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedForSubSurfaceEvaluation"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#DHLithology"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedForSubSurfaceEvaluation"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SubSurfaceAssay"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedForSurfaceEvaluation"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Map"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#appliedForSurfaceEvaluation"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceAssay"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#dealsWith"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationGeologist"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#describedBy"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Rock"/>
</ObjectPropertyDomain>
```

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<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#describes"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Lithology"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#determinedBy"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#DHAlteration"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#determines"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationGeologist"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#doneBy"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Mapping"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#drilledBy"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Drillhole"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#drills"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationCompany"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#evaluatedBy"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#RemoteSensing"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#evaluates"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationGeologist"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#explainedBy"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Mineralization"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#explains"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Alteration"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasAerialPhotography"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#RemoteSensing"/>
</ObjectPropertyDomain>
<ObjectPropertyDomain>
```

```xml
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasAlteration"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#GeologicalMap"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasAreaSelection"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#MineralExploration"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasChipSample"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Drillhole"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasCoreSample"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Drillhole"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasEmployee"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationCompany"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty
 IRI="http://www.gsu.edu/ontologies/MinExOnt#hasGeologicalStructure"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#StructuralMap"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasGravitimeter"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#GravitySurvey"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasLithology"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#GeologicalMap"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPChargeability"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ElectricalSurvey"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPConductivity"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ElectromagneticSurvey"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPDensity"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#GravitySurvey"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
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    <ObjectProperty
IRI="http://www.gsu.edu/ontologies/MinExOnt#hasMPMagneticSusceptibility"/>
      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#MagneticSurvey"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#RadimetricSurvey"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#MagneticSurvey"/>
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    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasReserveDefinition"/>
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  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
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  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasSatelliteImagery"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#RemoteSensing"/>
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  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasSurfaceSample"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#GeochemicalMap"/>
  </ObjectPropertyDomain>
  <ObjectPropertyDomain>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetDrilling"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#MineralExploration"/>
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    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetGeneration"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#MineralExploration"/>
  </ObjectPropertyDomain>
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<ObjectPropertyDomain>
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    <ObjectPropertyDomain>
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        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Magnetometer"/>
    </ObjectPropertyDomain>
    <ObjectPropertyDomain>
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        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Magnetometer"/>
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    <ObjectPropertyDomain>
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        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SubsurfaceEvaluation"/>
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        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SubsurfaceEvaluation"/>
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    <ObjectPropertyDomain>
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        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SubsurfaceEvaluation"/>
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        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceEvaluation"/>
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        <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#MineralExploration"/>
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    <ObjectPropertyDomain>
        <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#preparedBy"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Sample"/>
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    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#produces"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Mapping"/>
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  <ObjectPropertyDomain>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Sample"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationGeologist"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#CoreSample"/>
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    <ObjectPropertyDomain>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#uses"/>
      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#GeochemicalSurvey"/>
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      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceEvaluation"/>
    </ObjectPropertyRange>
    <ObjectPropertyRange>
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    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#describes"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Rock"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationGeologist"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#DHAlteration"/>
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      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasCoreSample"/>
      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#CoreSample"/>
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    <ObjectPropertyRange>
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      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Drillhole"/>
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    <ObjectPropertyRange>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Lithology"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Chargeability"/>
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  <ObjectPropertyRange>
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    <ObjectPropertyRange>
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      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SatelliteImagery"/>
    </ObjectPropertyRange>
    <ObjectPropertyRange>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasSurfaceSample"/>
      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#SurfaceSample"/>
    </ObjectPropertyRange>
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      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#hasTargetDrilling"/>
      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#TargetDrilling"/>
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      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#TargetGeneration"/>
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      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#RCDrilling"/>
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    <ObjectPropertyRange>
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      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationGeologist"/>
    </ObjectPropertyRange>
    <ObjectPropertyRange>
      <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#identifies"/>
      <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#DHLithology"/>
    </ObjectPropertyRange>
    <ObjectPropertyRange>
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    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#leadsToDHAlteration"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#DHAlteration"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#DHLithology"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#ExplorationGeologist"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Core"/>
</ObjectPropertyRange>
<ObjectPropertyRange>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#managedBy"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Geophysicist"/>
</ObjectPropertyRange>
<ObjectPropertyRange>
    <ObjectProperty IRI="http://www.gsu.edu/ontologies/MinExOnt#manages"/>
    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#GeophysicalSurvey"/>
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    <Class IRI="http://www.gsu.edu/ontologies/MinExOnt#Density"/>
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Alteration</Literal>
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minerals</Literal>
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    <IRI>http://www.gsu.edu/ontologies/MinExOnt#SiltSample</IRI>
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    <Literal datatypeIRI="&rdf;PlainLiteral">SoilSample</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">StreamSample</Literal>
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    <IRI>http://www.gsu.edu/ontologies/MinExOnt#StructuralMap</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">StructuralMap</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:comment"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#SubSurfaceAssay</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">SubSurfaceAssay equals to DHAssay </Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">SubSurfaceAssay</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#SubSurfaceLithology</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">SubSurfaceLithology</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">SubSurfaceEvaluation</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#SurfaceAlteration</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">SurfaceAlteration</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">SurfaceAssay</Literal>
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    <IRI>http://www.gsu.edu/ontologies/MinExOnt#SurfaceLithology</IRI>
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    <Literal datatypeIRI="&rdf;PlainLiteral">Technician</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">TopographicMap</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">analyzes</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">appliedFor</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">describedBy</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">describes</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">determinedBy</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">determines</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">doneBy</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasAerialPhotography</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasAreaSelection</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasChipSample</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasCoreSample</Literal>
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    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasDrillhole</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasDrillhole</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasEmployee</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasGeochemicalSurvey</IRI>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasGeophysicalSurvey</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasGeophysicalSurvey</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasGravitimeter</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasLithology</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasLithology</Literal>
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<AnnotationAssertion>
    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMPChargeability</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasMPChargeability</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMPConductivity</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasMPConductivity</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMPDensity</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasMPDensity</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMPMagneticSusceptibility</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasMPMagneticSusceptibility</Literal>
</AnnotationAssertion>
<AnnotationAssertion>
    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMPRadiation</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasMPRadiation</Literal>
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  <Literal datatypeIRI="&rdf;PlainLiteral">hasMPRemanence</Literal>
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  <AnnotationProperty abbreviatedIRI="rdfs:label"/>
  <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMPResistivity</IRI>
  <Literal datatypeIRI="&rdf;PlainLiteral">hasMPResistivity</Literal>
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  <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMagnetometer</IRI>
  <Literal datatypeIRI="&rdf;PlainLiteral">hasMagnetometer</Literal>
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  <AnnotationProperty abbreviatedIRI="rdfs:label"/>
  <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMapping</IRI>
  <Literal datatypeIRI="&rdf;PlainLiteral">hasMapping</Literal>
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  <AnnotationProperty abbreviatedIRI="rdfs:comment"/>
  <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter</IRI>
  <Literal datatypeIRI="&rdf;PlainLiteral">used as hasMP for sub-properties</Literal>
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  <AnnotationProperty abbreviatedIRI="rdfs:label"/>
  <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMeasuredParameter</IRI>
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  <AnnotationProperty abbreviatedIRI="rdfs:label"/>
  <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasMineralExplorationStages</IRI>
  <Literal datatypeIRI="&rdf;PlainLiteral">hasMineralExplorationStages</Literal>
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  <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasRemoteSensing</IRI>
  <Literal datatypeIRI="&rdf;PlainLiteral">hasRemoteSensing</Literal>
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  <AnnotationProperty abbreviatedIRI="rdfs:label"/>
  <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasReserveDefinition</IRI>
  <Literal datatypeIRI="&rdf;PlainLiteral">hasReserveDefinition</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasSatelliteImagery</IRI>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasSurfaceSample</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasSurfaceSample</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasTargetGeneration</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasTargetGenerationStages</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasTargetGenerationStages</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasTool</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasTool</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:comment"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasTypeOfDDrilling</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">Diamond Drilling</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasTypeOfDDrilling</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">hasTypeOfDrilling</Literal>
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    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasTypeOfRCDrilling</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">Reverse Circulation Drilling</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#hasTypeOfRCDrilling</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">hasTypeOfRCDrilling</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">identifies</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">leadsToDHAlteration</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#leadsToDHLithology</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">leadsToDHLithology</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">loggedBy</Literal>
</AnnotationAssertion>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#logs</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">logs</Literal>
</AnnotationAssertion>
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    <Literal datatypeIRI="&rdf;PlainLiteral">managedBy</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">manages</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">measuredBy</Literal>
</AnnotationAssertion>
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    <IRI>http://www.gsu.edu/ontologies/MinExOnt#measuredByGravitimeter</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">measuredByGravitimeter</Literal>
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    <IRI>http://www.gsu.edu/ontologies/MinExOnt#measuredByMagnetometer</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">measuredByMagnetometer</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">measures</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">measuresDensity</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#measuresRemanence</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">measuresRemanence</Literal>
</AnnotationAssertion>
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    <Literal datatypeIRI="&rdf;PlainLiteral">performedBy</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">preparedBy</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">prepares</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">produces</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">productOf</Literal>
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    <Literal datatypeIRI="&rdf;PlainLiteral">resultsIn</Literal>
</AnnotationAssertion>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
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    <Literal datatypeIRI="&rdf;PlainLiteral">resultsInDHAssay</Literal>
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    <AnnotationProperty abbreviatedIRI="rdfs:label"/>
    <IRI>http://www.gsu.edu/ontologies/MinExOnt#resultsInSurfaceAssay</IRI>
    <Literal datatypeIRI="&rdf;PlainLiteral">resultsInSurfaceAssay</Literal>
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    <IRI>http://www.gsu.edu/ontologies/MinExOnt#sampledBy</IRI>
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        <AnnotationProperty abbreviatedIRI="rdfs:label"/>
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<!-- Generated by the OWL API (version 3.3.1957) http://owlapi.sourceforge.net -->
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