Industrial Geological Information Capture with GeoStructure Ontology

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Abstract
Understanding geological structures plays an essential role in a wide range of industries. Various tools and software have been developed to support the observation and characterisation of the geological structures and they produce a large volume of heterogeneous data. Thanks to the development of semantic technologies, plenty of works have investigated industrial geological data. In contrast, geological sketches, figure interpretations, and illustrations as the initial data collection and analysis steps have received little attention. Most structure information is still reported as PDF files with forms, tables, and raster images with interpretations. We attempt to fill this gap by providing an ontology-based industrial geological information capture method to allow users to input and store structure information formally. Following users' sketches, the corresponding knowledge graphs will be generated. This work aims to make the first-hand geological structure information findable, accessible, interoperable, reusable (FAIR), and to support qualitative information reasoning, from a user-driven perspective, and to meet the needs of digitised industry.

Keywords
Geological information capture, Information modelling, Ontology engineering

1. Introduction

Many industries that nowadays serve as foundations of our society greatly rely on a solid understanding of geological structures, such as petroleum [1], mining [2], sustainable energy [3], and construction industries [4]. Geologists use sketches to, e.g., assist hydrocarbon exploration in the petroleum industry [5], to study regional geological structures in the mining industry [6], and to to evaluate fluid injection, transport, and storage in the sustainable energy industry [7].

Drawing sketches plays an essential role in representing geologists' understanding and conceptualisation of geological structures of the domain [8]. The sketching refers to the process where relevant geological entities from the field will be presented with certain graphical elements, while irrelevant entities will be abandoned [9], based on geologists' domain knowledge. As such a basic but essential knowledge sharing and recording method, sketching has been widely adopted by geology from the starting point of this domain. It is considered as a primary and necessary method to assist the geological study [10].

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Though pen and paper are still geologists' good friends, the need of digitising the geo-knowledge, allowing geologists to express knowledge in a machine-readable way and improving data interoperability has increased significantly. In the geology community and industries, digitisation is drawing significant attention in activities such as ontological modelling [11, 12], reasoning [13, 14], knowledge graph construction [15], etc.

However, in contrast to these development, sketching is still a few steps behind the digitisation, despite its important role as an initial data collection step. Many digitised geological methods work on visualisation and 3D modelling [16, 17, 18]. Some research bridge the animated interaction and drawing with ontologies [19, 20], but these cannot fulfil the needs of geologists and the industries.

To this end, we propose an ontology-based sketching system to allow users to document geological structure information formally so that computers can process them. This system contributes the encoding of first-hand geological structure information from a user-driven perspective, making the information findable, accessible, interoperable, reusable (FAIR), and suitable for inference, and meeting the needs of digitised industry. We present our on-going research on the ontology-based system in this paper, and it is organised as follows.

- A discussion of lack of studies on sketches (Section 2).
- A early phase work of the structural geology ontology (Section 3)
- A preliminary system architecture (Section 3) that consists of three layers: the user sketch interface layer, the domain ontology layer, and the intermediate mapping layer.
- A preview of the evaluation methods(Section 4)
- A general conclusion with our future work (Section 5)

2. Related Work

Industrial Impact of Geological Sketches. Geological sketches have long been used in industry. In the traditional petroleum industry, geologists use sketches to express their understanding of geological structure in the subsurface seismic to assist hydrocarbon exploration [5]. In the mining industry, one basic approach to prevent mining subsidence and failure is to study regional geological structures, especially preexisting faults [6]. In the sustainable energy industry, geothermal or carbon capture and storage require a sound examination of geological fracture systems to evaluate fluid injection, transport, and storage [7, 21], In the construction industry, especially in railway and tunnel construction, preventing landslide and tunnel water leakage, and reducing construction failure are also based on the study of geological structures [22].

Work on Semantification of Geological Data. Relying on semantic technologies, much work has been done to support and enhance industrial geological data interoperability, such as ontological modelling, reasoning, knowledge graph construction etc. Various ontologies have been proposed, such as the Ontology of Fractures [11] and the GeoCore Ontology [12]. Qualitative data-based geological multi-scenario reasoning has been proven its usefulness [13]. The work [13] designed an ontology-driven representation of knowledge to support the machine-readable geological knowledge interoperability. Based on natural language processing and data mining, a new approach has been developed to construct geological knowledge graphs [15].

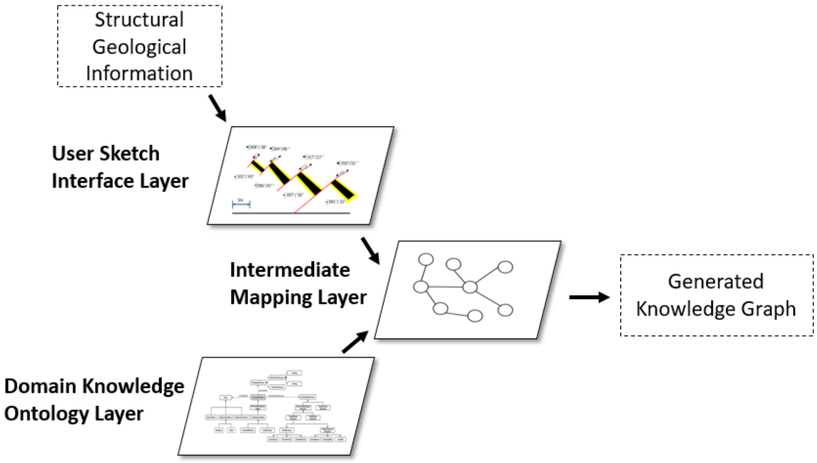

Figure 1: An illustration of the system's three-layered architecture. The intermediate mapping layer bridges the other two layers and generates the knowledge graphs.

Another work [14] aims at integrating reasoning rules to understand users' intentions and problems to improve information retrieval efficiency.

Lack of Study on Sketches. Some drawing tools are designed as digitised canvases to assist 2D/3D modelling, drawing, and visualisation [16, 17, 18], but these visualisation artefacts themselves contain no geological information, and are not machine-readable. Most information is still reported as PDF files with forms, tables, and raster images with interpretations. To solve this problem, ontology-based image annotation tools have been proposed to add meaning to images [23, 24]. Besides, some ontology-based approaches have been offered to harmonise the geological fault detection and geological layer horizon in seismic image interpretation and integrate with geological time [25, 26]. Wang et al. [27] developed a semi-automated method to utilise text content and elevation model in old geological paper reports to convert raster images (e.g.geologic illustrations) into vector profiles at low cost. Ontology-based CAD systems like FieldLog [28] had been implemented to enable geological database flexibility and balance the needs between users and industries. Ma et al. [20] built an ontology with animated interactive functions to improve data interoperability. An ontology-based sketching tool was designed by Forbus et al. [19] to make sketches, in general, more meaningful, though it was mainly used for education and cognitive science purpose. Inspired by several approaches with similar technologies or goals have been published, our work is having one step forward to satisfy the needs of the geology-relevant industries.

3. Our Sketch-Based System for Industrial Geological Information Capture

We now introduce our system and the methodology.

System Architecture. Our sketch-based system has a three-layered architecture: the user sketch interface layer, the domain knowledge ontology layer, and the intermediate mapping

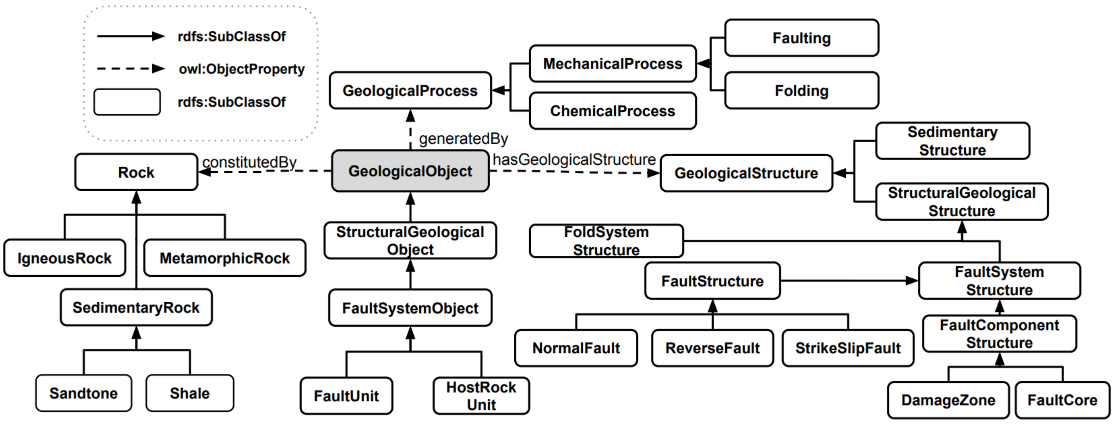

Figure 2: Schematic illustration of part of the tailored ontology in a hierarchical view

layer (Figure 1). The user sketch interface layer is a front-end layer that users draw and input their geological information. The domain knowledge ontology layer provides formal structural geology knowledge. The intermediate mapping layer takes the sketch input from the user sketch interface layer and links it with formal knowledge from the domain knowledge ontology layer, and generates the knowledge graph based on the mapping.

Process of Knowledge Engineering. As a work of developing an ontology-based sketch system for generating geologic structural information knowledge graphs, constructing a suitable ontology for the domain knowledge is the first step. The target domain knowledge is specified in describing the structural geologic scenarios agreed by domain experts. To do this, we first collect vocabularies that geologists use from structural geology publications. Due to the large range of the domain, we concentrate our knowledge acquisition work on geologic structural fault and its relevant concepts as the foundation.

After collecting vocabularies, together with domain experts, a taxonomy has been built to contain collected vocabularies. Based on domain experts' reflections, synonyms, conflicts, and ambiguities were discussed and sorted out during this process. The knowledge is formalised into a structure that is precise in meaning. In addition to the correctness of the conceptualisation, the unified terminologies, to a great extent, agreed by domain experts to balance the conciseness and clarity of our work. To not reinvent the wheel, the work was in alignment with existing ontologies e.g. Fracture Ontology [11] and GeoCore Ontology [12] to build object properties, data properties, and classes of the tailored ontology. With a unified top-level ontology as the backbone, this designed ontology will allow modifications to adapt different sub-domain usage of the geology. The schematic illustration of part of the tailored ontology is displayed in Figure 2 with four main classes of entities displayed in a hierarchical view.

Our GeoStructure Ontology. Figure 2 displays the sub-classes of the rock, geological object, geological process, and geological structure and their relationships in the domain of structural geologic fault. The geological object is displayed in the central and other three entities by different object properties. The system will generate corresponding knowledge graphs based on this ontology following users' sketching processes. A real-world structural geologic fault system has been used to examine the ontology's usability, completeness, and expressivity and the resulting knowledge graph is discussed in Sect. 4 and illustrated in Fig. 3.

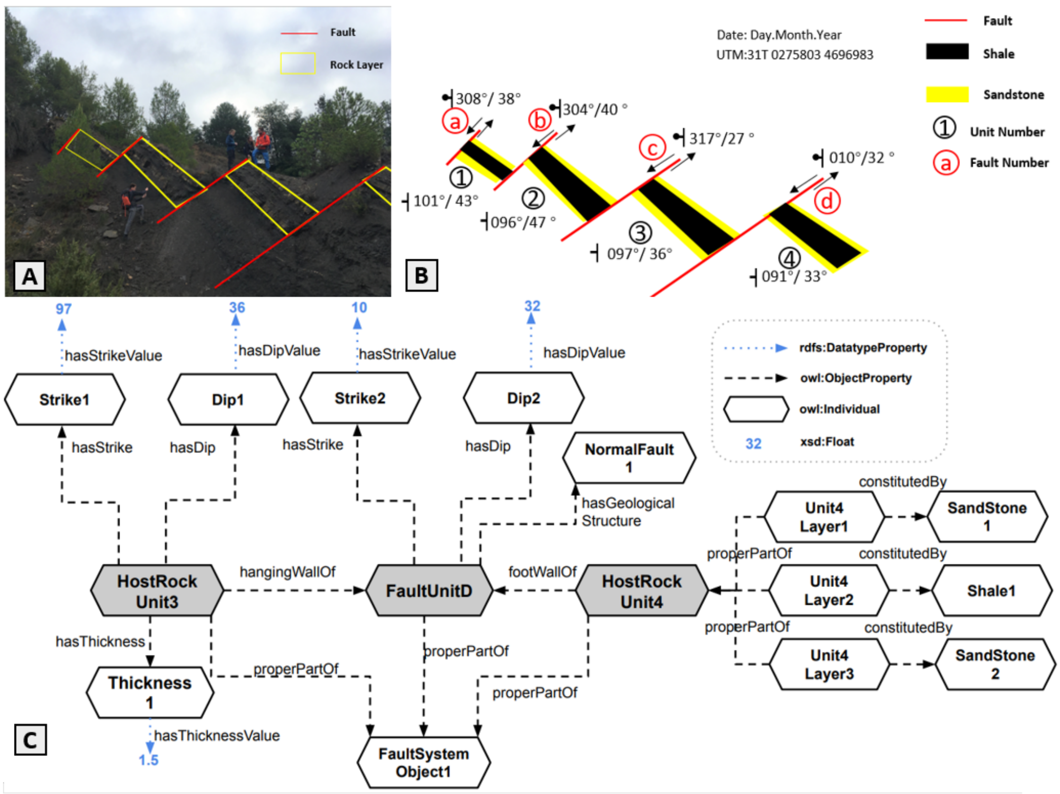

Figure 3: A real world structural geology scenario with targeting geological entities(A), an initial structural geological interpreting sketch of the scenario (B), and the schematic illustration of part of the generated knowledge graph of the scenario (C)

User Interface Design and Knowledge Mapping The user interface development is in the stage of wireframe designing. The challenges include how to bridge the graphic sketch part and the knowledge based part of the system and make the interface easy for industrial users and geologists. Using a high-level language to make ontology templates is a potential solution for the first challenge. Solving the second challenge will require a solid user study and interdisciplinary discussions.

4. Evaluation and Industrial Applications

System Verification. The verification of the ontology is designed in two parts. *(1) Competency Questions.* The competency questions are provided by domain experts, and reflect critical knowledge that needs to be captured in mainly three aspects: fault type, rock layer composition, and numeric properties. Questions asking for the type of a given fault, the composition of some layers, and the strike/dip values of the fault, will use to test the ontology. Such questions are expected to be answered by a knowledge graph adhering to the designed ontology. In addition to the ontology and knowledge graph verification, future evaluation will use workshops and interviews as user experience study methods to evaluate the usability of the system, and what components are required for the system. *(2) Examination of Use Cases.* In addition to the competency questions, real scenarios from on-shore field observation and offshore research work will be used to examine the ontology's correctness, completeness, and expressivity and ensure that it can fully describe the scenarios and approved by domain experts?

Examination: Sketch information capture with semi-automated KG generation. In the current stage, the generated knowledge graph's clarity is the main focus. To this aim, we proposed a real scenario in Fig. 3a to see how the a knowledge graph can describe it. Fig. 3a is a structural geology scenario with faults and host rocks; Fig. 3b is a simple geological sketch of the scenario in Fig. 3a; Fig. 3c is an illustration of part of the corresponding knowledge graph. The knowledge graph describes the fault type, the relationship between faults and host rocks, the composition of the host rocks, and the core numeric values of this scenario concisely.

Applications High quality information and access efficient are essential for digitised industries. Over time, semantically annotated sketches will form a searchable library, allowing more efficient access to information than with traditional text- and image-based publications. The generated information can also support supervised machine learning and qualitative geological information reasoning in the future to assist users' decision making. The applications' evaluation will be based on industrial needs to run workshops and demos to evaluate the system.

5. Conclusion and Outlook

Conclusion. This paper presents our ongoing research on providing an industrially relevant information capture method in structural geology. Based on domain experts' requirements and existing ontologies, a preliminary ontology has been tailored for the domain to formalise the knowledge. The capture system generates knowledge graphs in a semi-automated way based on users' sketch input. We use a real geological scenario to validate the usage of our knowledge model and the generated knowledge graph. The generated knowledge graph is retrievable, reusable, machine-readable, and suitable for inference.

Outlook. Beyond the current work, the front-end system is under development. Our next goal is to bridge the front-end graphical system and the back-end knowledge base and demonstrate the work to more users to evaluate the system's usefulness. The unified ontology shows great potential in adopting other disciplines of geology, which leaves the possibility for future extension.

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