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Semantics-informed geological maps: conceptual modeling and knowledge encoding

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Abstract

This paper introduces a novel, semantics-informed geologic mapping process, whose application domain is the production of a synthetic geologic map of a large administrative region. A number of approaches concerning the expression of geologic knowledge through UML schemata and ontologies have been around for more than a decade. These approaches have yielded resources that concern specific domains, such as, e.g., lithology. We develop a conceptual model that aims at building a digital encoding of several domains of geologic knowledge, in order to support the interoperability of the sources. We apply the devised terminological base to the classification of the elements of a geologic map of the Italian Western Alps and northern Apennines (Piemonte region). The digitally encoded knowledge base is a merged set of ontologies, called OntoGeonous. The encoding process identifies the objects of the semantic encoding, the geologic units, gathers the relevant information about such objects from authoritative resources, such as GeoSciML (giving priority to the application schemata reported in the INSPIRE Encoding Cookbook), and expresses the statements by means of axioms encoded in the Web Ontology Language (OWL). To support interoperability, OntoGeonous interlinks the general concepts by referring to the upper part level of ontology SWEET (developed by NASA), and imports knowledge that is already encoded in ontological format (e.g., ontology Simple Lithology). Machine-readable knowledge allows for consistency checking and for classification of the geological map data through algorithms of automatic reasoning.

Keywords: geologic knowledge encoding, geologic unit ontology, geodatabase, geological map, conceptual modeling of geologic knowledge, automatic reasoning

1. Introduction

This paper introduces a novel, semantics-informed geologic mapping process for the production of a synthetic geologic map of a large administrative region, concerning an orogenic system, namely the Geological Map of Piemonte, in the Alps-Apennines interference zone (Piana et al., 2017)¹. The task of geologic mapping requires the identification of the conceptual objects, or features, with two types of factors that control data-quality:

1. the accuracy of observation/measurement, such as, e.g., the geographic position or the composition of some feature, and
2. the suitability of the representation for the task at hand, such as, e.g., the descriptive elements of some feature.

Here we focus on the latter point, that is the representational issues that raise in the geologic mapping task. In particular, this paper presents a conceptual model that addresses bodies of materials in the Earth, named “geologic units”. Geologic units are 1) hierarchically organized into component units, with the most basic units including some compositions of Earth materials and 2) defined according to some basis (which can be chronological, lithological, etc.). The conceptual model provides a data organization: on the one hand, it is compliant with the general knowledge about the geologic units (the objects of the geomapping task); on the other, it contributes to achieve the objective of the task, a classification of the objects with the purpose of their representation on the map (as a graphic object or as a part of an informative system), following an established model of geotectonic evolution of the mapped region. The conceptual model encodes the geologic knowledge to yield a terminological base for the geologic units; the paradigm of linked data (Bizer et al., 2009) supports interoperability of several knowledge sources while keeping the same sources non redundant (see, e.g., the

¹For a review of the geology of the Alps-Apennines orogenic system, see (Mosca et al., 2009; Beltrando et al., 2010; Dal Piaz, 2010; d’Atri et al., 2016; Molli et al., 2010).

28 5* deployment schemata for open data²); machine-readability of the encod-
29 ing supports the applicability of automatic reasoning mechanisms, with the
30 goals of consistency checking and instance classification (through Description
31 Logic – DL – formalism (Nardi and Brachman, 2003; Baader et al., 2007) –
32 here expressed in Web Ontology Language OWL 2 (Hitzler et al., 2009a),
33 and reasoning tools – we employ Pellet (Sirin et al., 2007)).

34 However, the design and implementation of a conceptual model is not
35 straightforward. When semantics comes into play, Earth scientists and com-
36 puter scientists must address philosophical issues. The principles for data
37 organization raise classical ontological questions such as:

- 38 • Are the data at hand instances of general concepts (also called cate-
39 gories or classes)? And how do we motivate the existence of such classes
40 and not others?
- 41 • How do we define a correct classification of instances?
- 42 • What is the nature of relations existing over classes and instances?

43 Ontological representation has been the goal of philosophical disciplines for
44 centuries and then of computer science for decades (Hitzler et al., 2009b).
45 The definition and usage of the Semantic Web framework (Berners-Lee et al.,
46 2001) has envisioned a web with a relevant role of the deep meaning of objects,
47 beyond the mere textual format. In particular, a number of languages that
48 are suitable for knowledge representation and reasoning have been developed
49 and tested over several domains. Description logic, implemented through a
50 number of profiles of the Web Ontology Language (OWL) family, interprets
51 the world as classes and instances together with relations (or properties) that
52 provide class restrictions. Such languages are suitable for the classification
53 task that is relevant in geologic mapping and can provide 1) consistency
54 and interoperability of data, 2) a semantic approach to the representation,
55 and, through the machine-readable encoding, 3) an immediate support to
56 applications.

57 The knowledge sources for realizing such an encoding of classes and in-
58 stances of the geologic mapping task are 1) the GeoScience Markup Lan-
59 guage schemata and vocabularies, 2) the INSPIRE Data Specification on

²<http://5stardata.info/en/>

Geology directives, 3) the machine-readable encoding provided for some specific domain, such as the lithology domain (vocabulary Simple Lithology) and the geochronologic time scale (ontology “gts”), and finally 4) for the upper level knowledge, shared across several geologic domains, the upper part of the NASA SWEET ontology. The goal of this paper is to encode the statements reported in a number of authoritative sources into an interlinked machine-readable format; the result is a set of merged ontologies named OntoGeonous³. The source statements that are mostly expressed in natural language have been encoded through a process of semantic interpretation that has produced axioms in the OWL-2 language; the concepts and the relations referred to by the axioms are kept coherent in their meaning throughout the whole knowledge base (internal coherence) and with respect to external sources that were already encoded and that are imported into OntoGeonous (external coherence); the geomapping data are classified according to the ontology, consistency checking and novel knowledge inference is achieved through automatic reasoning. We consider our contribution an initial step for the geological knowledge to participate into the Linked Data challenge (the web as one big interlinked database). In large practical applications, our OWL-based approach will likely be replaced by RDF-based syntax and software architecture that scale to data warehouse and continuously changing data (Polleres et al., 2013).

The paper is organized as follows. The next section states the motivations for this work. In section 3, we report on some relevant related work. Section 4 describes the realization of the semantics-informed mapping. Section 5 presents our conclusions. In the following we will use a few schemata. In Figure 1 is the legend of the figures to come.

2. Motivations for this work

In this section, we introduce the data representation of the geologic units of the Piemonte Geological Map (Piana et al., 2017) and how the conceptual modeling can improve such representation. We go through an example

³For purposes of proof of concept, the current ontology can be retrieved at the URL: http://www.di.unito.it/~vincenzo/ontologies/20161013_OntoGeonous_Merge_Inst.owl, together with a human-readable version of it <http://www.di.unito.it/~vincenzo/ontologies/OntoGeonous.htm>. We will address the issue of url persistence in the near future, after the establishment of an effective general workflow.

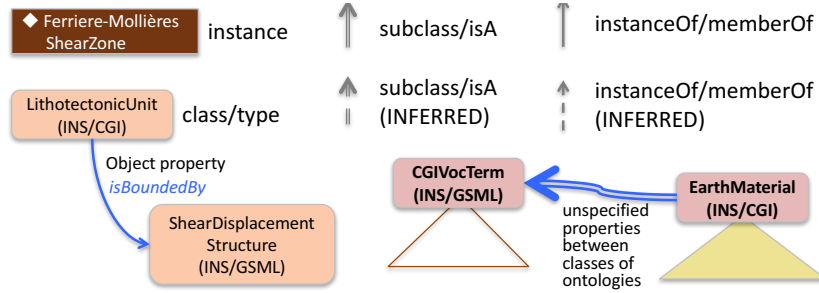


Figure 1: In the figures of this paper: sharp corner boxes with dark background and white text prefixed with diamonds are instances (e.g., Ferriere-Mollières ShearZone); rounded corner boxes with light background and black text are types or classes (e.g., LithotectonicUnit (INS/CGI)); unlabelled solid (dotted in the case of inferences) double vertical arrows are subclass (or isA) relations; unlabelled solid (dotted in the case of inferences) single vertical arrows are instanceOf (or memberOf) relations; curved labelled solid (dotted in the case of inferences) blue arrows indicate that there are Object Property relations between the classes; large curved unlabelled solid double blue arrows indicate that there a number of object properties hold over the classes of two ontologies. Triangles with some root class (e.g., CGIVocTerm) represent ontological encoding of some knowledge source.

90 from our geologic mapping task and we employ the major knowledge sources
 91 mentioned above to produce an item in the underlying data base⁴. The ex-
 92 ample concerns a specific geologic unit named “Formazione di Baldissero”
 93 (Baldissero Formation). If we employ the GeoSciML vocabularies and the
 94 INSPIRE directives (see references below), we can list the XML statements
 95 in the Listing 1.
 96 “Formazione di Baldissero” is a geologic unit, with an identifier (gml:id, line
 97 03), reported after the namespaces involved (xmlns), a description and a
 98 name (both in Italian, original language of the geomapping database, lines
 99 04 and 05), and an occurrence in the map (line 06). It has a geologic history
 100 (lines 07–11), here related to one or more geologic events (not furtherly spec-
 101 ified). Its type is the lithostratigraphic unit (lines 12–14), whose definition
 102 is at a precise URL in the CGI vocabulary of the GeologicUnitType. It is
 103 composed (gsmlb:composition) of two parts (gsmlb:CompositionPart), lines
 104 17–31 and lines 34–48 respectively, each with a specific role (stratigraphic

⁴The current encoding is underlying the visualization accessed at the url <http://arpapiemonte.maps.arcgis.com/apps/webappviewer/index.html>

Listing 1 Example of geologic mapping for the geologic unit Formazione di Baldissero, encoded in XML format, with tags from GeoSciML vocabularies.

```

01. <gsmlb:GeologicUnit
02. <!-- all xmlns required -->
03. gml:id="Formazione_di_Baldissero">
04. <gml:description>Successioni arenaceo-pelitiche e marnose burdigaliano-langhiane.</gml:description>
05. <gml:name>Formazione di Baldissero</gml:name>
06. <gsmlb:occurrence gml:id="BAD_MF1"/>
07. <gsmlb:geologicHistory>
08.   <gsmlb:GeologicEvent gml:id= ... >
09.     <!-- geologic event attributes -->
10.   </gsmlb:GeologicEvent>
11. </gsmlb:geologicHistory>
12. <gsmlb:geologicUnitType
13.   xlink:href="http://resource.geosciml.org/classifier/cgi/geologicunittype/lithostratigraphic_unit"
14.   xlink:title="lithostratigraphic unit"/>
15. <!-- There are two component lithologies in this example -->
16. <gsmlb:composition>
17.   <gsmlb:CompositionPart>
18.     <gml:name>Formazione di Baldissero CP1</gml:name>
19.     <gsmlb:role
20.       xlink:title="stratigraphic_part"
21.       xlink:href="http://inspire.ec.europa.eu/codelist/CompositionPartRoleValue/stratigraphicPart"/>
22.     <gsmlb:material>
23.       <gsmlb:RockMaterial gml:id="Areniti_ibride_Baldissero_RM1">
24.         <gsmlb:lithology
25.           xlink:href="http://inspire.ec.europa.eu/codelist/LithologyValue/arenite"
26.           xlink:title="arenite"/>
27.         </gsmlb:RockMaterial>
28.       </gsmlb:material>
29.       <gsmlb:proportion>
30.         <!-- what pertains proportions of materials -->
31.       </gsmlb:proportion>
32.     </gsmlb:CompositionPart>
33.   </gsmlb:composition>
34.   <gsmlb:composition>
35.     <gsmlb:CompositionPart>
36.       <gml:name>Formazione di Baldissero CP2</gml:name>
37.       <gsmlb:role
38.         xlink:title="stratigraphic_part"
39.         xlink:href="http://inspire.ec.europa.eu/codelist/CompositionPartRoleValue/stratigraphicPart"/>
40.       <gsmlb:material>
41.         <gsmlb:RockMaterial gml:id="Marne_con_intercalazione_arenacee_Baldissero_RM2">
42.           <gsmlb:lithology
43.             xlink:href="http://inspire.ec.europa.eu/codelist/LithologyValue/impure_carbonate_sedimentary_rock"
44.             xlink:title="impure_carbonate_sedimentary_rock"/>
45.           </gsmlb:RockMaterial>
46.         </gsmlb:material>
47.         <gsmlb:proportion>
48.           <!-- what pertains proportions of materials -->
49.         </gsmlb:proportion>
50.       </gsmlb:CompositionPart>
51.     </gsmlb:composition>
52.   </gsmlb:GeologicUnit>

```

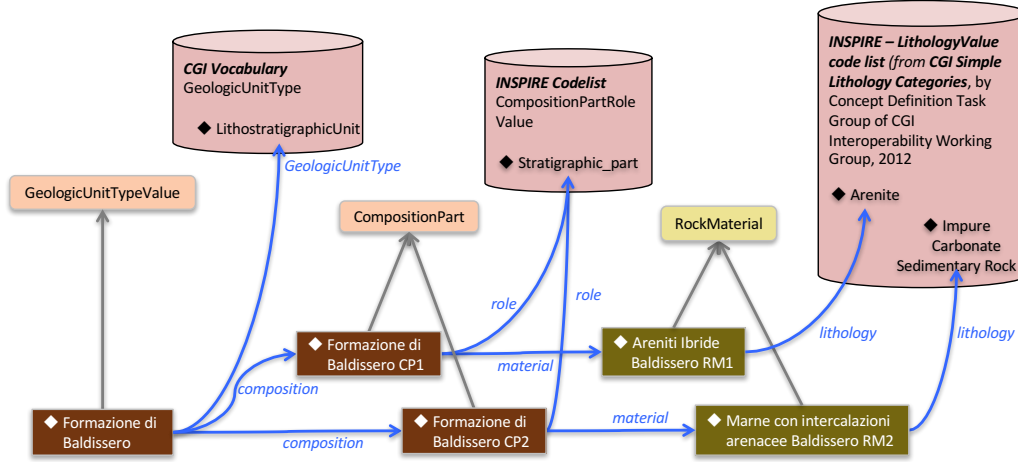


Figure 2: Schematic representation of the GeoSciML encoding for the geologic unit “Formazione di Baldissero” (Baldissero Formation, bottom left corner), with two composition parts, made of materials hybrid arenite and marl with interbedded arenite, respectively.

part in both cases, lines 20 and 37 respectively) and material (some lithology, lines 24 and 41 respectively). Each composition part occupies some proportion of the total (not reported in this example, lines 28–30 and 45–47 respectively). Figure 2 shows a schematic representation of such metadata, in which we have made explicit the connections that are positionally represented in the XML representation over the instances and the types.

The geomapping task requires a framework for the adequate description of the elements in the Listing 1. However, in the XML representation, types or classes (gml tags⁵) have not an explicit definition and the several concepts are not formally interconnected. Values for descriptions should be searched in the mostly informal external resources (CGI vocabularies, INSPIRE codelists, ...), which are not verified automatically for possible inconsistencies or overlaps. The contribution of this paper is to introduce an interlinked machine-readable encoding of geologic knowledge to serve as a consistent terminological base for the geomapping task. Figure 3 shows a

⁵The OpenGIS Geography Markup Language Encoding Standard (GML) is a XML grammar for expressing geographical features - <http://www.opengeospatial.org/standards/gml>.

120 schematic representation of the same geologic unit of Figure 2 (“Formazione
 121 di Baldissero”) in the OntoGeonous encoding. Tags are not mere strings,
 122 but references to logical concepts (also called classes) inserted into a large
 123 knowledge base. To prevent redundancy, classes are organized hierarchi-
 124 cally through the principle of set inclusion (or isA relation, represented by
 125 the triangles). Whenever possible from the authoritative sources, we intro-
 126 duced class definitions, which state the necessary and sufficient conditions for
 127 the class existence and are paramount for the automatic classification task
 128 over instances. Classes belonging to external specific ontologies are not re-
 129 encoded; though according to the linked data paradigm we can refer to such
 130 classes from the OntoGeonous ontology through some IRI (Internationalized
 131 Resource Identifier), in the current implementation, we directly imported
 132 the whole external ontology for prototype validation. The several sources
 133 mentioned above, which were referred through URL’s to specific concepts,
 134 are now interconnected and reasoning mechanisms can be applied to check
 135 the knowledge consistency at large and to classify instances according to the
 136 relations that hold over instances. This encoding of community standards
 137 as well as of the instances in the map is a step towards interoperability:
 138 another geomapping process would refer to the same knowledge base, fa-
 139 voring consistency of representations and comparisons over several projects,
 140 with mutual benefits in terms of ease of geomapping implementation and of
 141 application/services development.

142 **3. Related work**

143 The sources that make up the backbone of our approach are addressed
 144 later in the paper. Here, we refer to a number of approaches that apply
 145 a semantics-informed interpretation of datasets (especially in the context
 146 of geomapping tasks) and that we have taken into account during our re-
 147 search. We address three types of related works: the technical infrastructures
 148 for semantics-informed applications, the ontological encoding of specialized
 149 domains, and the usage of authoritative resources (such as GeoSciML and
 150 INSPIRE).

151 The technical infrastructures are very numerous in the geomatic litera-
 152 ture. They are complementary to OntoGeonous: where they introduce tech-
 153 nicality for realizing services, we introduce content (or knowledge) to support
 154 those services. Eventually, in general, all these infrastructures could benefit

166 to ontology SWEET (Zhao et al., 2009). OntoGeonous could be a domain
167 ontology in this application.

168 AuScope⁸ is an integrated national framework that uses vocabulary-
169 based services for querying geological maps (Woodcock et al., 2010). The
170 British Geological Survey (BGS) has developed and implemented a cyber-
171 infrastructure that makes explicit much of the implicit knowledge acquired
172 by new geological surveys (Howard et al., 2009). SETI (Semantics Enabled
173 Thematic data Integration)(Durbha et al., 2009) is a system that enables
174 the retrieval of information from thematic data archives via semantics-driven
175 searches. In these projects, ontologies were developed for the classification
176 schemes and a shared-ontology approach for integrating the application level
177 ontologies; however, they are not available for further usages and consistency
178 checking has not been an issue in these projects.

179 More restricted in focus are CHRONOS (Fils et al., 2009), which inte-
180 grates stratigraphic databases, and Hydroseek (Beran and Piasecki, 2009), an
181 ontology-aided search engine, that allows users to query multiple hydrologic
182 repositories, with a knowledge base that covers water quality, meteorology
183 and hydrology domains.

184 Finally, related to Ma’s ontology mentioned above is the pilot interactive
185 multimedia project developed by (Ma et al., 2012), who provided an animated
186 visualization and interaction functions over the Geologic Time Scale ontology
187 (Ma, 2011). OntoGeonous could be used for connecting specific knowledge
188 with general geologic knowledge; however, this would require an adaptation
189 of the present ontologies for the sake of the interoperability goal.

190 Approaches aimed at the ontological encoding of specialized domains are
191 Virtual Solar–Terrestrial Observatory (VSTO) and Space Physics Archive
192 Search and Extract (SPASE). VSTO⁹ is a semantic data framework based
193 on an ontology of the domains of solar physics, space physics and solar-
194 terrestrial physics (Fox et al., 2009). As in the case of OntoGeonous, VSTO
195 also refers to the functional decomposition of SWEET, reusing, e.g., the
196 notions of Earth and sun realms, respectively. The SPASE consortium¹⁰
197 have been creating a comprehensive space physics data model (Narock et al.,
198 2009), converted into an OWL ontology, consists of agreed-upon terminology

⁸https://www.researchgate.net/publication/234183449_AuScope's_use_of_Standards_to_Deliver_Earth_Resource_Data

⁹<https://www.vsto.org>

¹⁰<http://www.spase-group.org/>

199 and –definitions for use in the community and use in virtual observatories.

200 These approaches employ ontological encoding of specialized domains;
201 as such, these ontologies approach the terminological problem within some
202 separate domain, with limited inter-connections or integrated applications.
203 OntoGeonous could embed the data model here built to provide intercon-
204 nections upon all the branches of geologic knowledge, improving consistency
205 and interoperability.

206 Finally, there are a number of approaches that make the effort of rely-
207 ing on authoritative resources (such as GeoSciML), without introducing ad
208 hoc knowledge specifications. All these approaches currently make a very
209 basic use of ontological encoding: OntoGeonous improves such methods by
210 providing a comprehensive approach to the formal encoding of the geologic
211 knowledge, aimed at subsequent automatization of application algorithms.
212 OneGeology¹¹ has the goal of creating a worldwide geological map by har-
213 monizing data from different providers, using GeoSciML standard. Taxon-
214 Concept¹² (Huber and Klump, 2009) allows to store Open Nomenclature
215 synonymy lists (list of citations related to a taxon name), in the field of
216 taxonomic classification of fossil species. The United States Geoscience In-
217 formation Network¹³ aims to facilitate the access to geoscience information
218 provided by state and federal geological surveys of the United States, with
219 GeoSciML as data transfer standard (Richard and Allison, 2016).

220 The approach described in this paper departs from such initiatives in
221 contributing to an integration of the knowledge sources in the terms of a
222 machine-readable encoding, addressing the convergence on a shared knowl-
223 edge kernel. In order to make things concrete, the encoding is immediately
224 applied to the geomapping task to demonstrate the usefulness and the feasi-
225 bility of the enterprise.

226 4. Realization of OntoGeonous

227 OntoGeonous is a merged ontology consisting of a number of ontologies,
228 some realized anew and some already existing: this implements the paradigm

¹¹<http://portal.onegeology.org/OnegeologyGlobal/> and <http://onegeology-europe.brgm.fr/geoportal/viewer.jsp>

¹²<http://taxonconcept.stratigraphy.net/>

¹³<http://www.dgs.udel.edu/projects/united-states-geoscience-information-network-usgin>
and <http://usgin.org/>

229 of linked data and avoids the re-encoding of existing machine-readable knowl-
230 edge.

231 The knowledge sources we have taken into account are the statements,
232 schemata, vocabularies, and encoded ontologies, from major authoritative
233 institutions (Table 1 summarizes the markers that identify the sources):

- 234 • GeoScience Markup Language (GeoSciML)¹⁴ expressed in a number of
235 UML schemata (classes, features, attributes, associations) and state-
236 ments in natural language, to be encoded in OWL;
- 237 • INSPIRE (Infrastructure for Spatial Information in the European Com-
238 munity)¹⁵ aimed at creating a European Union spatial data infrastruc-
239 ture, expressed through natural language statements, to be encoded in
240 OWL;
- 241 • SWEET (Semantic Web for Earth and Environmental Terminology)¹⁶,
242 developed by NASA–Jet Propulsion Laboratory since 2002, a set of
243 ontologies for environmental and Earth system science terms (Raskin
244 and Pan, 2005; Barahmand et al., 2010), expressed in OWL;
- 245 • vocabularies of specific subdomains of geologic knowledge that are rel-
246 evant for the geomapping task¹⁷, encoded in the SKOS format (Sim-
247 ple Knowledge Organization System¹⁸) and available in .rdf and .ttl
248 versions. For example, we have imported the lithology domain vo-
249 cabulary named Simple Lithology¹⁹, through a simple encoding that
250 creates taxonomic classes as translated from narrower/broader rela-
251 tions over individuals. For the geological timescale, we have integrated
252 ICS Geological Time Scale Ontology (Ma, 2011) as a subtaxonomy of
253 the Geochronologic Unit class of SWEET Representation. In partic-
254 ular, the Geochronologic Unit class of OntoGeonous corresponds to

¹⁴Version 4.0 (2015), <http://www.geosciml.org>

¹⁵D2.8.II.4 INSPIRE Data Specification on Geology Technical Guidelines v. 3.0.
(10.12.2013) (http://inspire.jrc.ec.europa.eu/documents/Data_Specifications/INSPIRE_DataSpecification_GE_v3.0.pdf)

¹⁶(<https://sweet.jpl.nasa.gov/>

¹⁷<http://resource.geosciml.org/vocabulary/cgi/201211/>

¹⁸<https://www.w3.org/2004/02/skos/>

¹⁹<http://resource.geosciml.org/vocabulary/cgi/201211/simplelithology.rdf>

255 SWEET GeologicTimeUnit class (actually the hierarchical path Rep-
 256 resentation – NumericalEntity – Interval – Duration – GeologicTimeU-
 257 nit). We selected Ma’s ICS Geological Time Scale because, in spite of
 258 the simplicity of encoding, it allows the inheritance of a large number of
 259 attributes (multilingual thesaurus, ICS standard RGB code, relations
 260 between concepts). For a more complete ontological approach, we are
 261 considering to integrate Cox and Richard’s GTS ontology in the future
 262 (Cox and Richard, 2015).

Authoritative source	Annotation string
GeoSciML schemata	"GSML"
CGI vocabularies	"CGI"
INSPIRE	"INS"
CGI and INSPIRE shared	"CGI-INS"
GSML and INSPIRE shared	"GSML-INS"
International Commission on Stratigraphy	"ICS"

Table 1: Suffixes for concept terms to mark the provenance from some authoritative source.

263 Once we have identified the domain elements that are relevant for the ge-
 264 omapping task, the steps for the realization of OntoGeonous have been the
 265 following:

- 266 1. taxonomization, that is the identification of the subsumption relation
 267 over classes inferred to exist from the general schemata and vocabular-
 268 ies;
- 269 2. concept axiomatization, that is the introduction of definitions of con-
 270 cepts, i.e. statements that define a concept through the enumeration of
 271 necessary and sufficient conditions for its existence; the goal here is the
 272 issue of disambiguation within the classification task, that is the possi-
 273 bility of unambiguously classifying some object; when this is possible,
 274 we are able to implement automatic reasoning and then classification;
- 275 3. incremental validation of knowledge through the encoding of examples
 276 drawn from the map and automatic verification of consistency with
 277 respect to the whole knowledge base.

278 In our case, the objects that result from the conceptual modeling task are
 279 the geologic units, accurately identified on the map, bordered by geologic

280 structures and related to geologic events. In the following, we address the
 281 individual encoding phases as separate, linearly ordered processes. However,
 282 the real encoding has proceeded through several adjustments in parallel on
 283 the several phases.

284 *4.1. Identification of knowledge sources and big picture*

285 Figure 4 illustrates a schematic interconnection of the knowledge sources
 286 that compose OntoGeonous. The triangles represent the major concept tax-
 287 onomies, concerning different realm (kept distinct by colors). In the upper
 288 left corner, the original sources: GeoSciML–INSPIRE and SWEET ontology
 289 on the left, ICS GTS and Simple Lithology ontologies on the right (notice that
 290 the latter two are already in ontological format, OWL file format). The most
 291 relevant taxonomy of concepts is provided by GeoSciML–INSPIRE source.

292 The core of the geologic knowledge is the (orange-colored) taxonomy
 293 rooted by Geologic Feature, with four major subclasses, GeoMorphologicFea-
 294 ture, GeologicUnit, GeologicStructure, and GeologicEvent (see below). This
 295 taxonomy is connected to all those features, attribute, properties, that con-
 296 stitute generic knowledge, shared with other scientific disciplines. These
 297 connections are illustrated as curved blue lines. All the knowledge sources
 298 that merge into OntoGeonous make a reference to the frameworks (such as
 299 SWEET) that encode the concepts that are abstractions of the specific ones
 300 employed in the Earth sciences.

301 The concept GeologicFeature, which encompasses all the geologic core
 302 knowledge, is related to many external concepts, which define its major dis-
 303 tinctive attributes. We enumerate these external concepts going downwards
 304 on the blue arrows from GeologicFeature in Figure 4. First, GeologicFeature
 305 is related to some MappedFeature, a fundamental relation for the geomap-
 306 ping task. A mapped feature is the spatial extent of the geologic feature on
 307 the map. In turn, a mapped feature is related to some geometrical object
 308 (such as, e.g., a polygon), a subconcept of the generic concept of Represen-
 309 tation, in the upper part of the ontology SWEET. Second, GeologicFeature
 310 is related to some GeoChronologicUnit, root of the ICS GTS taxonomy (the
 311 light blue triangle in Figure 4 – upper right) and identified with the cor-
 312 responding concept in the Representation taxonomy of ontology SWEET.
 313 Finally, GeologicFeature is related to the CGIVocabularyTerm vocabularies
 314 (a taxonomy), which provide specific concepts for the several subdomains,
 315 such as the ones for the Earth materials, and to the abstract descriptions in
 316 GeoSciML, which encode attributes, such as the unit thickness.

317 GeologicFeature is subdivided into four sub-taxonomies, namely Geo-
 318 MorphologicFeature, GeologicUnit, GeologicStructure, GeologicEvent. Each
 319 of these concepts addresses some distinctive object of the geologic knowledge:

- 320 1. GeoMorphologicFeature describes the landforms, which have event pro-
 321 cesses as their major distinctive attribute. Event processes, which
 322 concern the creation, modeling, etc. of geomorphologic features, are
 323 described by a taxonomy/ontology whose major subclasses are Natu-
 324 ralEarthProcess and HumanActivity. The event process taxonomy can
 325 be considered as a mid-level ontology subsumed by the concept Process
 326 (in turn, subclass of Phenomenon) in the SWEET ontology.
- 327 2. GeologicUnit describes a body of some material, which has the compo-
 328 sition material as distinctive attribute. As it happens with EventPro-
 329 cess, also EarthMaterial, which specifies the Substance concept in the
 330 SWEET ontology and includes the ontology SimpleLithology, is a tax-
 331 onomy with a number of subclasses and related vocabularies (CGIVo-
 332 cabularyTerm taxonomy and GSML Abstract Description). In partic-
 333 ular, CompoundMaterial, a subclass of EarthMaterial, is the object
 334 of CompositionPart, an intermediate representation concept that ad-
 335 dresses the splitting of some body of material into several parts accord-
 336 ing to their composition materials.
- 337 3. GeologicStructure describes the configurations or patterns in which the
 338 geologic units are arranged, either internally or externally. In partic-
 339 ular, GeologicStructure is mainly described through some abstraction,
 340 such as inhomogeneity, internal deformation, pattern, or some actual
 341 features such as fracture or fault, occurring in the Earth material.
- 342 4. GeologicEvent describes the relevant events in geology. Given the IN-
 343 SPIRE definition as “an identifiable event during which one or more
 344 geological processes act to modify geological entities” and that “should
 345 have a specified geologic age and process, and may have a specified en-
 346 vironment”, we assume that a GeologicEvent is characterized by both
 347 an EventProcess and an EventEnvironment. The latter two are sub-
 348 classes of the PlanetaryRealm and Phenomena concepts in SWEET,
 349 respectively, and refer to specific vocabularies in GeoSciML.

350 4.2. *Taxonomization of concepts and criteria of subsumption*

351 Each of the four major concepts is then developed into a taxonomy. In
 352 this section, we illustrate the taxonomy of the Geologic Unit (see Figure 5) by

364 pression “is defined on the basis of”, which recurs regularly in CGI/INSPIRE
 365 definitions. This happens because, though a geologic unit can in principle
 366 belong to several classes, there are preferred factors that determine its actual
 367 classification. For example, a unit can be bounded by a shear displacement
 368 structure as well as contain fossils; so, it can be classified preferably on the
 369 basis of either the type of its bounding geologic structure or the type of its
 370 fossil content; the geologist usually takes such decision according to her/his
 371 classification task and the knowledge encoding must support such decision.
 372 An interesting future research area could be the devise of heuristics for estab-
 373 lishing such preferences: now the system reasons on whatever property has
 374 been encoded for some instance and generally yields multiple classifications
 375 for it.

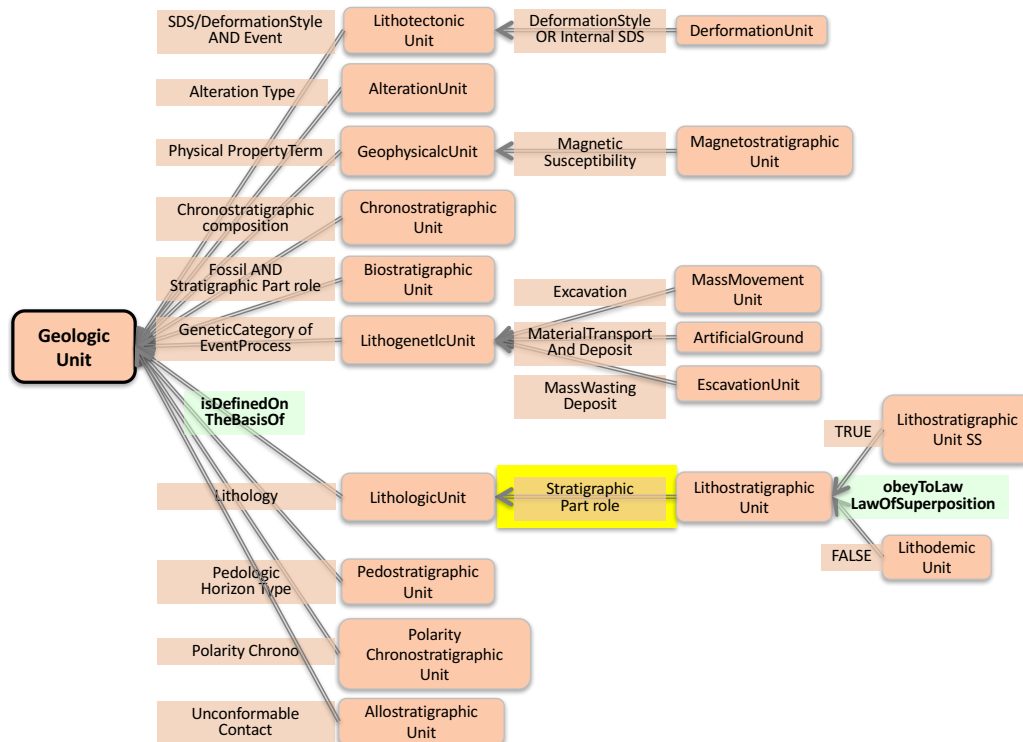


Figure 5: The criteria for subclasses of geologic unit.

376 4.3. Concept axiomatization of major classes

377 The concept axiomatization process is a fundamental part of the onto-
378 logical encoding because of its relevance for the classification task. The goal
379 of this process is to produce an axiom, that is an absolute truth about a
380 concept: operationally, this means to identify the necessary and sufficient
381 conditions for an object to be classified as an instance of some concept. This
382 is why a concept is often called a class in the modern ontological terminology.
383 In order to illustrate the concept axiomatization process, which goes through
384 semi-formal steps of semantic interpretation of natural language definitions
385 and UML schemata, we introduce a running example (Lithotectonic Unit).

386 First, we select the relevant statements from the knowledge sources. For
387 the example of the Lithotectonic unit, the main knowledge sources are the
388 INSPIRE directive (GeologicUnitTypeValue²⁰) and the CGI GeologicUnit-
389 Type vocabulary²¹. The definition reported in INSPIRE is:

390 Geologic unit defined on basis of structural or deformation fea-
391 tures, mutual relations, origin or historical evolution. Contained
392 material may be igneous, sedimentary, or metamorphic.

393 Second, on the basis of such statement, possibly merged with expressions
394 from other knowledge sources, we produce a *protoaxiom*. A protoaxiom is
395 a statement expressed in a controlled natural language: the table 2 reports
396 schematically the protoaxiom production process for the case of the Litho-
397 tectonic unit.

398 The fact that a Lithotectonic unit is a Geologic unit of some sort is
399 translated into the fact that a Lithotectonic unit is a subclass of the Geologic
400 unit class (table header). The notion of equivalence (EQUIVALENT TO)
401 corresponds to the notion of definition, that is in providing the necessary and
402 sufficient conditions for classification. The conditions are in the third and
403 fourth rows of the table, where we can find, on the left (the first column),
404 the expressions in natural language and, on the right (the second column)
405 the expression in pseudo-logic language, that make use of restrictions (object
406 properties – OP and datatype properties – DP) over classes.

407 In the third row, the expression

²⁰[http://inspire.ec.europa.eu/codelist/GeologicUnitTypeValue/
lithotectonicUnit/](http://inspire.ec.europa.eu/codelist/GeologicUnitTypeValue/lithotectonicUnit/)

²¹[http://resource.geosciml.org/classifier/cgi/geologicunittype/
lithotectonic_unit](http://resource.geosciml.org/classifier/cgi/geologicunittype/lithotectonic_unit)

INS - CGI: "Geologic unit"	subclass of CLASS GeologicUnit- GSML/INS
	EQUIVALENT TO
INS - CGI: "defined on basis of structural or deformation features, mutual relations, origin or historical evolution"	"Structural features": OP isBoundedBy some class ShearDisplacementStructure GSML/INS OR "Deformation features": OP hasDeformationStyle some class DeformationStyle - CGI OR "Origin or Historical evolution": OP isRelatedToEvent some class GeologicEvent-GSML/INS NOTE: "Mutual Relations" interpreted as spatial relations imposed by a SDS, i.e. OP isBoundedBy class ShearDisplacementStructure)
INS - CGI: "Contained material may be igneous, sedimentary, or metamorphic"	hasComposition some class CompositionPart - GSML AND hasMaterial some class CompoundMaterial - GSML (inherited from CLASS GeologicUnit - GSML/INS) NOTE: igneous + sedimentary + metamorphic = class CompoundMaterial (IGNORED)

Table 2: Construction of the protoaxioms: left column: expression from the information source; right column: protoaxiom expressed in pseudo-Manchester syntax style.

408 ... defined on basis of structural or deformation features, mutual
409 relations, origin or historical evolution.

410 is split into several parts that are intended as the conjunctive terms of the
411 definition: "structural or deformation features", "mutual relations", "origin
412 or historical evolution". The first part is in turn subdivided into "struc-
413 tural features" and "deformation features", intended as possible alterna-
414 tives (not necessarily exclusive). "Structural features" can be interpreted
415 as "a geologic unit that is bounded by a shear displacement structure":
416 this is encoded as a restriction on the GeologicUnit class through the ob-
417 ject property **isBoundedBy**, whose range is the GeologicStructure subclass
418 **ShearDisplacementStructure**. Similarly, "deformation features" can be in-
419 terpreted as "a geologic unit that has some form of deformation style": this
420 is encoded again as a restriction on the GeologicUnit class through the object
421 property **hasDeformationStyle**, whose range is the vocabulary derived class
422 **DeformationStyle**. The second part, "mutual relations" is included in the
423 "structural features" interpretation as "the spatial relations imposed by the
424 related geologic structure", and so does not contribute further to the defini-
425 tion. Finally, the third part, "origin or historical evolution", can be inter-
426 preted as a generic relation to some geologic event, through the object prop-

erty `isRelatedToEvent`, whose range is the generic class `GeologicEvent`.

The fourth row makes reference to the composition material of the geologic unit. Though the right column reports an encoding in terms of class restrictions, as reported in the note, we interpreted the statement as redundant, since it reports all the possible materials, and decided not to add any logic statement to the previous definition.

Third, the protoaxiom is encoded in OWL language, to form the axiom. The example of axiom concerning the Lithotectonic Unit is the following:

```

435 CLASS LithotectonicUnit CGI/INS EQUIVALENT TO
436 CLASS GeologicUnit - GSML/INS and
437 ((hasDeformationStyle some DeformationStyle) or
438 (isBoundedBy some ShearDisplacementStructure))
439 and
440 (isRelatedToEvent some GeologicEvent)

```

Notice that the connectives **and/or** are nested in the representation above: in fact, deformation style and shear displacement structure can be alternative (though also co-existent, inclusive **or**), while the relationship with some event is necessary for the definition. Figure 6 shows a graphic representation of the axiom.

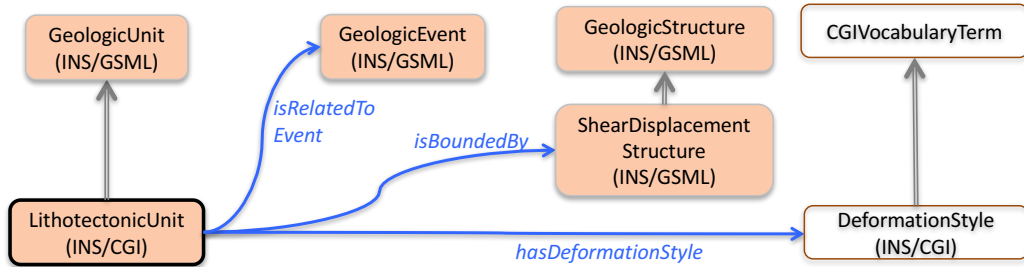


Figure 6: Axiom of the lithotectonic unit in graphic format. The defined class is in bold; the reported object properties are the ones that define the class.

4.4. Encoding of instances and incremental validation of knowledge

Each time a novel axiom is added to the knowledge base, some instances that are related to the axiom are encoded to test the consistency through an application of automatic reasoning. In Figure 7 we report the encoding

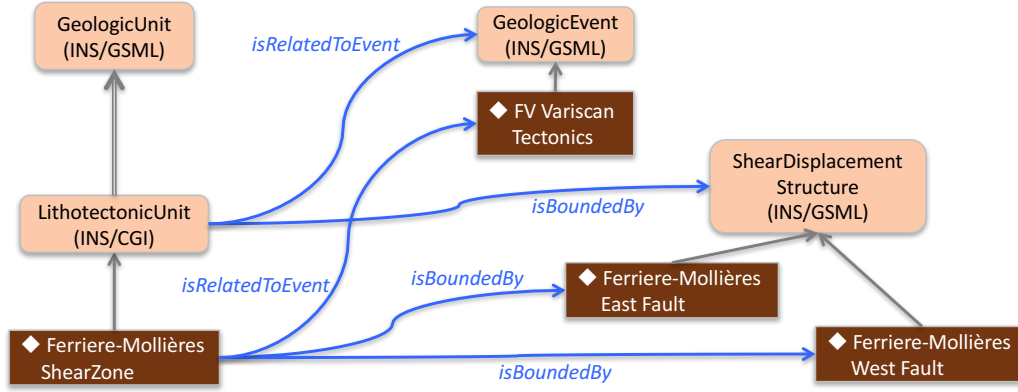


Figure 7: Encoding an instance of geologic unit from the map. The identifiers prefixed with a diamond, in white text on dark background, are instances of the classes connected to them through upward-directed simple arrows.

450 of one instance of Lithotectonic unit, namely the Ferriere–Mollières Shear
 451 Zone, which is bounded by two faults and is related to a tectonic event.

452 The consistency of the knowledge base is tested through the application
 453 of automatic reasoning techniques, which reveal possible inconsistencies and
 454 infer novel knowledge. Figure 8 shows two inferences employed to verify the
 455 consistency of the knowledge base. Ferriere–Mollières Shear Zone is created
 456 as instance of the generic class GeologicUnit and engaging into object prop-
 457 erties of isBoundedBy, hasDeformationStyle, and isRelatedToEvent types,
 458 respectively. According to the definition above, such an instance is classified
 459 automatically as a Lithotectonic unit and, in turn, as a Deformation unit,
 460 because it is both inferred as Lithotectonic and restricted by the “hasDeform-
 461 ationStyle” property (cf. taxonomy in Figure 5). This result shows that
 462 the reasoning mechanism can support the filling of the database and check
 463 the consistency of the knowledge base as it grows, incrementally.

464 Currently, the OntoGeonous ontology contains 707 concepts, split into
 465 the core ontology of the geologic features (and geologic units in particu-
 466 lar, while still lacking geologic structures, geomorphologic features, geologic
 467 events), the Earth materials, the geochronologic units, the environments and
 468 the events, the upper level concepts equalled to SWEET upper concepts (cf.
 469 the big picture in Figure 4). Concepts are restricted through 100 object
 470 properties, which connect some concept to some other concept, mainly em-

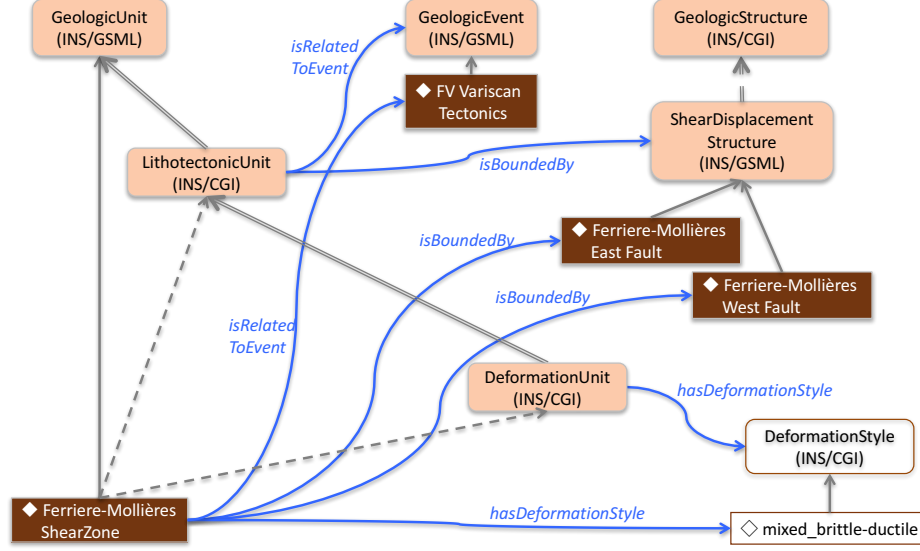


Figure 8: Encoding of the example (solid arrows) and automatic classification (hyphenated arrows marked in yellow).

471 ployed for axiom definition (a geologic unit is a geologic feature restricted to
 472 have some composition of bodies), and 41 datatype properties, which connect
 473 some concept to some attribute (e.g., a boolean value – true/false –
 474 representing that the law of superposition holds). We have introduced 83
 475 equivalence axioms, that is concept definitions that state the necessary and
 476 sufficient conditions for the existence of some class.

477 In order to classify the instances of geologic units in the Piemonte geolog-
 478 ical map, with their Earth materials, the geochronologic unit associated, the
 479 geologic structures that bound the units, the geologic events that originated
 480 the units, we have currently introduced 520 instances. Of such instances, 34
 481 are geologic units (over a totality of about 6,000 geologic units in the map).
 482 These 34 units were selected to cover the most of the classes contained in the
 483 ontology; the rest of the instances account for all the concepts that contribute
 484 to the definitions of the unit classes. We encode the rest of the units through
 485 an ingestion program that creates the instances after a direct retrieval from
 486 the current data base underlying the map.

487 We conclude this section with one example of query on the current knowl-
 488 edge base. If we pose OntoGeonous the query “get all the instances that are

489 GeologicUnit and have a sedimentary rock composition”, that is encoded as

```
490 GeologicUnit and
491 (hasComposition some (CompositionPart and
492   (hasMaterial some (EarthMaterial and
493     (hasLithology some SedimentaryRock))))))
```

494 we get as result the instance “Formazione di Baldissero”. The Figure 9 re-
 495 ports the explanation for the result: the instance with the identifier `Formazione_di_Baldissero`
 496 (Baldissero Formation) is a geologic unit (row 11), that has the composition
 497 part instance `Formazione_di_Baldissero_CP1` (rows 9 and 5), whose mate-
 498 rial is `Areniti_Ibride_Baldissero_RM1` (Baldissero Hybrid Arenite, row 8);
 499 `Areniti_Ibride_Baldissero_RM1` has a lithology instance `arenite` (row 4),
 500 whose class is `Arenite`, subclass of `Sandstone`, subclass of `ClasticSedimentaryRock`,
 501 subclass of `SedimentaryRock` (rows 3, 2, and 1).

Explanation for: <code>Formazione_di_Baldissero Type GeologicUnit and (hasComposition some (CompositionPart and (hasMaterial some (EarthMaterial and (hasLithology some SedimentaryRock))))</code>		
1) <code>ClasticSedimentaryRock</code> SubClassOf <code>SedimentaryRock</code>	In NO other justifications	?
2) <code>Sandstone</code> SubClassOf <code>ClasticSedimentaryRock</code>	In NO other justifications	?
3) <code>Arenite</code> SubClassOf <code>Sandstone</code>	In NO other justifications	?
4) <code>Ariniti_Ibride_Baldissero_RM1</code> hasLithology <code>arenite</code>	In NO other justifications	?
5) <code>Formazione_di_Baldissero_CP1</code> Type <code>CompositionPart</code>	In NO other justifications	?
6) <code>arenite</code> Type <code>Arenite</code>	In NO other justifications	?
7) <code>CompoundMaterial_EM</code> SubClassOf <code>EarthMaterial</code>	In ALL other justifications	?
8) <code>Formazione_di_Baldissero_CP1</code> hasMaterial <code>Ariniti_Ibride_Baldissero_RM1</code>	In NO other justifications	?
9) <code>Formazione_di_Baldissero</code> hasComposition <code>Formazione_di_Baldissero_CP1</code>	In NO other justifications	?
10) hasLithology Domain <code>CompoundMaterial_EM</code>	In 2 other justifications	?
11) <code>Formazione_di_Baldissero</code> Type <code>GeologicUnit</code>	In 2 other justifications	?

Figure 9: Explanations for the results of the query “Get all the instances that are GeologicUnit and have a sedimentary rock composition”. Screenshot from the Protégè editor.

502 In this example, we only got one result because of the limited number
 503 of instances that currently populate the knowledge base. We are going to
 504 fill the knowledge base with several thousands of geological features of the
 505 Piemonte Geological Map, in order to offer web services based on the rea-
 506 soning capabilities we have exhibited here²².

²²This service will be hosted on Arpa Piemonte Environmental Agency geoport-
 tal - <http://arpapiemonte.maps.arcgis.com/apps/webappviewer/index.html?id=fff173266afa4f6fa206be53a77f6321>)

507 5. Conclusion

508 This paper has introduced a deep semantic representation into the geo-
509 logic mapping process. We have developed a logical encoding of the general
510 geologic knowledge, the OntoGeonous initiative, based on authoritative re-
511 sources, such as GeoSciML and INSPIRE, and referring to widely accepted
512 upper level ontological concepts (such as the ones reported in NASA SWEET
513 ontology), also importing knowledge that is already encoded in the OWL
514 format (such as Simple Lithology). So, OntoGeonous is a merged set of
515 computational ontologies. The knowledge base has then been applied to the
516 classification of the elements of a geologic map after the development of a
517 suitable conceptual model. Machine-readable knowledge allows for consis-
518 tency checking, interoperability, and classification of the geomapping data
519 through the algorithms of automatic reasoning.

520 OntoGeonous has been the product of the interaction between geologists
521 and computer scientists, who exchanged many ideas during the encoding
522 process. During the ontology development, an effective tool for discussion of
523 the axiomatic encoding ongoing was the implementation of a wiki²³. Now,
524 the wiki is released as a resource for further investigation as well as a hu-
525 man readable version of the knowledge (cf. (Howard et al., 2009) on the
526 importance of wiki's for knowledge creation).

527 The formal encoding of the geological knowledge opens new perspectives
528 for the analysis and representation of the geological systems. These often
529 have a very complex internal setting and a large range of physical properties,
530 acquired in distinct geochronological steps (punctuated by geologic events),
531 but rarely fully explicitly described (Balestro and Piana, 2007) (Loudon,
532 2000) (Frodeman, 1995) (Brodaric et al., 2004). In fact, once that the major
533 concepts employed in the implementation of a geological map data base are
534 defined, with their meaning explicitly expressed through a computational
535 ontology, the resulting formal conceptual model of the geologic system can
536 hold across different technical and scientific communities.

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²³<https://www.di.unito.it/wikigeo/>

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