Ontology-aided annotation, visualization and generalization of geological time scale information from online geological map services

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Abstract
Geological maps are increasingly published and shared online, whereas tools and services supporting information retrieval and knowledge discovery are underdeveloped. In this study, we developed an ontology of geological time scale by using a RDF (Resource Description Framework) model to represent the ordinal hierarchical structure of the geological time scale and to encode collected annotations of geological time scale concepts. We also developed an animated graphical view of the developed ontology, and functions for interactions between the ontology, the animation and online geological maps published as layers of OGC\textsuperscript{®} Web Map Service. The featured functions include automatic annotations for geological time concepts recognized from a geological map, changing layouts in the animation to highlight a concept, showing legend of geological time contents in an online map with the animation, and filtering out and generalizing geological time features in an online map by operating the map legend shown in the animation. We set up a pilot system and carried out a user-survey to test and evaluate the usability and usefulness of the developed ontology, animation and interactive functions. Results of the pilot system and the user-survey demonstrate that our works enhance features of online geological map services and they are helpful for users to understand and to explore geological time contents and features, respectively, of a geological map.

Keywords: Geological data interoperability; Geological knowledge discovery; Semantic Web; Web Map Service (WMS); Styled Layer Descriptor (SLD); Visualization of ontology

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1 Introduction
The cyber-infrastructure enables faster and easier creation, storage and transfer of data, yet services facilitating efficient information retrieval and knowledge discovery are still underdeveloped (Hey and Trefethen, 2005; Stafford, 2010). In the field of geology, it has been extensively discussed that a geoscience cyber-environment includes not only digitized geological data but also expertise and tools that support the transformation of data to knowledge (Brodaric and Gahegan, 2006; Howard et al., 2009; Loudon, 2009; McGuinness et al., 2009). Such services of expertise and tools are useful for studies of geology within a cyber-environment and, more importantly, they provide supports to address geology-related societal challenges, such as resources exploration, urban development and hazards mitigation, etc., in the context of the cyber-infrastructure (Broome, 2005; OneGeology-Europe Consortium, 2010; Sinha et al., 2010).

Ontologies, as shared conceptualizations of domain knowledge (Gruber, 1995; Guarino, 1997), can help to improve the interoperability of geological data and facilitate the transformation of geological data into geological knowledge in the cyber-infrastructure (Brodaric and Gahegan, 2006; Galton, 2009; Loudon, 2000; Reitsma et al., 2009). There are several forms of geological ontologies with varying semantic richness (i.e., preciseness of meanings of concepts and relationships between concepts). Following a general direction from informal to formal semantics, geological ontologies include controlled vocabularies (e.g., Bibby, 2006; Ma et al., 2010; Richard and Soller, 2008), conceptual schemas (e.g., Brodaric, 2004; NADM Steering Committee, 2004; Richard, 2006) and RDF1/OWL2-based ontologies (e.g., Ludäscher et al., 2003; Raskin and Pan, 2005; Tripathi and Babaie, 2008), etc.

In several recent projects, ontologies have been applied to provide featured functions in geospatial data infrastructures, thereby promoting services of geological data and tools that support information retrieval and knowledge discovery. In the GEON project3, ontologies were used to mediate conceptual schemas of heterogeneous geological maps and enable semantic integration (Baru et al., 2009; Ludäscher et al., 2003). The AuScope project4 built vocabulary-based services for querying geological maps, which overcame differences in geoscience terms due to language, spelling, synonyms and local variations and, thus, help users to find desired information (Woodcock et al., 2010). The OneGeology (1G) project5 promoted the GeoSciML (Sen and Duffy, 2005) as a common conceptual schema, which improved the interoperability of online geological maps distributed globally (Jackson, 2007). GeoSciML was also applied in the OneGeology-Europe (1G-E) project6 and, compared to the 1G, the 1G-E extended vocabulary-

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based services and enabled multilingual annotation and translation of geological map contents among 18 Europeans languages (Laxton et al., 2010).

Through the aforementioned projects, substantial developments have been made in conceptualizing geological knowledge into ontologies and using defined ontologies to mediate and/or integrate heterogeneous geological data. However, services using ontologies to support the interpretations of geological data are still underdeveloped. Provision of those services is necessary, nevertheless, because they are vital for comprehending the usability (i.e., as an essential part of interoperability (Bishr, 1998; Harvey et al., 1999)) of geological data served in a data infrastructure. Services using ontologies enable users, especially those who are not familiar with geology, not only to find desired data but also to understand and use the data appropriately (cf. Bond et al., 2007; Broome, 2005; Gahegan et al., 2009).

In the present study, an ontology of geological time scale is applied to support annotation, visualization, filtration and generalization of geological time scale (GTS) information from online geological map services. The present study aimed to: (1) show methods of using proper datatype and object properties to represent the structure of a domain (i.e., GTS) in geosciences; (2) develop functions of ontology-based annotations and visualizations to help users to understand GTS contents of online geological maps; (3) develop ontology-based interactive functions to help users retrieve GTS information and discover GTS knowledge in online geological maps; and, as a whole, (4) show a novel way of using ontologies to improve geological data interoperability and facilitate geological knowledge discovery in the context of the Semantic Web.

2 Building and visualizing a GTS ontology

2.1 Incorporating annotations in a GTS ontology

We developed the GTS ontology with a RDF model (Fig. 1a). Properties used in the ontology include two parts: datatype properties and object properties. The former are used to define differentiating qualities of concepts (Fig. 1b) and the latter are used to define relationships between concepts (Fig. 1c). We referred to the GTS thesauri and ontologies developed in the GeoSciML project (Cox and Richard, 2005), the SWEET project (Raskin and Pan, 2005) and the CHRONOS project (Fils et al., 2009) for methods in modeling and encoding. We defined all GTS concepts as instances of GTS classes in our work, including “Supereonothem”, “Eonothem”, “Erathem”, “System”, “Subsystem”, “Series” and “Stage”.

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(a) Source code.

```
<gs:Series rdf:ID="Lower_Triassic">
  <skos:prefLabel xml:lang="en">Lower Triassic</skos:prefLabel>
  <skos:prefLabel xml:lang="de">Untertrias</skos:prefLabel>
  <skos:prefLabel xml:lang="es">Triásico Inferior</skos:prefLabel>
  <skos:prefLabel xml:lang="fr">Trias Inférieur</skos:prefLabel>
  <skos:prefLabel xml:lang="cn">下三叠统</skos:prefLabel>
  <skos:prefLabel xml:lang="jp">下部三叠系</skos:prefLabel>
  <skos:prefLabel xml:lang="nl">Onder Trias</skos:prefLabel>
  <skos:altLabel xml:lang="en">Early Triassic</skos:altLabel>
  <skos:altLabel xml:lang="de">Olenekian</skos:altLabel>
  <skos:altLabel xml:lang="es">Middle Triassic</skos:altLabel>
  <skos:altLabel xml:lang="fr">Induan</skos:altLabel>
  <skos:altLabel xml:lang="cn">早三叠世</skos:altLabel>
  <skos:altLabel xml:lang="jp">前期三叠纪</skos:altLabel>
  <skos:altLabel xml:lang="nl">Vroeg Trias</skos:altLabel>
  <gs:lowerBoundaryTime>~245.9 Ma</gs:lowerBoundaryTime>
  <gs:upperBoundaryTime>251.0±0.4 Ma</gs:upperBoundaryTime>
  <gs:comment xml:lang="en">The lower series of the Triassic System of the Standard Global Chronostratigraphic Scale, above the Permian System of the Paleozoic Era and below the Middle Triassic Series. Also the time during which these rocks were formed, the Middle Triassic Epoch. </gs:comment>
  <gs:basalGsspInfo>
    [Subcommission for Stratigraphic Information of ICS, 2010, GSSP Table]/gs.basalGsspInfo
  </gs:basalGsspInfo>
</gs:Series>
```

(b) Graphic view of datatype properties.
There are both a hierarchal structure and an ordinal temporal sequence among GTS concepts (Cox and Richard, 2005; Michalak, 2005). We encoded the hierarchical structure among GTS concepts with two object properties “gts:supersetOf” and “gts:subsetOf”, and the ordinal structure with other two object properties “gts:lowerThan” and “gts:upperThan” (Fig. 1c). We also used two datatype properties “gts:upperBoundaryTime” and “gts:lowerBoundaryTime” to record the time boundaries of each GTS concept (Fig. 1b).

We used two SKOS7 datatype properties “skos:prefLabel” and “skos:altLabel” in Fig. 1b to encode preferred and alternative labels of the concept “Lower_Triassic”. These multilingual labels were adopted from our previous work of a SKOS-based thesaurus of GTS (Ma et al., 2011), because the SKOS model is compatible with the RDF. We used another datatype property “gts:cgmwRgbColor” to encode the related RGB (red-green-blue) code (in hexadecimal format) of a GTS concept (Fig. 1b). These RGB codes of GTS concepts are specified by the CGMW8 and are commonly used (e.g., the International Stratigraphic Chart9).

Recent studies (Lumb et al., 2009; Reitsma, 2010) have shown that including commonly accepted explanations of concepts as annotations in an ontology enhances the compatibility of that ontology. We used two datatype properties “rdfs:comment” and “gts:basalGsspInfo” to encode annotations in the developed GTS ontology (Figs. 1a, b). The property “rdfs:comment”

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recorded explanations of GTS concepts. We retrieved explanations of most GTS concepts from the Glossary of Geology (Neuendorf et al., 2005), which is a reliable resource for explanations of geological concepts. For some concepts not defined in that glossary, we edited explanations for them (e.g., the explanation of “Lower Triassic” in Fig. 1) following the style of the glossary. The other property “gts:basalGsspInfo” recorded web addresses of basal GSSP (Global Boundary Stratotype Section and Point) information of GTS concepts. The targeted webpages are maintained by the Subcommission for Stratigraphic Information of the International Commission on Stratigraphy.\(^\text{10}\)

### 2.2 An animation based on developed GTS ontology

Animation is an interactive way for interpreting geological data and conveying geological knowledge (Kulawiak et al., 2010; Reitsma, 2010). In order to set up a GTS animation, we started from visualizing concepts and relationships in the developed RDF-based GTS ontology. There are vast methods and techniques for visualizing ontologies (Katifori et al., 2007; Krivov et al., 2007). Among the commonly used layouts of hierarchical visualizations (e.g., rooted tree, radial tree, balloon tree, and tree-map, etc.) (Holten, 2006), we chose the rooted tree and the radial tree for developing the GTS animation in order to achieve both an intuitive layout and an efficient space usage on a user interface. Web-based visualizations and animations can be realized with various technologies, such as JavaScript, SVG (Scalable Vector Graphics) and Flash, etc., for many of which open-source libraries are available on the Web (D’Ambros et al., 2010). SVG (e.g., Ipfelkofer et al., 2006) and JavaScript (e.g., Ma et al., 2011) have already been used to visualize ontologies and interact with online maps. Although Flash has been used to publish online maps (e.g., Kraak, 2004; Youn et al., 2008) and to visualize ontologies (e.g., Geroimenko and Geroimenko, 2006), the application of ontology-based Flash animation and interactions with online map services is underdeveloped. This partly due to the shortage of functions for communications between ontology-based Flash animations and online map services.

In order to fill this gap, we chose Flash as the format of the GTS animation and we used the ActionScript language and the Flare\(^\text{11}\) library to develop it. The developed GTS animation has two parts: a rooted tree (Fig. 2a) and a radial tree (Fig. 2b).

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\(^{10}\) https://engineering.purdue.edu/Stratigraphy [accessed February 05, 2011].

\(^{11}\) http://flare.prefuse.org [accessed February 05, 2011].
Fig. 2. Layout of developed GTS animation with details of two parts. The radial tree in (b) is the main user interface and the rooted tree in (b) is set as a complementary view. Nodes in (a) and (b) are equivalent, and animations in in (a) and (b) are synchronized. "Precambrian" is the only node at the level of “Supereonothem”, as shown in (b) and (c); and “Mississippian” and “Pennsylvanian” are the only two nodes with names at the level of “Subsystem”, as shown in (b) and (d). In (b), the filling colors of un-named nodes at the “Subsystem” level are the same as
their parent nodes to show that those un-named nodes represent no “Subsystem” concepts. This rule also applies to equivalent nodes in (a).

Arrangements of nodes in the animation represent relationships between GTS concepts. From left to right in the rooted tree and from core to edge in the radial tree, the hierarchical layouts of nodes move from the higher to the lower levels of GTS concepts in the ontology. Meanwhile, the bottom-up and clockwise arrangements of nodes in, respectively, the rooted and radial trees follow the ordinal (i.e., earlier to later) sequence of geological time. It is noteworthy that we set a gap in the radial tree (see top middle part of Fig. 2b) because the GTS is not cyclic. In the radial tree, we labeled names of each node with English labels recorded with “skos:prefLabel” in the GTS ontology, whereas in the rooted tree we omitted these names due to the limitation of space here. The filling colors of nodes in the animation were retrieved from RGB codes recorded with “gts:cgmwrgbColor”.

We incorporated several functions with the GTS animation, which can change the layouts of the animation dynamically according to the input queries. For example, a basic function is collapsing or expanding the two trees into different levels in the GTS hierarchy (Fig. 3), as triggered by a query of chronostratigraphic unit. Another function is collapsing into a node and highlighting it with a blue outline (Fig. 4), as triggered by a query of GTS concept name. The rules of the collapse (or animation) function are (1) showing the located node, its brother nodes, ancestor nodes and brother nodes of ancestor nodes, while (2) hiding all other nodes. We set a blank brother node of “Precambrian” at the level of “Supereonothem” (Figs. 1, 2c), as the father node of “Phanerozoic”, to make perfect the implementation of the designed rules of the collapse function. Besides the aforementioned functions, we also developed several other functions to implement interactions between the GTS ontology, the GTS animation and online geological map services.
Fig. 3. Screenshots of developed GTS animation showing that it collapses or expands to different levels of GTS concepts. Levels of GTS concepts in this figure follow a sequence of higher to lower chronostratigraphic units Eonothem, Erathem, System, Subsystem, Series and Stage.

![Fig. 3](image)

(a) Cenomanian  
(b) Upper Cretaceous  
(c) Lower Cretaceous  
(d) Cretaceous

Fig. 4. Collapsing into and highlighting a node in developed GTS animation. Layout of each of the four diagrams is triggered by an input GTS concept name: (a) Cenomanian, (b) Upper Cretaceous, (c) Lower Cretaceous, (d) Cretaceous. Nodes highlighted in both trees are equivalent in each diagram. For rules of collapse see text.

3 Interactions between GTS ontology, GTS animation and online geological map services

An essential feature of ontologies is their ability of using semantic inferences (i.e., logical reasoning operations using definitions of concepts and relationships between concepts) to reach conclusions and reveal new information (Katifori et al., 2007). Incorporating functions of semantic inferences in visualized ontologies has been increasingly studied in recent years, leading to novel features in vast applications. The OZONE (Suh and Bederson, 2002) visualizes query conditions and provides interactive searching and browsing of ontological information. The OntoTrack (Liebig and Noppens, 2005) provides a graphical layout for handling ontologies, in which each editing step is synchronized with an external “reasoner” and the result is shown instantly with animations and colorful marks. The CRAFT (Gruen et al., 2008) represents
collective knowledge of cooperating analysts and handles reasoning tasks via interconnected graphical models built upon a shared evolving ontology. The Wivi (Lehmann et al., 2010) visualizes the structure of visited online articles and emphasizes relevant topics, acting as a guide for exploring larger information networks. Although significant progress has been made in incorporating semantic inferences in visualized ontologies, relevant studies are limited in the field of geological ontologies, and methods of using semantic inferences of visualized ontologies to interact with online geological map services are wanting.

We designed a workflow in this study to conduct interactions between the GTS ontology, the GTS animation and Web Map Services (WMS) of geological maps (Fig. 5). One part of the interactions (right of Fig. 5) is explaining the GTS record retrieved from a polygon in a geological map. GTS terms are first recognized from the original GTS record. For every GTS term, the GTS ontology is searched to find a corresponding GTS concept. Then, annotations (e.g., time span in numbers, definition in text and links to GSSP and Wikipedia webpages) of this GTS concept are retrieved from the GTS ontology and shown in the user interface, and the layout of the GTS animation is changed instantly to highlight this GTS concept.
An online geological map, the GTS ontology, the GTS animation, a user interface in a browser

Style information of all polygons
Spatial features of GTS in the map (Polygons)
GTS record of one polygon

Filter the GTS animation to show all GTS concepts included in the map; mark nodes in the animation after semantic inferences (e.g., Fig. 6)
Take a single GTS term from the record and compare it with labels of GTS concepts in the GTS ontology

Click one node in the filtered GTS animation and get a GTS concept to filter spatial features in the map
Find a corresponding GTS concept?

With semantic inferences (aided by the GTS ontology)?

Showing annotations of this GTS concept (e.g., Fig. 9) and changing layout of the GTS animation (e.g., Figs. 4 and 9) in the user interface

With symbolical generalization (aided by the GTS ontology)?

Render spatial features of this GTS concept and its child concepts in the color of this GTS concept (e.g., Fig. 7k)

Yes
NO
Revise the GTS ontology

Show spatial features of this GTS concept and its child concepts (e.g., Figs. 7i and j)

Show spatial features of this GTS concept (e.g., Figs. 7e–h)

End

Fig. 5. Workflow for interactions between developed GTS ontology, GTS animation and online geological maps.

Another part of the interactions (top left of Fig. 5) is showing all GTS concepts included in a WMS geological map with a filtered GTS animation. We developed a function to (a) retrieve scripts of the GTS style information (i.e., legend) of a map; (b) parse the style information and recognize all GTS concepts; (c) find corresponding GTS concepts by searching the GTS ontology; and (d) send a list of found GTS concepts to the GTS animation. If an original GTS term is a synonym, it is identified by the GTS ontology and then a note is attached in the list sent
to the GTS animation. After receiving such a list of GTS concepts, a function in the GTS animation (a) hides nodes whose corresponding GTS concepts are not included in the received list (Figs. 6a, b); (b) marks nodes, whose original GTS terms are synonyms as noted in the received list, with green outlines (Fig. 6c); and (c) shows and marks nodes, whose corresponding GTS concepts are not included in the received list but whose child nodes are not hidden, with red outlines (Fig. 6d). Step (c) of the described function in the GTS animation uses semantic inferences based on relationships between nodes in the animation. The filtered GTS animation (Figs. 6a, b) represents a legend of GTS features in a WMS geological map. We applied techniques of communication between Flash, JavaScript and HTML (Elst et al., 2006) to transfer data between the GTS ontology, the GTS animation and WMS geological maps in the developed functions.

(a) Filtered rooted tree.  (b) Filtered radial tree.
Fig. 6. Filtered GTS animation with marked results of semantic inferences after analyzing GTS data retrieved from a geological map. (c) and (d) are two enlarged parts of (b), showing in detail the marked results of semantic references. For methods used in filtering and semantic inferences see text.
The legend in Figs. 6a and b presents the map users with a clear ordinal hierarchical structure of GTS contents included in a map layer. By reading the legend, users can obtain a direct impression of the GTS features of the map layer. They can also operate the legend to filter out and/or generalize spatial features of certain GTS concepts that they are interested. Besides the aforementioned functions, we developed another function (middle and bottom left of Fig. 5) with the filtered GTS animation to filter out and generalize GTS features in the original geological map. This function operates with the following steps: (a) a node in the filtered radial tree of the GTS animation is clicked (e.g., one of the nodes in Fig. 6e), and the user is provided two options by a question “With semantic inferences?”; (b) if the user chooses “NO”, the GTS animation sends only the name of this node (i.e., the label of the corresponding GTS concept) to a function outside the GTS animation; if the user chooses “YES”, the GTS animation sends a list of names of this node and all its visible child nodes (by using semantic inferences) to the function outside; (c) after receiving a GTS name or a name list, the function searches the “gts:cgmwRgbColor” properties in the GTS ontology and finds RGB codes for each GTS concept in the list and, then, the function creates a Style Layer Descriptor (SLD) file following OGC® standards (OGC, 2007a; OGC and ISO, 2010) and sends it to the WMS geological map for filtering out and rendering GTS features (Figs. 7e–j); and (d) if there are more than one GTS concepts received from the GTS animation, a symbolical generalization can be done by replacing the RGB codes of all GTS concepts with that of the top GTS concept in the SLD file and then sending it to the WMS geological map (Fig. 7k). In steps (c) and (d) of this function, an alternative operation is to parse the original style information obtained from the WMS geological map and to get RGB codes for each GTS concept, which can then be used to filter out and render GTS features (Figs. 7a–d) and do symbolical generalizations.
Fig. 7. Filtering out and generalizing GTS features of an online geological map aided by developed GTS ontology and GTS animation. (a) to (h) show results of direct filtering out (i.e., each filtered map shows features of only one GTS concept and polygons in the map are rendered in only one color). (a) to (d) use RGB codes from the style information retrieved from the online geological map, and (e) to (h) use RGB codes from the developed ontology. (i) shows a combination of polygons in (e) and (f) after semantic inference, because “Cenomanian” is a child concept of “Upper Cretaceous”. (j) shows a combination of polygons in (e) to (h), because “Lower Cretaceous” and “Upper Cretaceous” are both child concepts of “Cretaceous”. (k) shows a symbolical generalization of (j) (i.e., polygons in (j) are rendered in four colors, and polygons in (k) are rendered in only one color). RGB codes shown in this figure are in hexadecimal format. Original geological map (1:625,000 scale onshore bedrock age map of United Kingdom) reproduced with the permission of British Geological Survey © NERC. All Rights Reserved.
In the source code of a SLD file generated in this study for filtering out and rendering GTS features of “Cretaceous” in a WMS geological map (Fig. 8), the element “<sld:Name>” (line 3) records the WMS map to which the SLD file is sent. The element “<sld:Rule>” (lines 6–19) records the conditions for filtering out GTS features recorded as “CRETACEOUS” (lines 7–12) and for rendering the GTS features filtered out (lines 13–18). The result generated by this SLD file is shown in Fig. 7h. The developed function can add more elements of “<sld:Rule>” in the SLD file for filtering out and rendering features of more than one GTS concepts in the same WMS geological map. For example, in the SLD file for Fig. 7j, there are four elements of “<sld:Rule>”, which set filtering and rendering conditions for GTS concepts “Cenomanian”, “Upper Cretaceous”, “Lower Cretaceous” and “Cretaceous”, respectively, each with a unique GTS concept name and a unique RGB code. In the SLD file for Fig. 7k, there are also four elements of “<sld:Rule>”, with four different GTS concept names but only one RGB code (i.e., RGB code of “Cretaceous”) to finish the symbolical generalization.

Fig. 8. Source code of a SLD file sent to an online geological map for filtering out and rendering GTS features of “Cretaceous”. The result is shown as Fig. 7h. The RGB code in line 15 is retrieved from the developed GTS ontology.

4 Pilot system, results and evaluation
We set up a pilot system to test and evaluate the usability and usefulness of the aforementioned works. In the pilot system, we linked to a WMS server provided by the British Geological Survey (BGS), from where we retrieved the 1:625,000 scale onshore bedrock age map of United

12 http://ogc.bgs.ac.uk/cgi-bin/BGS_Bedrock_and_Superficial_Geology/wms [accessed August 10, 2010].
Kingdom (625k UKBRA) and showed it in a map window (left part of Fig. 9) in a user interface. The system gets the GTS record (e.g., “PERMIAN”) of a polygon after a click on it in the map window, and then shows it below the map window. After that, the system parses the GTS ontology and retrieves annotations (middle part of Fig. 9) for each GTS concept (e.g., “Permian”) recognized from the GTS record, and generates links to corresponding GSSP and Wikipedia pages. Meanwhile, the rooted tree and radial tree in the GTS animation (right part of Fig. 9) collapse into the corresponding node (e.g., “Permian”) and highlight it with a blue outline.

Fig. 9. User interface of developed pilot system. The user interface includes three interactive parts: an online geological map in the left, annotations of GTS concepts in the middle, and a GTS animation in the right. Original geological map reproduced with the permission of British Geological Survey © NERC. All Rights Reserved.

A GTS record may use synonyms (i.e., terms not included in the International Stratigraphic Chart) as names of GTS concepts. If a synonym is recorded as a “skos:altLabel” in the GTS ontology, then by parsing the GTS ontology the system can find its corresponding GTS concept(s) and then “skos:prefLabel” as standard name(s). The GTS animation will then collapse into the corresponding node(s) and will highlight them with green outlines (Fig. 10).
Fig. 10. Nodes highlighted with green outlines due to a synonym used in an original GTS record. (a) shows an example of GTS features of “LOWER CAMBRIAN” in the 1:625,000 scale onshore bedrock age map of United Kingdom. “Lower Cambrian” is not a standard term in the International Stratigraphic Chart, but with developed GTS ontology, “Lower Cambrian” is recognized as a union of “Terreneuvian” and “Series 2”. Then in (b) the GTS animation collapse into nodes of these two GTS concepts and highlight them with green outlines, indicating the GTS term used in the original record is a synonym. Original geological map reproduced with the permission of British Geological Survey © NERC. All Rights Reserved.
We carried out a case study of filtering out and generalizing GTS features in the 625k UKBRA map. Figs. 11a–d and 11e–h are results of filtered out GTS features by clicking nodes in the filtered GTS animation (Fig. 6b), which is generated by clicking the button “See legend in GTS pie” in the bottom left part of the user interface (Fig. 9). Figs 11i–l are results of symbolical generalizations using RGB codes from the GTS ontology.
Fig. 11. Filtering results and symbolical generalizations of GTS features in the 1:625,000 scale onshore bedrock age map of United Kingdom with RGB codes from developed GTS ontology: (a) Cretaceous, (b) Jurassic, (c) Triassic, (d) Mesozoic, (e) Cretaceous after semantic inference, (f) Jurassic after semantic inference, (g) Triassic after semantic inference, (h) Mesozoic after semantic inference, (i) Cretaceous after generalization, (j) Jurassic after generalization, (k) Triassic after generalization, and (l) Mesozoic after generalization. (h) is equivalent to a combination of (d), (e), (f) and (g). (l) is a symbolical generalization of (h). Original geological map reproduced with the permission of British Geological Survey © NERC. All Rights Reserved.

In the same map, we also generalized features at different GTS levels (i.e., Supereonothem, Eonothem, Erathem, System, Series and Stage from higher to lower). The level of details of GTS records in the map influences the results of symbolical generalizations. For example, we generalized the map at the System level and found that some areas in the generalized map were blank (Fig. 12a). That is because the original GTS records of those blank areas are GTS concepts whose levels are higher than System (i.e., Erathem, Eonothem and Supereonothem) and, therefore, they cannot be generalized to a lower level (i.e., System). Similar cases arose when we generalized the same map at the Erathem level (Fig. 12b) and the Eonothem level (Fig. 12c). Only in the generalization of “Precambrian” and “Phanerozoic” (i.e., the two highest GTS concepts) were all polygons in the original map filtered out and re-rendered (Fig. 12d).
Fig. 12. Symbolical generalizations of different levels of GTS features in 1:625,000 scale onshore bedrock age map of United Kingdom with RGB codes from developed GTS ontology. Major difference between (c) and (d) is the area of Na h-Eileanan Siar (or Western Isles) at the top left part of the two maps. Original geological map reproduced with the permission of British Geological Survey © NERC. All Rights Reserved.

To evaluate the usefulness of key functions developed in the pilot system, we made a user-survey wherein 19 PhD students participated. The particular objective of this survey was to determine if users of the system, especially those who are unfamiliar with geology, are able to comprehend usability of geological data (i.e., as an essential part of their interoperability) (Bishr, 1998; Harvey et al., 1999; Bond et al., 2007; Broome, 2005; Gahegan et al., 2009). The 19 participants we selected are all earth scientists in the Faculty of Geo-Information Science and Earth
Observation (ITC), University of Twente. They fall into two groups: (1) nine are familiar with GTS and (2) 10 are unfamiliar with GTS. We expected that these two groups have different opinions about the usefulness of the system in terms of its five functions (Appendix A), with the “familiar” group’s opinions as references for usefulness.

On average, the “familiar” group scored all the individual functions, except the Annotation function, lower than the “unfamiliar” group (Tables 1, 2). The average scores by the “familiar” were mostly between “Useful” and “Very Useful”, except that their average scores for the Collapse (or Animation) and Legend functions tend only toward the “Useful” category (Table 2, Appendix A). In contrast, the average scores by the “unfamiliar” group tend more toward the “Very useful” category. An explanation for this is that geologists, compared to other earth scientists, historically tend to be reluctant in using computer technology (cf. Hubaux, 197; Rock, 1991; Huff, 1998; Clegg et al., 2006). Results of two-sample t-tests show that the scores given by the two groups are not significantly different for all functions except Collapse (Appendix B, Table 2). In particular, both groups similarly found that Annotation, Visualization and Filtering are “Useful” to “Very Useful”, and both groups similarly found that Legend is more “Useful” than “Very useful”. However, the “familiar” group found that Collapse (or Animation) is just “Useful” while the “unfamiliar” group found this function to be “Very useful”. The results tell us, therefore, that the developed GTS ontology and the associated functions to facilitate GTS information retrieval and knowledge discovery are useful not only for those who are familiar but also to those who unfamiliar with geology. Nevertheless, the results of the survey remind us that the Collapse and Legend functions need further re-thinking to improve their usefulness for geologists. For example, we can let the radial tree automatically zoom in on an outlined node after the collapse, thus users can also read the GTS name of the node. We can also update the Legend function to show instructions in the Flash animation when a user is moving the mouse over nodes in the legend.
Table 1 Scores given by participants on usefulness of functions in developed GTS (geological time scale) pilot system. For meanings of column heads and scores see Appendix A.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Annotation</th>
<th>Visualization</th>
<th>Collapse</th>
<th>Legend</th>
<th>Filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Familiar with GTS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>3</td>
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<tr>
<td>Unfamiliar with GTS</td>
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</tbody>
</table>

Table 2 Results of two-sample $t$-tests on scores given by two groups of participants (Table 1). For meanings of variables and details of conducted $t$-tests see Appendix B.

| Function    | $\bar{x}_f$ | $s_f$ | $\bar{x}_u$ | $s_u$ | $|\bar{x}|$ | $df$ | $t^*$ | $P$-value |
|-------------|---------------|-------|-------------|-------|-------------|------|-------|-----------|
| Annotation  | 2.667         | 0.500 | 2.600       | 0.699 | 0.241       | 16.236 | 2.120 | 0.187     |
| Visualization | 2.556       | 0.726 | 2.700       | 0.483 | 0.504       | 13.704 | 2.160 | 0.378     |
| Collapse    | 2.222         | 0.833 | 3.000       | 0.001 | 2.800       | 8.000  | 2.306 | 0.977     |
| Legend      | 2.222         | 0.972 | 2.600       | 0.699 | 0.963       | 14.410 | 2.145 | 0.648     |
| Filtering   | 2.667         | 0.500 | 2.900       | 0.316 | 1.200       | 13.268 | 2.160 | 0.749     |

5 Discussion
The GTS ontology developed in this study shares a same basic reference (i.e., the International Stratigraphic Chart) with the geological time vocabularies/ontologies developed in the
GeoSciML, SWEET and CHRONOS projects. Compared to the vocabularies/ontologies in those projects, the GTS ontology in this study is simplified. This is because one primary purpose of the developed GTS ontology is to provide annotations to GTS concepts/terms in geological maps. We applied a GTS term-oriented point of view (i.e., time boundaries are attributes of GTS terms), not a time boundary-oriented one (i.e., GTS terms are attributes of time boundaries), nor a combination of both (e.g., the geological time model in GeoSciML\textsuperscript{13}), in modeling and encoding the GTS ontology. The developed GTS ontology does not map or link to upper-level ontologies (e.g., the W3C working draft of a time ontology\textsuperscript{14}) yet, since its current version fulfills the primary purpose of annotating GTS terms and works well in visualized interactions with online geological maps. Nevertheless, because using foundational constructs from widely used upper-level ontologies (e.g., the geological time model in GeoSciML, the geological time ontology in SWEET\textsuperscript{15}, the W3C time ontology and some standard OWL properties) can improve the interoperability of resulting ontologies (cf. Tripathi and Babaie, 2008), the GTS ontology developed in this study can be refined in further studies. Since the core issues, such as GTS terms, time boundaries, ordinal hierarchical structure of GTS, etc., of the GTS ontology in this study are consistent with the International Stratigraphic Chart, there are no major difficulties to refine our ontology following the methods of modeling and encoding in the GeoSciML, SWEET and CHRONOS projects (cf. Perrin et al., 2011).

Annotations in ontologies and vocabularies have been increasingly studied in recent years. In the field of genetic ontologies, it was extensively discussed that using commonly accepted annotations in an ontology can enhance the interoperability of datasets underpinned by this ontology (Camon et al., 2003; Dimmer et al., 2008; Hong et al., 2008). Recently, it was also discussed (Rhee et al., 2008) that collecting reliable annotations in an ontology is crucial to reduce incorrect results and conclusions in studies using this ontology. Our approaches for arranging annotations in the GTS ontology are similar to those studies of genetic ontologies. We collected labels and definitions of GTS concepts from international standards and commonly used resources, so that the developed ontology can provide reliable explanations of GTS concepts. Similar opinions on annotations were also expressed in several recent studies on geoscience ontologies (Klien, 2007; Lumb et al., 2009; Visser et al., 2002). In the field of GTS ontologies/vocabularies, the 1G-E project presented featured services of vocabulary-based annotations with online geological maps to facilitate GTS data interoperability and information retrieval (Asch et al., 2010; Laxton et al., 2010). Our work of combining ontology-based annotations with WMS geological maps is similar to that of the 1G-E project. The difference is that the GTS ontology in our work provides more information of GTS concepts and we complemented annotations with an animation.

\textsuperscript{14} http://www.w3.org/TR/owl-time [Accessed July 10, 2011].
\textsuperscript{15} http://sweet.jpl.nasa.gov/2.2/stateTimeGeologic.owl [Accessed July 10, 2011].
Incorporating functions of reasoning in visualized ontologies is important to support interactive learning and knowledge discovery (Min et al., 2009). In Section 3 we already described several related studies. Some recent applications can be found in medical researches. Zillner et al. (2008) incorporated external semantics into patient data visualization and realized semantic facet browsing and semantic tree-map visualization using class-based reasoning. Gonçalves et al. (2009) developed an application of ontology for representation, reasoning and visualization of heart electrophysiology on the Web. Dupplaw et al. (2009) developed an ontology-driven framework with multimedia processing, annotation and reasoning to support multidisciplinary meetings that take place during breast cancer screening for diagnosing the patient. In a recent geospatial study, Willems et al. (2010) developed a system for analyzing the behavior of moving objects, which can abstract and simulate trajectory sensor data in an ontology, fuse multiple heterogeneous data sources into a knowledge base, and then conduct visual analysis of the combined data sources. For coupling reasoning and visualization with ontologies, the approach applied in our works of the GTS ontology and the GTS animation is similar to those aforementioned studies. However, the background of our works is geology and the GTS ontology and GTS animation we developed are used to complement online geological map services.

Understanding the meanings and interrelationships of concepts represented by map features is essential for users to explore information and knowledge contained in maps (Kraak, 2008; Neun et al., 2008). Ontologies help users to understand map features and can be used to generalize maps (Kulik et al., 2005). Our current method of ontology-based map generalization used only the hierarchical structure among GTS concepts, whereas other sophisticated algorithms can be further studied, such as genetic algorithm (Ware et al., 2003), supervised Bayesian inference (Lüscher et al., 2009), and heuristic methods for generalization of large datasets (Haunert and Wolff, 2010). In the developed generalization functions, we do not change the outlines of polygons in a WMS map, but we change the filling colors of sub-class concepts into colors of super-class concepts to realize the symbolical generalization. The 1G-E web portal16 provides a vocabulary-supported geological map generalization service using user-assigned RGB codes. Our work of ontology-based map generalization is similar to that of the 1G-E project, but the difference is that we provide a GTS animation as the operation panel to simplify the operations of generalizations and the RGB codes used in our work are controlled by the GTS ontology.

The GEON project and the OneGeology-Europe project have developed vocabulary/ontology-based functions (e.g., filtration and (re-)rendering) to access distributed geological map services. In the current pilot system of this study, the developed interactive functions were deployed to

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16 http://onegeology-europe.brgm.fr/geoportal [accessed February 27, 2011].
access single data sources respectively, and did not access multiple data sources at the same time. Nevertheless, the visualized user interface with the GTS animation in this study can be regarded as an extension to the functions in GEON and OneGeology-Europe. The GTS ontology in this study takes the International Stratigraphic Chart as the basic reference, so the interactive functions based on it can access online geological maps that use the same chart as a conceptual reference or controlled vocabulary. However, at regional and national levels, there are also local classifications of GTS that are different from the International Stratigraphic Chart (Haq, 2007), and those local classifications are also used in many geological maps. If two geological maps use different classification systems of GTS, then the work of aligning and accessing the two maps first requires a compare between the two GTS classification systems. If the two classification systems cannot be aligned with each other, they both may be mapped to a common ontology, which in turn can be used to align and access the two maps (cf. Ludäscher et al., 2003).

Two lessons are learned from this study. The first is that detailed metadata from data sources can support efficient use and re-use of data. Metadata is a much discussed topic either in general computer science (e.g., Gray et al., 2005; Schofield et al., 2009) or in geo-information science (e.g., Green and Bossomaier, 2002; Ma et al., 2007; Tilmes et al., 2010). Here, we want to address the convenience that metadata can bring to ontology-based online geological data applications. If a geological data source provides detailed metadata about subjects (e.g., GTS), languages (e.g., English), and standards used (e.g., the International Stratigraphic Chart), etc., of maps published on its data server, users can apply corresponding ontologies (e.g., a GTS ontology) in applications after they retrieve data from the server. Although the “GetCapabilities” query in WMS and the Catalog Service for the Web (CSW) (OGC, 2007b, Chen et al., 2010; Gebhardt et al., 2010) can be used to obtain metadata, the details of the metadata still depend on what are registered by the data providers. The second lesson we learned is that standardization of data in geological map services influences the results of ontology-based applications. In this study, we obtained satisfactory results in the pilot system. This is mainly due to (1) the compatibility of the GTS ontology and (2) the high standardization of GTS contents in the 625k UKBRA map. If a geological data server does not address standardization strictly and result in heterogeneous datasets, we should either update the ontology in order to recognize concepts in these datasets or, if the results are still not satisfactory, we may redesign strategies and methods of applying ontology-based tools with online geological map services.

From this study, we also see directions for future works. The first is the multilingual annotation of GTS concepts. In the GTS ontology, we already collected multilingual labels of GTS concepts. Enhancing multilingual annotations in the GTS ontology can potentially broaden the scope of applications of the ontology. The second direction is collecting more conceptual mapping cases in the GTS ontology. By accessing the 625k UKBRA map we collected two mapping cases: “Lower Cambrian = Terreneuvian + Series 2” and “Middle Cambrian = Series 3”. More such mapping cases will be useful for understanding and mediating heterogeneous datasets. The third
direction is updating methods for filtering out GTS features in a map. In our current work, by clicking a node in the filtered GTS animation, only those map features with one GTS concept in its attribute record can be retrieved. Each GTS feature in the 625k UKBRA map has only one GTS concept, so we obtained satisfactory results in the pilot system. If we want to make the functions of filtering and generalization also apply for map features with several GTS concepts, new methods should be developed. Finally, studies of ontologies and visualization techniques with WFS and KML geological maps can be considered in the future (cf. De Paor and Whitmeyer, 2011).

6 Conclusions
Geospatial data infrastructures have been widely used in publication and sharing of geological maps, whereas tools and services for information retrieval and knowledge discovery are underdeveloped compared to the massive geological data available online. In this study we developed a RDF-based ontology of geological time scale, an animation based on this ontology, and interactive functions among the ontology, the animation and online geological map services. We built a pilot system with the developed ontology, animation and interactive functions, and we obtained positive results in a user-survey on usefulness of the developed works. Our study shows that annotations in an ontology and ontology-based visualizations are useful to help people to understand concepts defined in the ontology. In addition, incorporating ontology-based annotations, visualizations and interactive functions with online geological map services are helpful for users to understand information in a map and to conduct further operations of knowledge discovery.

Acknowledgements
We thank staff members in the ESA and GIP departments of Faculty ITC at University of Twente for their comments on an earlier pilot system. In particular, the first author wants to thank Mr. Dongpo Deng for discussing applications of ontologies and Mr. Barend Köbben for discussing techniques of programming with JavaScript. We are grateful to Dr. Simon Cox and another anonymous reviewer for their insightful comments and suggestions which led to the improvements in the manuscript.

References


Appendix A

1) Meanings of abbreviated function names

<table>
<thead>
<tr>
<th>Annotation</th>
<th>Showing annotations of GTS concepts using the GTS ontology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visualization</td>
<td>Showing the conceptual structure of GTS with a rooted tree (both expanded)</td>
</tr>
<tr>
<td>Collapse (or Animation)</td>
<td>Collapsing into and highlighting a chosen GTS concept in the rooted tree and the radial tree</td>
</tr>
<tr>
<td>Legend</td>
<td>Showing legend of GTS contents in a map with the rooted tree and the radial tree</td>
</tr>
<tr>
<td>Filtering</td>
<td>Filtering out of certain GTS features in a map with the rooted tree and the radial tree</td>
</tr>
</tbody>
</table>

2) Meanings of scores on usefulness of a function

<table>
<thead>
<tr>
<th>Score</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Very useful</td>
</tr>
<tr>
<td>2</td>
<td>Useful</td>
</tr>
<tr>
<td>1</td>
<td>Somewhat useful</td>
</tr>
<tr>
<td>0</td>
<td>Not useful at all</td>
</tr>
</tbody>
</table>
Appendix B

1) Reasons for using the two-sample t-test
The “familiar” and “unfamiliar” groups are independent, and their sizes are small and different \((n_f=9, n_u=10)\). Variances of scores by either group are unknown and are assumed unequal.

2) Hypotheses of the two-sample t-test

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_0: \mu_f \neq \mu_u)</td>
<td>Null hypothesis: The “familiar” and “unfamiliar” groups have different opinions about the usefulness of a function.</td>
</tr>
<tr>
<td>(H_a: \mu_f = \mu_u)</td>
<td>Alternative hypothesis: The “familiar” and “unfamiliar” groups have similar opinions about the usefulness of a function</td>
</tr>
</tbody>
</table>

3) Meanings of variables used in the two-sample t-test.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>(n_f)</td>
<td>Size of “familiar” group</td>
</tr>
<tr>
<td>(n_u)</td>
<td>Size of “unfamiliar” group</td>
</tr>
<tr>
<td>(\bar{x}_f)</td>
<td>Mean of “familiar” group’s scores on the usefulness of a function</td>
</tr>
<tr>
<td>(\bar{x}_u)</td>
<td>Mean of “unfamiliar” group’s scores on the usefulness of a function</td>
</tr>
<tr>
<td>(s_f)</td>
<td>Standard deviation of “familiar” group’s scores</td>
</tr>
<tr>
<td>(s_u)</td>
<td>Standard deviation of “unfamiliar” group’s scores</td>
</tr>
<tr>
<td>(t)</td>
<td>Two-sample t-value</td>
</tr>
<tr>
<td>(df)</td>
<td>Estimated degrees of freedom using the Welch–Satterthwaite equation</td>
</tr>
<tr>
<td>(P)-value</td>
<td>Probability (two-sided) that the null hypothesis is true</td>
</tr>
<tr>
<td>(t^*)</td>
<td>Critical t-value at the significance level of 0.05</td>
</tr>
</tbody>
</table>

4) Equation for calculating \(t\)

\[
t = \frac{\bar{x}_f - \bar{x}_u}{\sqrt{\frac{s_f^2 + s_u^2}{n_f} \frac{s_f^2 + s_u^2}{n_u}}}
\]

5) The Welch–Satterthwaite equation for calculating \(df\)

\[
df = \frac{1}{\frac{s_f^2}{n_f n_f - 1} + \frac{s_u^2}{n_u n_u - 1}}
\]