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A systematic literature review on ontologies for Geology

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ABSTRACT

In Computer Science, ontologies are explicit formal specifications of shared conceptualizations. They are mainly used to capture the conceptual structure of a domain and can be used to structure domain data according to this conceptual structure, promoting semantic interoperability. In recent years, ontologies have been applied in various areas of Geology, so several studies have proposed a large number of ontologies. However, the literature offers no systematic reviews of studies proposing ontologies in Geology. This lack of a systematic review makes it difficult to identify the ontologies already proposed in the field and to pinpoint trends in terms of research and development for ontologies within this domain. This study aims to conduct a systematic review of the literature on studies presenting ontologies for Geology. In this work, 23 articles proposing ontologies for the Geology domain were identified after applying exclusion and inclusion criteria. From this set of articles, we gathered data to answer 8 research questions as well as to provide an overall panorama of the papers proposing ontologies in Geology. It is hoped that this study will promote the potential reuse of the identified ontologies and enable the identification of trends in research and development of ontologies for Geology.

Keywords: Ontology. Geology. Semantic Interoperability.

Uma revisão sistemática da literatura em ontologias no domínio das Geologia

RESUMO

Em Ciência da Computação, ontologias são especificações formais explícitas de conceitualizações compartilhadas. Eles são usados principalmente para capturar a estrutura conceitual de um domínio, e podem ser usados para estruturar dados de domínio de acordo com essa estrutura conceitual, promovendo a interoperabilidade semântica. Nos últimos anos, ontologias têm sido aplicadas em diversas áreas de geociências, por isso diversos estudos têm proposto um grande número de ontologias. No entanto, a literatura não oferece revisões sistemáticas de estudos que proponham ontologias em geociências. Essa falta de revisão sistemática dificulta a identificação das ontologias já propostas na área e a identificação de tendências em termos de pesquisa e desenvolvimento de ontologias dentro desse domínio. O objetivo deste estudo é realizar uma revisão sistemática da literatura sobre estudos que apresentem ontologias para a Geologia. Neste trabalho, 23 artigos propondo ontologias para o domínio da Geologia foram identificados após a aplicação dos critérios de exclusão e inclusão. A partir desse conjunto de artigos, reunimos dados para responder 8 questões de pesquisa, bem como para fornecer um panorama geral dos artigos que propõem ontologias em Geologia. Espera-se que este estudo promova o potencial de reaproveitamento das ontologias identificadas e possibilite a identificação de tendências em pesquisa e desenvolvimento de ontologias para a Geologia.

Palavras-chave: Ontologia. Geologia. Interoperabilidade semântica..

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

BFO	Basic Formal Ontology
DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering
SUMO	Standard Upper Merged Ontology
TOTVE	Toronto Virtual Enterprise
OWL	Web Ontology Language
SWEET	Semantic Web for Earth and Environmental Terminology

CONTENTS

1 INTRODUCTION

Ontology, a term found in Philosophy, Computer Science, and Knowledge Engineering, serves different purposes in each of these disciplines. In Philosophy, Ontology is the study of the nature of existence. In Computer Science and Knowledge Engineering, it takes on a more practical role. A widely accepted definition provided by Studer, Benjamins and Fensel (1998) described ontology as "a formal explicit specification of a shared conceptualization". In essence, ontologies represent (or seek to represent) reality, and they do so in such a way that many different persons can understand the terms they contain and so learn about the entities in reality that these terms represent (ARP; SMITH; SPEAR, 2015).

While ontologies play a crucial role in numerous fields, their application in Geology can represent a significant advancement in how we understand and manage geological data. By providing a formal, explicit specification of shared conceptualizations, ontologies enhance logical consistency and improve interoperability between different applications (YANG; CORMICAN; YU, 2019). This focus on ontologies within the context of Geology is particularly pertinent to our discussion.

Geology is the study of Earth's interior and its exterior surface, the minerals, rocks and other materials that are around us, the processes that have resulted in the formation of those materials, the water that flows over the surface and through the ground, the changes that have taken place over the vastness of geological time, and the changes that we can anticipate will take place in the near future (MOORES; WAHL, 1988). This field of study provides insights into the planet's physical features, processes, and changes over time and encompasses all aspects, including the composition, structure, and history of the planet and the processes that are shaping the features on the surface (COMPTON; COMPTON, 1985). Understanding these elements is critical in comprehending the various geographical components of our habitat. Geologists play a crucial role in natural resource prospecting, aiding long-term planning and sustainability. Over the years, the area has witnessed a significant transformation, with the assimilation of digital data through the construction of ontologies. This modern approach facilitates the organization and integration of vast geological information (WANG; MA; CHEN, 2018).

In the context of the geological domain, data and knowledge are scattered over many files and databases. Thus, ontologies arise as a natural solution to enhance data interoperability in the domain (ABEL et al., 2015). However, developing an ontology is a time and resource-consuming task. Hence, the reuse of existing ontologies should be the starting point when needing such formalized knowledge (ABEL et al., 2015). However, one of the significant challenges nowadays is the fact that there isn't a central repository or even a literature survey that centralizes information regarding the available ontologies for the geological domain. Thus, the lack of works that compile and review these artifacts makes it difficult to identify and reuse these ontologies effectively.

The main objective of this work is to present a systematic review of the literature on ontologies within the Geology domain, specifically focusing on identifying and compiling their main properties. Our goal is also to provide a structured overview of these ontologies and discern emerging trends and challenges in the field.

The systematic review should be carried out by answering some specific research questions related to the domain. In this work, we analyze various aspects of the proposed ontologies within the domain to answer specific research questions. By conducting this comprehensive review, we seek to list the existing ontologies and their applicability.

The following sections of this work are structured in the given manner. Chapter 2 focuses on the theoretical foundations needed for a full understanding of this work, discussing the Geology domain, ontology, and systematic review. In Chapter 3, we delve into the systematic literature review, explaining its goals, methodologies, and criteria for paper selection. Chapter 4 presents the results analysis, providing an overview and statistics, detailing various domains, methodologies, and applications, and discussing the research questions. Lastly, Chapter 5 presents our concluding remarks and discusses future works.

2 THEORETICAL FOUNDATIONS

In this chapter, the essential context needed to fully comprehend this study is provided. Primarily on Section 2.1, an overview of the Geology domain is given, with an emphasis on explaining some of its various subdomains. Next, on Section 2.2 we discuss the notion of ontology, detailing its use, the concept of top-level ontology, and the methodologies involved in constructing a new ontology. Lastly, in the Section 2.3 we present an overview of a systematic review process. This will cover its goal, importance, and how it is conducted.

2.1 Geology Domain

Geology is the science which investigates the successive changes that have taken place in the organic and inorganic kingdoms of nature: it inquires into the causes of these changes and the influence which they have exerted in modifying the surface and external structure of our planet (LYELL, 2023).

Through these researches into the state of the earth in former periods, we acquire a more accurate knowledge of its present condition and more comprehensive views concerning the laws now governing its animate and inanimate productions. When we study history, we obtain a more profound insight into human nature by instituting a comparison between the present and former states of society. We trace the long series of events that have gradually led to the actual posture of affairs, and by connecting effects with their causes, we are enabled to classify and retain in the memory of a multitude of complicated relations, the different degrees of moral and intellectual refinement, and numerous other (LYELL, 2023).

The subject of Geology encompasses aspects including the composition, structure, physical properties, and history of a planet's (like Earth's) interrelated components and the processes that are shaping the features on the surface. Geologists are the scientists who study the origin, occurrence, distribution, and utilities of all materials(metallic, nonmetallic, inorganic, etc), minerals, rocks, sediments, soils, water, oil, and all other inorganic natural resources. It is a vast subject covering a wide spectrum of scientific principles and holding several distinct scientific branches (BALASUBRAMANIAN, 2017).

It is important to note that Geology has a broad influence on the world around us. For instance, they play a critical role in providing insights into issues like climate change and global warming, finding solutions to the exhausting water supplies, and providing forecasts about the possibilities of natural disasters like floods, earthquakes, and landslides (CRANE; KASTING; KUMP, 2010). Furthermore, the exploration and exploitation of natural resources, which are key aspects of Geology, are crucial to modern civilization (MARSHAK, 2015). They explain how and where these resources are formed and provide methods of managing them to minimize environmental impacts. In conclusion, the exploration of Geology is vital to improving our current understanding of the earth and the processes that govern it.

The word "Geology" is derived from the Greek word "geo" means globe and "logos" means logical discourse. Hence, Geology is defined as the logical study of the planet. Today, Geology does not restrict its domain to the study of the planet Earth alone. It also includes the study of the other planets and moons of the entire solar system. Geology is a very vast subject and involves the study of Earth's materials, such as minerals and rocks, as well as the processes operating on and within the Earth and on its surface, as well as the sequential changes that have happened and evolved continuously during the past 4.6 billion years on the planet. It has several different sub-areas.

Geophysics is a major subject of natural science. It is a core branch of Geology. Its coverage includes exploring the Earth's magnetic, electric, and gravitational fields and its interior by studying seismic waves from earthquakes (TELFORD; GELDART; SHERIFF, 1990). Geophysicists often use remote sensing techniques and satellite data for these investigations. The knowledge produced in this field is indispensable for resource explorations such as petroleum and minerals and for environmental management and predicting geological hazards.

Stratigraphy represents another critical domain within Geology. It is the study of rock layers (strata) and their temporal and spatial relations, groupings, and ages (SMITH et al., 2016). This branch is essential in revealing Earth's history and particularly focuses on deciphering the indication of the Earth's past climates and ecosystems. Stratigraphic studies also provide critical information for identifying and exploiting fossil fuels and water aquifers.

Petroleum Geology studies the origin, occurrence, movement, accumulation, and exploration of hydrocarbon fuels. It refers to the specific set of geological disciplines that are applied to the search for hydrocarbons (oil exploration). Petroleum Geology is principally concerned with the evaluation of several key elements in sedimentary basins, such as, source, reservoir, seal, trap, timing, maturation, and migration. In general, all these elements must be assessed from exploration wells. Recently, the availability of inexpensive, high-quality 3D seismic data (from reflection seismology) and data from various electromagnetic geophysical techniques (such as Magnetotellurics) has greatly aided the accuracy of such interpretation in oil exploration (BALASUBRAMANIAN, 2017).

Geology is always in the service of humankind (BALASUBRAMANIAN, 2017). Each sub-discipline provides critical perspectives on the different aspects of the Earth's complex interplay of physical and chemical processes.

2.2 Ontology

Ontology is a concept that originated in Philosophy and has expanded into various fields, such as Computer Science and information technology, particularly in the discipline of Artificial Intelligence (AI) (ARP; SMITH; SPEAR, 2015).

As a philosophical study, ontology examines the nature of being, existence or reality, and their relationships (ALFAIFI, 2022). In the context of Computer and Information Science, ontology refers to a model for describing the world that consists of a set of types, properties, and relationship types (ALFAIFI, 2022). In Geology, ontologies are utilized for modeling complex concepts and their interrelations, thus facilitating data integration and information exchange in an automated environment (BORGO; MASOLO, 2010). This process is an integral part of developing ontologies for Geology, which falls within the realm of Computer Science.

Underlying the notion of ontology within the realm of Computer Science is the need for a systematic categorization and organization of knowledge into an accessible and interpretable format. An ontology in this context can be simply defined as a representational artifact, including a taxonomy as a proper part, whose representations aim to identify some fundamental concepts, defined classes, and certain relations among them. An ontology, in its function as a representational artifact, seeks to represent reality in a manner that's comprehensible to a wide range of persons, thereby enabling them to learn about the entities within that reality. In essence, ontology strives to represent general knowledge of a particular domain in lieu of specific instances or individual data points (ARP; SMITH; SPEAR, 2015). Creating an ontology can be a very time-consuming and error-prone task. It can be performed in many different ways, including knowledge acquisition steps that can involve literature analysis or interviews with domain experts (ABEL et al., 2015).

A conceptual model of an ontology serves as a formal representation of knowledge within a specific domain, outlining the relevant concepts and the relationships between them. According to Guizzardi (2005) these models provide a structured framework that helps in effectively capturing the semantics of the domain being studied. This structured framework not only facilitates a deeper understanding of the domain but also enhances communication between domain experts and system developers by providing a clear and shared vocabulary. Such conceptual models are essential in the development of ontologies because they act as blueprints that guide the creation of ontological architectures, ensuring that they align closely with both the theoretical fundamentals and the practical applications of the domain concerned.

Additionally, developing an ontology structure involves using ontology representation languages to create a machine-readable conceptual model. This ensures that the ontology, as a conceptual model, can be implemented and processed by a computer. The process of implementing the conceptual model for computer processing involves representing it using an ontology representation language. Standards like Web Ontology Language (OWL) (OWL. . . ,), Description Logic (DL), and Resource Description Framework (RDF) (RDF. . . ,) enhance formal and explicit representations of a specific domain. Selecting an implementation language for an ontology already defined as a conceptual model, it is essential to factor in the non-functional aspects of the project, such as scalability, performance, interoperability, and maintainability. Making an informed choice on the implementation language depends heavily on the specific requirements and constraints that the project demands (GUIZZARDI, 2005).

Regardless of the discipline it is applied to, from health care to artificial intelligence, ontology remains a vital tool for enabling the meaningful organization and representation of knowledge.

2.2.1 Top-level Ontologies

Top-level ontologies, or upper-level ontologies, form the critical backbone in creating meaningful data relationships in a diverse range of applications. They are essentially a set of concepts, categories, and relations that are relevant and prevalent across various domains. For example, common concepts such as object, process, or event fall under the purview of a top-level ontology. These high-level, general concepts serve as a foundational construct for more specific, domain-related items, providing a larger semantic framework that spans across different domain ontologies.

Implementing a top-level ontology has vast implications in controlling the potential chaos that can emerge from many disparate domain ontologies forming perspectival silos. As more researchers begin to realize the potential of ontology for managing complex data, they also find that these domain ontology projects are vastly different and incompatible, making data exchange and comprehensibility a challenge. However, with a top-level ontology acting as the root node - a kind of universal parental construct to all domain ontologies - definitions and meanings of terms can be more uniform. For instance, the primary purpose of top-level ontologies lies in providing a broad view of the world suitable for many different target domains (GUARINO; OBERLE; STAAB, 2009).

The concept of interoperability is one of the primary reasons for adopting a shared top-level ontology. Semantic interoperability is the faculty of interpreting knowledge imported from other languages at the semantic level to ascribe to each imported piece of knowledge the correct interpretation or set of models. It is a very important requirement for delivering a worldwide semantic web (WACHE et al., 2001).

Semantic interoperability, in particular, can be enhanced by such consistency among domain ontologies, making the exchange and understanding of data meaning among different systems a far more efficient process. Furthermore, top-level ontologies also pave the way for sophisticated formal reasoning, offering deeper insight into relationships between data points that might otherwise seem unrelated.

Examples of top-level ontologies include Basic Formal Ontology (BFO) (ARP; SMITH; SPEAR, 2015), Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) (GANGEMI et al., 2002), and Standard Upper Merged Ontology (SUMO) (NILES; PEASE, 2001). Each of these ontologies brings different world views, providing different advantages, and their use helps to bring about a more unified and seamless handling of knowledge representation in various fields, providing coherent foundation for a variety of different ontologies, easily allowing interoperability among specific domain ontologies. Therefore, the use of a shared, common top-level ontology can significantly enhance the effectiveness of communication and collaboration among different communities of researchers, making it a crucial component of efficient scientific computation.

2.2.2 Ontology development methodologies

The development of ontologies is a sophisticated task that involves key decision-making processes and methodologies to ensure the resultant ontology is fit for purpose. Ontology development methodologies, therefore, guide developers through the process of building ontologies from scratch. They provide a structured approach to creating, implementing, and evaluating ontologies, providing clarity and precision in what could otherwise be a complex and overwhelming task.

Existing ontology development methodologies differ in various ways, such as the set of steps that should be carried out, the ordering in which those steps should be performed, the incorporation of tools and techniques, and the nomenclature used to define the steps. However, despite these dissimilarities, these methodologies generally share commonalities at a conceptual level. Systematic steps always guide developers in identifying the domain, capturing the knowledge, defining the classes and relationships, and implementing, testing, and validating the ontology.

In the development of ontologies, while implementation is an essential step present in nearly all methodologies, other critical steps arguably hold greater significance. The conceptualization phase, where a conceptual model is elaborated, and the formalization phase, in which this model is translated into a formal representation, are often considered more critical. During conceptualization, ontology developers outline the knowledge and relationships essential to the domain, creating a clear and coherent model. Following this, the formalization phase involves formalizing an ontology as a conceptual model using a logical language, mainly to eliminate ambiguities in the definitions of classes and relationships. This formal language is generally based on expressive logic (such as first-order logic), which is undecidable. The implementation step then serves as the final phase, where the formalized model is represented computationally using some ontology representation language with desirable computational properties, such as decidability and efficiency. This step ensures that the ontology meets the desired objectives and is ready for testing, evaluation, and practical application (NOY; MCGUINNESS et al., 2001).

For instance, the TOronto Virtually-based Enterprise (TOVE) methodology (FOX, 1992) targets the business domain. TOVE aims to create shared and explicit conceptualizations applicable to various aspects of an enterprise, like activities, resources, or time, to aid in decision-making and managing complexities within business organizations.

On the other hand, the Skeletal methodology (USCHOLD; KING, 1995) reduces the complexity involved in the ontology-building process by offering 'skeletons,' or incomplete ontological structures that can be reused and refined. Notably, the Skeletal methodology emphasizes the reusability of ontological structures, a premise not as prevalent in the other methodologies.

The METHONTOLOGY approach deeply explores the granular aspects of ontology creation. It offers a systematic, piecemeal procedure for ontology development from scratch, honing in on essential details of ontology development. These specifics are categorized across three dimensions: lifecycle or stages of process, components, and roles. The lifecycle in METHONTOLOGY encapsulates distinct steps ranging from the identification of needs to maintenance. The process kick-starts with a pre-development phase that includes identifying the purpose, scope, and potential uses of the ontology, and this is similar to the first stage of the seven-step methodology. Following this, METHONTOLOGY proceeds uniformly through stages such as specification, conceptualization, formalization, implementation, and maintenance. Components of the ontology, such as terms, relationships, axioms, and instances, are defined subsequently, and the roles dimension focuses on the people involved in the ontology creation process. This includes roles like the domain expert who ensures the accuracy of the ontology and the knowledge engineer responsible for implementing the ontology within the system (FERNÁNDEZ-LÓPEZ; GÓMEZ-PÉREZ; JURISTO, 1997). A remarkable point about METHONTOLOGY is its granularity in providing guidelines for the ontology-building process compared to other methodologies. It offers more details on designing, deploying, and maintaining ontologies. Hence, whether an organization is creating an ontology for the first time or looking to refine an existing one, METHONTOLOGY provides a detailed road map for the complete ontology lifecycle (FERNÁNDEZ-LÓPEZ; GÓMEZ-PÉREZ; JURISTO, 1997).

Furthermore, the On-To-Knowledge Methodology (OTKM) stands out by framing ontology development in the broader context of knowledge management. It includes the extraction of knowledge from heterogeneous sources and ontology learning, considering the practical aspects of ontology usage (SURE; STAAB; STUDER, 2004).

Lastly, the NEON Methodology handles the challenge of developing and maintaining multiple, interrelated ontologies. It focuses on aspects like reuse, alignment, and modularization, targeting networked ontology development (SUÁREZ-FIGUEROA et al., 2012).

All these methodologies present diverse perspectives and approaches that cater to various scenarios, requirements, and domains that you can check in Table 2.1. Despite the differences, each methodology, including the Seven-Step methodology, aims to create contextually relevant, useful, and meaningful ontologies, which are fundamental in knowledge representation and management.

Table 2.1: Methodologies and the steps

Methodology	*Ontology development process*
TOTVE	(1) Identify motivating scenario, (2) define informal competency questions, (3) define the terminology of the ontology, (4) define formal competency questions, (5) specify the definitions and constraints on the terminology, (6) test the competency of the ontology
Skeletal Methodology	(1) Identify the purpose, (2) build the ontology (ontology capture, ontology coding, and integrating existing ontologies), (3) evaluation, (4) documentation, (5) guidelines for each phase
METHONTOLOGY	(1) Specification; (2) Knowledge acquisition; (3) Conceptualization, (4) Integration, (5) Implementation, (6) Evaluation, (7) Documentation
Simple Knowledge Engineering Methodology	(1) Determine the domain and scope of the ontology, (2) consider reusing existing ontologies, (3) enumerate important terms in the ontology, (4) define the classes and the class hierarchy, (5) define the properties of classes, (6) define the restriction of the classes, (7) create instances
The OnToKnowledge Methodology	(1) Feasibility study (2) Knowledge Kick-off, (3) Refinement, (4) Evaluation, (5) Maintenance
NEON	(1) Specification (2) Reuse of ontologies, (3) Reengineering of non-ontological resources, (4) Integration, (5) Selection and customization of ontology design patterns, (6) Testing, (7) Create instances, (8) Maintenance

Source: The author

2.3 Systematic Literature Review

In Computer Science, a systematic literature review is a methodology used to comprehensively review current research to answer questions (KITCHENHAM; BRERETON, 2013). It encompasses clearly defined methods for identifying, analyzing, and interpreting all studies relevant to these questions. This approach aims to offer objective results, reduce bias in analyses, support reliable findings, and form a solid basis for decision-making. Notably, through resulting insights, this approach can uncover research gaps, identify practical implications, and guide future studies (KITCHENHAM; BRERE-

TON, 2013).

Systematic literature review also follows established protocols to ensure consistency and reliability (KITCHENHAM; BRERETON, 2013). This protocol encompasses pre-defined objectives, criteria for the inclusion or exclusion of studies, strategies for data extraction, and means of assessing the risk of bias in the studies. This planning guarantees standard procedure and sets expectations for the entire process, enhancing transparency and providing a well-defined pathway for replication.

This protocol begins with formulating a clear set of objectives, followed by defining criteria for the inclusion and exclusion of studies. *Inclusion criteria* specify the characteristics that studies must consider, such as relevant populations, interventions, outcomes, and study designs. *Exclusion criteria*, on the other hand, outline characteristics that disqualify studies from consideration, such as irrelevant subject matter, insufficient methodological quality, or outdated data.

Once the criteria are established, strategies for data extraction are planned. This typically involves using data extraction forms or software tools to systematically collect relevant information from each study, such as study design, sample size, outcomes measured, and key findings (KITCHENHAM; BRERETON, 2013). Additionally, assessing the risk of bias in the studies is crucial; this step involves evaluating each study's methodological quality to determine its findings' reliability.

After setting clear objectives, the process typically starts with a comprehensive search of databases and other sources to identify relevant studies. This step often includes defining search strings and keywords and choosing appropriate databases. The search strategy must be both exhaustive and replicable. Next, the initially identified studies undergo a selection process wherein they are screened based on the pre-defined inclusion and exclusion criteria. This usually involves reading titles, abstracts, and sometimes full texts to decide which studies meet the set criteria.

Following the identification and selection of relevant studies, data extraction forms or systems are employed to systematically extract pertinent data from each study. These forms typically capture information about the study's objectives, methodologies, sample sizes, results, and any limitations noted by the authors. This structured data extraction is crucial for ensuring that the analysis phase can be performed efficiently and accurately. Once the data is extracted, each study's quality is assessed to evaluate the risk of bias. Finally, the extracted and assessed data is analyzed and synthesized to produce findings that answer the initial research questions. This synthesis often involves qualitative or quantitative methods, such as meta-analysis, to combine data from multiple studies and draw more generalizable conclusions (KITCHENHAM; BRERETON, 2013).

In software engineering, a systematic literature review is a methodology for comprehensively reviewing current research to answer specific questions pertinent to the field (KITCHENHAM; BRERETON, 2013). Although it is not the same thing, this rigorous review approach can also be adapted for ontology engineering. The systematic methodology helps ensure that the review process is thorough, unbiased, and replicable, proving invaluable in synthesizing existing knowledge, identifying trends, and uncovering gaps in ontology research and development. By leveraging this structured framework, ontology engineers can better understand the existing landscape and make more informed decisions in their own work."

3 SYSTEMATIC LITERATURE REVIEW PROCESS

In this chapter, we delve into the systematic literature review process, starting with discussing its goals. We elucidate the primary objectives of conducting this systematic literature review. Subsequently, we describe the methodology employed, detailing each process stage. This includes a comprehensive account of the paper selection procedure, specifying the databases and sources consulted to ensure a thorough and unbiased search. Additionally, we outline the inclusion and exclusion criteria applied to filter the literature, ensuring that only the most relevant and high-quality studies are considered. These criteria were defined to maintain the integrity and relevance of the review, ultimately contributing to an insightful synthesis of existing knowledge.

We began our systematic literature review by formulating clear research questions, which guided the entire process. Once the research questions were established, we defined a specific analysis period to focus our review on recent and relevant literature. With this foundation, we then constructed precise query strings tailored to capture the necessary data from various academic databases. Using these query strings, we conducted searches across selected databases and retrieved the resulting articles. We applied our predefined inclusion and exclusion criteria to filter the relevant studies. These criteria ensured that the studies selected were pertinent to our research questions, had appropriate methodological quality, and fell within the defined period.

After applying the inclusion and exclusion criteria, we read the selected articles in-depth to gain a comprehensive understanding of the content. From these studies, we systematically extracted relevant information that would aid in answering our research questions. With the extracted data in hand, we conducted a thorough analysis to identify patterns, trends, and key insights. Finally, we compiled and reported our findings, presenting a cohesive narrative that addresses the research questions and provides valuable insights into the topic under review.

3.1 Goals

Our review aims to answer key research questions related to the development and application of ontologies in Geology.

- **RQ-1** Which ontologies have been proposed?

- **RQ-2** For which specific domain of Geology was the ontology built? (e.g., Structural Geology, Sedimentology, Stratigraphy, etc.)
- **RQ-3** Was an established methodology used for construction? If so, which one?
- **RQ-4** Are top ontologies specialized? Which ones?
- **RQ-5** Are other ontologies being reused apart from top ontologies?
- **RQ-6** Were they implemented in a machine-processable language? If so, which one?
- **RQ-7** Is the ontology publicly available?
- **RQ-8** Is the ontology serving any specific purpose or application? If so, what is it?

These questions aim to identify the key characteristics of ontologies developed in the Geology domain, their domains of specialization, reusability, implementations, availability, and the purposes they serve. The findings from this systematic literature review would thus contribute to a comprehensive understanding of the landscape of ontologies specific to Geology, potentially revealing existing trends, gaps, and issues for further research. Additionally, by uncovering the characteristics of each ontology, other researchers in the field can more easily identify ontologies that suit their purposes, thereby promoting the reuse of ontologies. This enhanced visibility and understanding could lead to greater collaboration and efficiency within the domain, as researchers can build upon established frameworks rather than starting from scratch.

3.2 Methodology

This section outlines the protocol followed during the systematic literature review describing the methodology employed, detailing each stage of the process. This entails a thorough account of the paper selection procedure, including the specific databases and sources consulted to guarantee a comprehensive and unbiased search.

The protocol of the systematic review followed in this investigation consists of several stages:

- Review Questions Formulation: The questions were specifically targeted toward creating ontologies in the field of Geology. The questions aimed to understand the domain each ontology covers, whether it is publicly available for reuse, the methodology employed for its construction, and other relevant aspects.

- Temporal Scope: The review considered studies published within a specific time frame to ensure the relevance and currency of the findings. For instance, this review has included publications from the past 10 years, from 2014 to 2023, to capture the most recent trends and advancements in ontology creation for Geology
- Relevant Studies Identification: An exhaustive search was conducted on databases and other research repositories to identify articles, conference papers, theses, and other scholarly writings relating to the topic.
- Studies Selection: Based on the predetermined inclusion and exclusion criteria, studies were screened for their relevance to the review questions.
- Data Extraction: Relevant data was extracted from the chosen studies.
- Data Analysis: Finally, the collected data was systematically analyzed to answer the research questions.

This systematic literature review provides an understanding of how ontologies are constructed in the domain of Geology, the extent of their coverage, and their availability for public reuse. These findings can guide researchers, software engineers, and other stakeholders in understanding and applying leading practices in the development of ontologies for Geology.

3.2.1 Academic Databases

In order to reach as many relevant papers as possible, five well-known academic databases commonly used in Computing reviews were considered in this work (ALFAIFI, 2022) (CONNOLLY et al., 2012) :

- IEEE Explorer;
- ACM Digital Library;
- Springer Link;
- Scopus
- Science Direct

Due to the diverse search engines properties, a particular search query was proposed to each database, as follows:

- ACM Digital Library, Springer Link, Scopus and Science Direct use similar query syntax. The query for these databases was: (ontology OR ontologies) AND (geology OR geoscience OR "earth science" OR "earth sciences")

- IEEE Explorer[1] recommends using few words and short expressions. In fact, it does not work properly with many disjunction terms. Due to that, a concatenation of the results of all possible variations of one term of each column of the Table 3.1 related to the terms of the other columns by AND operator was considered:

Table 3.1: Elements of the research query for IEEE Explorer

Ontology Ontologies	Geology Geoscience "Earth Science" "Earth Sciences"

An example of a query extracted from Table 3.1 is: Ontology AND "Earth Sciences";

The research query is primarily directed towards obtaining papers that delve into the application of ontologies within the Geology domain, although the term ’Earth Sciences’ was included in the query because many papers focus on this broader subject, often mentioning ’Earth Sciences’ while covering Geology as a sub-branch. This approach was adopted to ensure that no relevant articles were overlooked during the query phase. Regardless of the specific subdomain within Geology, all relevant discussions are welcome as this distinction task will be left for the screening process.

3.2.2 Paper Selection

The process for the selection of potential papers was carried out using inclusion and exclusion criteria. This is a crucial step in the systematic literature review, as it helps filter out the set of results and extracts only those papers that are pertinent to the research context. The inclusion and exclusion criteria represent a set of desirable and undesirable traits, respectively, of a primary study. These criteria are essential to direct the selection of studies apt for the research (BRERETON et al., 2007).

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[1] IEEE search guidelines are presented in https://ieeexplore.ieee.org/Xplorehelp/ieee-xplore-training/user-guides

3.2.2.1 Inclusion criteria

The inclusion criteria were defined with the intent of sorting the potential papers primarily based on their content and their relevance to the predetermined research subject matter. The introduced inclusion criteria compromise the following elements:

- **IC-1** The paper presents or proposes an ontology.
- **IC-2** The paper is relevant to Geology in a manner that is directly tied to the primary scope of the study, instead of merely citing it as a referenced term.

To verify compliance with the Inclusion Criteria IC-2, for a study to be considered valid, it must present or discuss an ontology that is directly related to Geology, at its main focal point, rather than simply referencing it:

- **IC-2.1** The author thoroughly reviewed each paper to ascertain if it was relevant to Geology.
- **IC-2.2** To ensure that only papers with pertinent context were considered, the selected papers were further evaluated by two experts, making them the final filtering barrier in this process.

3.2.2.2 Exclusion criteria

The following exclusion criteria were used to filter out unsuitable papers, based on the format, language, accessibility, length, time of publication, and content:

- **EC-1** The paper is not peer-reviewed.
- **EC-2** The paper is written in a language other than English.
- **EC-3** The paper was published before 2014.
- **EC-4** The paper was published after 2023.
- **EC-5** Papers that don't have "ontology" or "ontologies" in the abstract or title.
- **EC-6** The paper has fewer than 4 pages.
- **EC-7** The paper is not a primary study.
- **EC-8** The paper is inaccessible.

EC-1, EC-2, EC-3 and EC-4 were applied directly to the search query results. The application of EC-5, EC-6, EC-7, EC-8 exclusion criteria required manual verification to gauge the suitability of the papers. Here's how those criteria were individually approached:

The application of EC-5 required a more specialized method of verification. Using the RYYAN[2] tool, a Research Information System (RIS), files of the articles were screened. By doing this, we could identify the presence of the terms "ontology" or "ontologies" in either the title or the abstract.

To verify EC-6, each paper had to be opened individually. By doing so, were able to assess the document's length to confirm whether it met the minimum page requirement.

To verify EC-7 we carried out a comprehensive analysis of the entire text of each paper. The main focus was to identify the nature of the paper, where only primary studies were deemed eligible. A non-primary study can be, for example, systematic reviews of ontologies, surveys, etc. They do not propose novel ontologies, instead they only examine and interpret previously conducted primary research in a structured manner.

Verifying EC-8 involved a case-by-case analysis. Each document was thoroughly inspected by attempting to access the full content of the publication. The papers that restricted full content access were deemed inaccessible and subsequently excluded.

3.3 Limitations

In conducting this study, we acknowledged several limitations that may have impacted the analyses' comprehensiveness and inclusivity. Despite efforts to establish criteria that would yield a representative sample of ontologies for the Geology domain, practical limitations in available resources and project timelines required some compromises.

- **Keyword selection:** The choice of keywords for literature queries significantly influenced the scope of the sample. Specifically, the focus on general domain terms like "Geology", "Geoscience," and "Earth Sciences" may have led to the omission of works focused on specific subdomains, such as Stratigraphy or Sedimentology that did not include the general terms in the text. Also, the focus on the term "ontology", might have inadvertently excluded relevant articles that described ontologies using different terminologies, such as "knowledge models", "knowledge graphs", or "semantic models".
- **Database choice:** The databases selected for this study are traditionally adopted within the Computing community. As a result, our sample may exhibit a bias towards articles published in venues commonly adopted by this community. This

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[2] https://www.rayyan.ai/

focus also implies that our sample is limited to articles indexed by these particular databases, potentially overlooking pertinent works disseminated through other channels.

- **Scope of works analyzed:** By concentrating on articles that explicitly propose an ontology, our analysis has excluded papers discussing ontological aspects of Geology without presenting a complete ontology. Notable exclusions due to this criterion include works (WERLANG et al., 2014), (ABEL et al., 2016), and (GARCIA et al., 2019).
- **Focus on peer-reviewed works:** Our decision to include only peer-reviewed papers means that ontologies put forward by corporations or presented in non-peer-reviewed formats were omitted. Consequently, significant contributions like (BRODARIC, 2021) have not been included in our analysis.
- **Temporal Scope:** The temporal scope defined for our selection criteria also influenced the inclusivity of our sample, resulting in the exclusion of seminal contributions that fall outside the predetermined timeframe. This includes impactful works such as (BABAIE et al., 2006), (COX; RICHARD, 2005), (PERRIN et al., 2011), (RASKIN; PAN, 2005), (QU et al., 2024) and (GEOSIRIS et al., 2024)

While we strived to perform a systematic and balanced review of the literature in the field of Geology ontologies, it is essential to interpret the findings presented in Sections 4 and 4.9 considering of these limitations, their potential implications and also having in mind that this analysis is tied to the articles selected on this work.

4 REVIEW ANALYSIS

This chapter presents and analyzes the outcomes derived from the systematic literature review process. It is structured in a way that each section presents one of the dimensions associated with the research questions analyzed. Section 4.1 begins with an overview of the findings of the systematic review, providing a comprehensive snapshot of the entire study. This is followed by a deep dive into the data collected related to the domains of Geology for which the ontologies were proposed. Next, Section 4.3 delve into the methodologies utilized in the construction or modification of the ontologies, and after a look at Section 4.2 presenting the geological topics, this is followed by an examination of the top-level ontologies on Section 4.4, and an exploration of previously existing ontologies that have been reused or adapted on Section 4.5. We then move on to Section 4.6, presenting the languages used for implementing the ontologies. Section 4.7 analyzes the specific applications for which ontologies were proposed, and Section 4.8 presents the public availability of the proposed ontologies. The work follows with Section 3.3 delving in limitations of this systematic literature review and closes on Section 4.9 with a discussion of the data that have been discovered within these dimensions, providing insights and interpretation of what these findings may mean in a broader context.

To enhance comprehension, the systematic review was structured into two distinct phases, which encompass all the previously mentioned steps:

1. Applying a research query within several academic databases to accumulate potential scholarly papers.
2. Entailed the manual implementation of specified inclusion and exclusion criteria to the assembly of papers obtained in the first phase. This step was crucial in refining the results and isolating the most pertinent studies.

Table 4.1 shows the set of papers resulting of each step:

Table 4.1: Selection of papers

Step	*Set of Papers*
Query Application + Automatic exclusion criteria	4332
Manual EC-5	1362
Manual EC-6	282
Manual EC-7	268
Manual EC-8	254
Manual IC-1	118
Manual IC-2.1	49
Manual IC-2.2	23
Final set	23

Source: The author

The Manual IC-2.1 is considered as containing only relevant content to the research by the author, although during the reading of the articles on step IC-2.2, 26 of them were considered not relevant per not being focused on Geology by the experts as in during the review, the terms "Earth Science" and "Earth Sciences" were utilized to locate articles across various branches of earth science beyond just Geology. Within Table 4.2, we have detailed these specific areas and provided the number of articles found for each:

Table 4.2: Not relevant papers

Subjects	*Set of Papers*
Remote sensing	12
Geography	7
Disaster Management	5
Meteorology	1
Agriculture	1

Source: The author

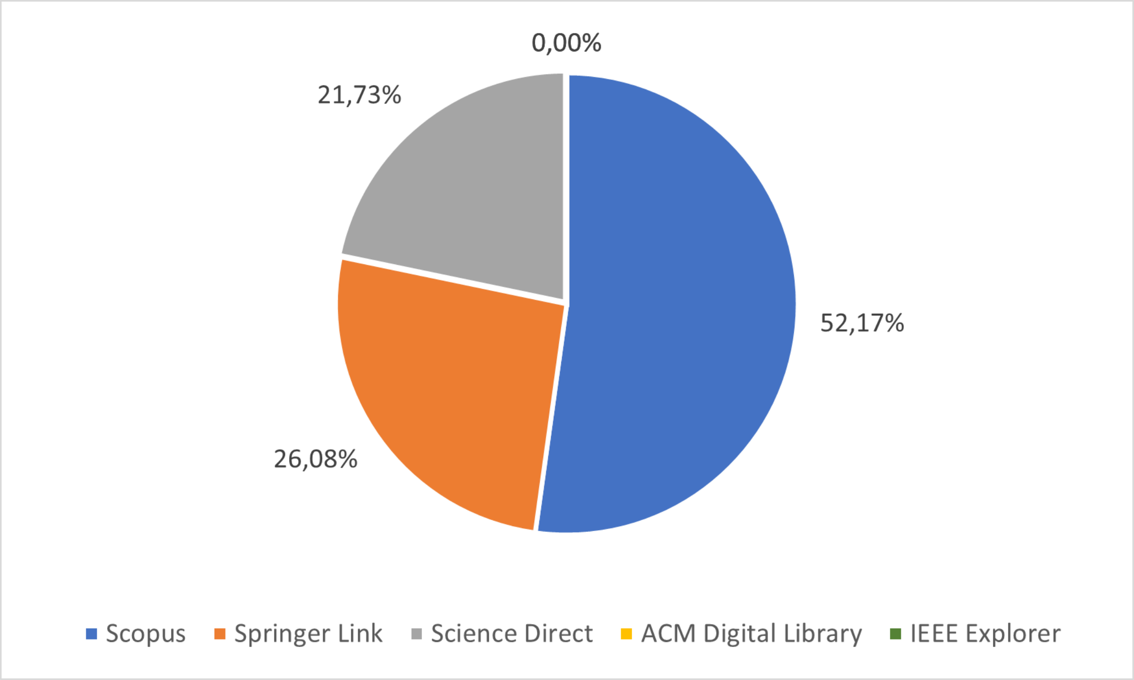
As indicated in Table 4.2, the category that encompasses the majority of the irrelevant papers is "Remote Sensing". These papers intersect heavily with the field of Geology but primarily concentrate on remote sensing concepts, properties, and relationships, and they are not focused on geological concepts and phenomena. For instance, in Kuo and Chou (2023) and Sambandam et al. (2023), authors propose ontologies focused on the notion of data, capture devices and surface features that are observed. Although Remote Sensing is indeed a data acquisition technique used in Geology, it isn't restricted to this particular field. The next category with substantial representation is "Geography." Papers falling into this category usually deal with phenomena that have geographical and socioeconomic aspects, such as migration, but they do not touch upon geological matters in depth.

Following that, we have papers under "Disaster Management". At first glance, one might assume these to be related to Geology due to their relations with geohazards. However, upon closer inspection, it becomes apparent that these papers are more focused on emergency responses to geohazards, and don't delve into geological phenomena themselves.

Lastly, "Meteorology" and "Agriculture" constitute the least represented categories. Papers in these categories tend not to provide sufficient detail and primarily support meteorological and agricultural applications. Geology, in these papers, is often featured as a side subject rather than a main focus.

Figure 4.1 illustrates the number of papers retrieved from each database we adopted. It is important to note that we included all the databases in the graph, even those from which no relevant papers were found. This helps provide a comprehensive overview of our data sources and their contributions to our research.

Figure 4.1: Papers per database

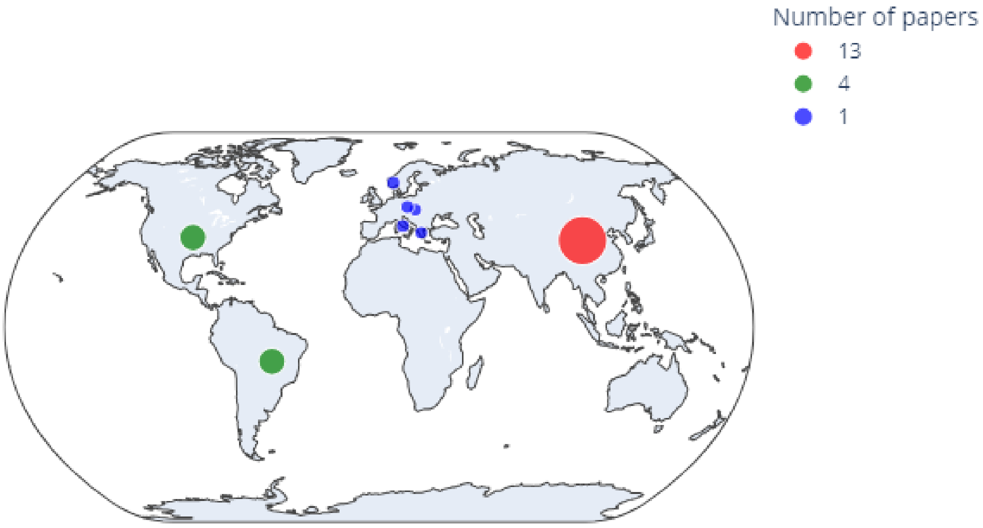


Source: The author

As depicted in Figure 4.1, the majority of the papers were found in the Scopus database. In contrast, we did not retrieve any relevant papers from IEEE Xplore or the ACM Digital Library. This highlights the dominance of Scopus in our search and indicates that IEEE Xplore and ACM Digital Library may have limited publications relevant to our specific area of interest.

Figure 4.2 illustrates the distribution of published articles per country. Note that

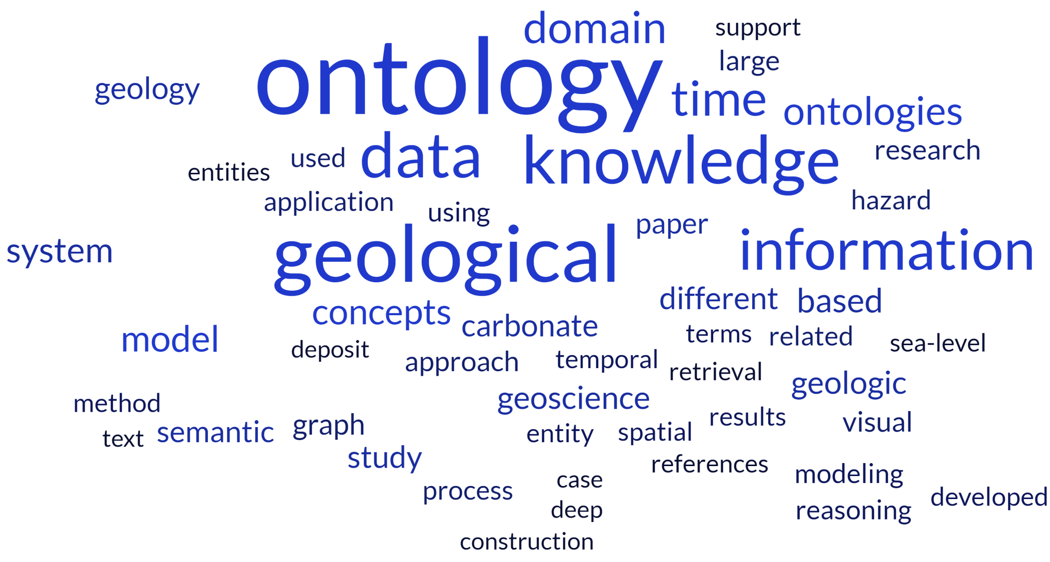
Figure 4.2: Papers per country



Source: The author

this chart depicts the countries of origin of each individual paper published by the contributing institutions. Consequently, the total number seen here exceeds the number of papers selected in the systematic review due to the inclusion of multi-authored papers contributed by institutions based in different countries. Upon analyzing the graph, it becomes evident that a significant collaborative effort exists, particularly attributed to China, Brazil, and the United States.

Figure 4.3: Abstract papers word cloud



Source: The author

Figure 4.3 presents a word cloud generated from a text resulting from the concatenation of the abstracts of all the papers selected in the systematic review conducted for this study. This visualization highlights the most frequently occurring terms within the abstracts, providing insights into common themes and topics addressed in the literature. The prominence of specific words in the word cloud offers a quick, intuitive understanding of the focus areas and reveals significant patterns across the reviewed articles.

In Figure 4.3, it is possible to distinguish several groups of frequently occurring terms. One of the groups is associated with the concepts of ontology and knowledge modeling, which includes terms such as: ontology, model, knowledge, semantics, modeling, reasoning, concepts, entities, etc. Another group is more closely associated with Geology, which is the target application domain, with terms such as: geology, geological, geologic, carbonate, etc. The frequency of terms related to time and space is also notable, as these concepts hold significant importance in Geology. Additionally, terms like "data" and "information" are prevalent, primarily because ontologies are used to structure data and information. The most frequent terms highlighted in this visualization align with the expectations, as they directly relate to the scope of this review, which focuses on ontologies developed for the domain of Geology.

After removing the non-relevant papers, the resulting set of papers is presented in Table 4.3 and contains 23 papers to be analyzed. The papers are referenced by their number in the column "Paper" along this study.

Table 4.3: Selected papers in systematic literature review.

Paper	Authors	Title	Year
[1]	Chengbin Wang; Yuanjun Li; Jianguo Chen; Xiaogang Ma;	Named entity annotation schema for geological literature mining in the domain of porphyry copper deposits	2023
[2]	Huiqing Xu; Yingying Zhao; Hao Huang; Shaochun Dong; Yukun Shi; Chunju Huang; Huaichun Wu; Zhiqi Qian; Qiang Fang; Huaguo Wen; Zhongtang Su; Shuang Dai; Ronghua Wang; Chao Li; Chao Sun; Junxuan Fan;	A comprehensive construction of the domain ontology for stratigraphy	2023

Continued on next page

Table 4.3 – *Continued from previous page*

Paper	Authors	Title	Year
[3]	Shu Wang; Yunqiang Zhu; Yanmin Qi; Zhiwei Hou; Kai Sun; Weirong Li; Lei Hu; Jie Yang; Hairong Lv;	A unified framework of temporal information expression in geosciences knowledge system	2023
[4]	Min Wen; Qinjun Qiu; Shiyu Zheng; Kai Ma; Shuai Zheng; Zhong Xie; Liufeng Tao;	Construction and application of a multilevel geohazard domain ontology: A case study of landslide geohazards	2023
[5]	Han Wang; Hanting Zhong; Anqing Chen; Keran Li; Hang He; Zhe Qi; Dongyu Zheng; Hongyi Zhao; Mingcai Hou;	A knowledge graph for standard carbonate microfacies and its application in the automatical reconstruction of the relative sea-level curve	2023
[6]	Daniela Ponce; Martina Husáková; Tomáš Nacházel; Vladimír Bureš; Pavel Čech; Peter Mikulecký; Kamila Štekerová; Petr Tučník; Marek Zanker; Karel Mls; Ioanna Triantafyllou; František Babič;	Unification of tsunami-related terminology: Ontology engineering perspective	2023
[7]	Qinjun Qiu; Miao Tian; Kai Ma; Yong Jian Tan; Liufeng Tao; Zhong Xie;	A question answering system based on mineral exploration ontology generation: A deep learning methodology	2023
[8]	Qinjun Qiu; Zhong Xie; Die Zhang; Kai Ma; Liufeng Tao; Yongjian Tan; Zhipeng Zhang; Baode Jiang;	Knowledge Graph for Identifying Geological Disasters by Integrating Computer Vision with Ontology	2023
[9]	Yiwei Xu; Xiumian Hu; Zhong Han;	Carbonate Ontology and Its Application for Integrating Microfacies Data	2023
[10]	Jinglun Xi; Jin Wu; Mingbo Wu;	Design and Construction of Lightweight Domain Ontology of Tectonic Geomorphology	2023

Continued on next page

Table 4.3 – *Continued from previous page*

Paper	**Authors**	**Title**	**Year**
[11]	Qinjun Qiu; Zhen Huang; Dexin Xu; Kai Ma; Liufeng Tao; Run Wang; Jianguo Chen; Zhong Xie; Yongsheng Pan;	Integrating NLP and Ontology Matching into a Unified System for Automated Information Extraction from Geological Hazard Reports	2023
[12]	Fernando Cicconeto; Lucas Valadares Vieira; Mara Abel; Renata dos Santos Alvarenga; Joel Luis Carbonera; Luan Fonseca Garcia ;	GeoReservoir: Na ontology for deep-marine depositional system geometry description	2022
[13]	Yuanwei Qu; Baifan Zhou; Evgeny Kharlamov; Martin Giese;	Industrial Geological Information Capture with GeoStructure Ontology	2022
[14]	Yan Qun; Xue Linfu Liu Zeyu; Gao Xin; Wang Rui; Dai Junhao;	Construction of Deposit Model-oriented Knowledge Graph	2021
[15]	Luan Fonseca Garcia; Mara Abel; Michel Perrin; Renata dos Santos Alvarenga;	The GeoCore ontology: A core ontology for general use in Geology	2020
[16]	Fernando Cicconeto; Lucas Valadares Vieira; Mara Abel; Renata dos Santos Alvarenga; Joel Luis Carbonera;	A spatial relation ontology for deep-water depositional system description in Geology	2020
[17]	Wenjia Li; Liang Wu; Zhong Xie; Liufeng Tao; Kuanmao Zou; Fengdan Li; Jinli Miao;	Ontology-based question understanding with the constraint of Spatio-temporal geological knowledge	2019
[18]	Alexandre Rademaker; Alexandre Tessarollo; Henrique Muniz; Adam Pease;	Extending SUMO to geological times	2019

Continued on next page

Table 4.3 – *Continued from previous page*

Paper	**Authors**	**Title**	**Year**
[19]	Chengbin Wang; Xiaogang Ma; Jianguo Chen;	Ontology-driven data integration and visualization for exploring regional geologic time and paleontological information	2019
[20]	Hassan A. Babaie; Armita Davarpanah;	Semantic modeling of plastic deformation of polycrystalline rock	2018
[21]	Vincenzo Lombardo; Fabrizio Piana; Dario Mimmo;	Semantics–informed geological maps: Conceptual modeling and knowledge encoding	2018
[22]	S. J. D. Cox; S. M. Richard;	A geologic timescale ontology and service	2015
[23]	Joel Luis Carbonera; Mara Abel; Claiton M.S. Scherer;	Visual interpretation of events in petroleum exploration: An approach supported by well-founded ontologies	2015

Source: The author

4.1 Overview of fidings

Each paper selected through the systematic review protocol was meticulously read and analyzed on an individual basis. The focus of the analysis was to identify key information pertaining to the relevance of the article, as defined by the established objective.

This thorough examination included the identification of the proposed ontology, pinpointing the specific domain it falls under within the Geology domain, and recognizing the methodology employed in the development of the ontology. We also explored whether a top-level ontology was utilized or if any ontology was reused (other than top-level). Moreover, the language in which these ontologies were implemented was also identified, along with whether these ontologies are publicly available and serve any particular purpose.

The detailed results from this analysis are presented in Table 4.4 and are structured into six columns, effectively catering to the specifics of the identified parameters. This format is aimed at providing a clear and comprehensive overview of our findings.

Table 4.4: Overview of review findings.

Ref	Ontology	Topic	Methodology	Top Ontology	Reused Ontologies	Language
[1]	Ontology for porphyry copper deposit	Porphyry copper deposits	Own methodology	—	—	OWL
[2]	Ontology for stratigraphy	Stratigraphy	Seven Step Methodology	—	—	OWL
[3]	UTF - Unified Time Framework	Time	Not clear	—	—	RDF
[4]	Landslide hazard chain ontology	Geohazard	Seven Step Methodology and Skeleton Method	—	—	OWL
[5]	Standard carbonate microfacies ontology	Stratigraphy	Own methodology	—	—	Not clear

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Ref	Ontology	Topic	Methodology	Top Ontology	Reused Ontologies	Language
[6]	Tsunami-Related Ontology	Geohazard	Own methodology	—	—	OWL
[7]	Geological domain ontology	Mineral geology	Own methodology	—	—	—
[8]	Ontology schema of geological disasters	Geohazard	Own methodology	Not clear	Not clear	OWL
[9]	Carbonate ontology	Carbonate rocks, petrographic data of carbonate rocks, microfacies	Seven-Step Methodology	—	—	OWL
[10]	Ontology of Tectonic Geomorphology	Tectonic geomorphology	Seven-Step Methodology	—	—	OWL

Continued on next page

Continued from previous page

Ref	Ontology	Topic	Methodology	Top Ontology	Reused Ontologies	Language
[11]	Geological Hazard Ontology	Geohazard	Own methodology	—	—	Not clear
[12]	Geo Reservoir	Deep-marine depositional system geometry	METHONTOLOGY	BFO	GeoCore	OWL
[13]	GeoStructure Ontology	Structural geology	Own methodology	—	Fracture Ontology and GeoCore Ontology	Not clear
[14]	Deposit Ontology	Ore deposits	Own methodology	—	—	Not clear
[15]	GeoCore	Geology	Own methodology	BFO	—	OWL
[16]	Spatial relation ontology for deep-water depositional system description	Geological spatial relations	Not clear	BFO	GeoCore	OWL

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Ref	**Ontology**	**Topic**	**Methodology**	**Top Ontology**	**Reused Ontologies**	**Language**
[17]	Geological Event Ontology (Geo-event ontology)	Geological events	Own methodology	—	Time Ontology in OWL	OWL
[18]	—	Geological time	Own methodology	SUMO	—	SUO-KIF
[19]	Ontology for the local geologic time scale of North America	Local geologic time scale of North America	Own methodology	—	—	JSON-LD
[20]	Plastic Rock Deformation (PRD) ontology	Plastic rock deformation	Own methodology	BFO	Multiple (14 ontologies listed)	OWL
[21]	OntoGeonous	Geological mapping	Own methodology	NASA SWEET	GeoScienceML (?), Simple Lithology, ICS Geological Time Scale Ontology	OWL

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Ref	Ontology	Topic	Methodology	Top Ontology	Reused Ontologies	Language
[22]	Geologic timescale ontology (GTS)	Geological time	Own methodology	—	Temporal Hierarchical Ordinal Reference System (THORS)	OWL
[23]	Well-founded domain ontology for Sedimentary Stratigraphy	Sedimentary stratigraphy	Own methodology	—	Ontology for imagistic domains: Combining textual and pictorial primitives	OWL

Source: The author

The findings presented in Table 4.4 will be further discussed in the following sections, focusing on the data related to each research question.

4.2 Geological Topics

The analysis of the relevant research papers has revealed a broad spectrum of geological topics represented in the literature. A notable variety in the range of topics, indicating the diversity and complexity of the studies being conducted in the field of Geology is observed. These topics are scattered across the spectrum, with a tendency towards areas such as Geological Hazard, Time, and Stratigraphy being more prevalent.

Table 4.5: Geological Topics

Topics	*Set of Papers*
Geological Hazard	4
Time	4
Stratigraphy	3
Porphyry copper deposits	1
Deep-marine depositional system geometry	1
Geology	1
Plastic Rock Deformation	1
Geological mapping	1
Tectonic geomorphology	1
Structural geology	1
Geological spatial relations	1
Ore deposits	1
Geological events	1
Carbonate rocks	1
Mineral geology	1

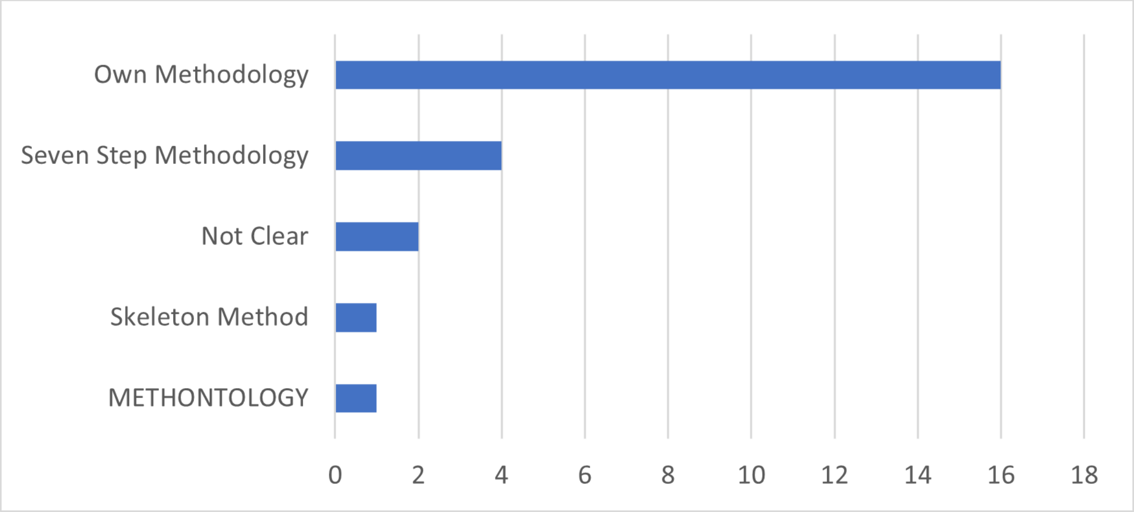
Source: The author

4.3 Methodologies

The ontology development methodology serves as a series of steps to be applied in a knowledge domain, aiming to promote efficient conversion of this knowledge into computer language. It aspires to ensure widespread acceptance of its validity.

In Figure 4.4, it is possible to see that much of the literature reviewed failed to conform to any recognized ontology-building methodology. Instead, they have chosen to implement their own methodologies, often without disclosing methodology details and lacking clearly defined criteria. In some instances, researchers referred to methodologies

Figure 4.4: Used methodologies



Source: The author

found within the literature but still crafted a customized approach to ontology construction.

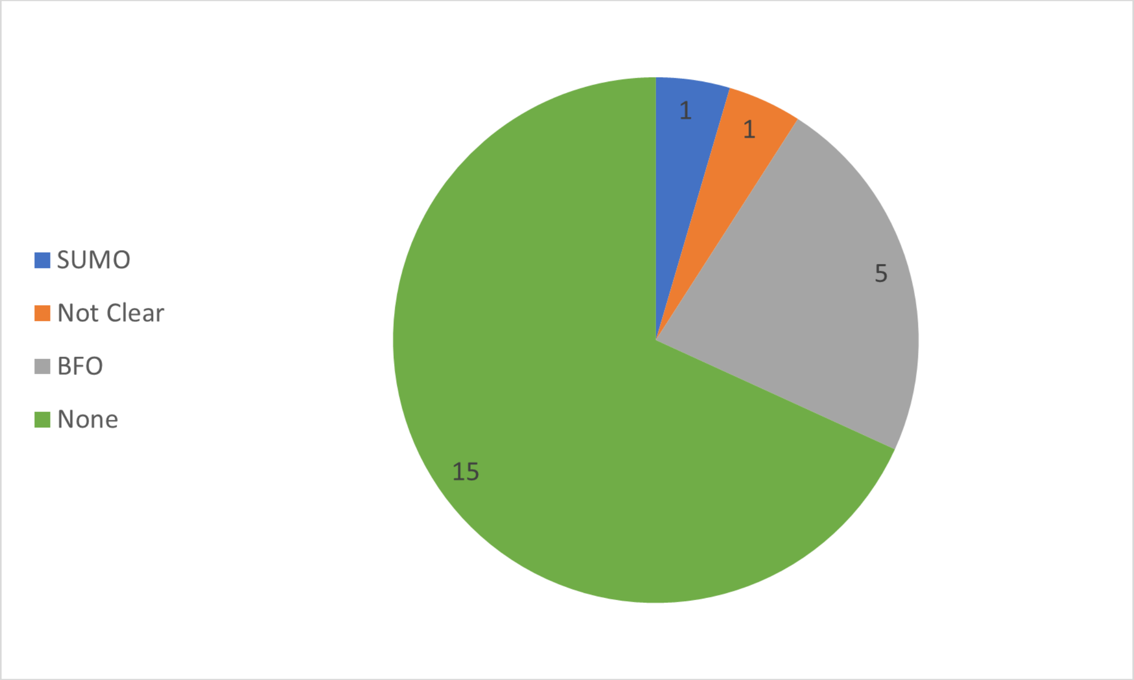
Failing to utilize established methodologies in the ontology construction process can lead to increased complexity, reduced systematic organization, potential negative effects on the ontology's uniformity, and a less reusable final artifact (GÓMEZ-PÉREZ; FERNÁNDEZ-LÓPEZ; CORCHO, 2006). It's crucial to emphasize that this does not inherently imply a lack of quality or rigor in the work conducted, but the importance of adhering to well-established ontology construction methodologies as recognized in literature cannot be overstated (GRUBER, 1995).

4.4 Top-level ontology

The analysis showed in Figure 4.5 that the use of top-level ontologies to guide construction is not a common practice in the articles examined, and the lack of reuse of top-level ontologies could lead to differing concepts within their applications, complicating the reuse process. The most common occurrence is articles not utilizing a top-level ontology at all (classified as None), followed by the Basic Formal Ontology (BFO), which is broadly used within the scientific community.

Being extensively used by the scientific community demonstrates its effectiveness in aiding the structuring and integration of various ontologies within different contexts. BFO's popularity could be attributed to it is an ontology that was developed to integrate

Figure 4.5: Top Ontologies



Source: The author

data and knowledge from scientific domains. It is small and stable and has a large user community, which increases the possibility of reuse (ARP; SMITH; SPEAR, 2015).

On the lower end of the spectrum, the Suggested Upper Merged Ontology (SUMO) (PEASE; NILES; LI, 2002) were recorded as having only a single occurrence. Suggested Upper Merged Ontology (SUMO) is a large standard upper ontology that enables interoperability among domain-specific ontologies.

Moreover, there have been works where top-level ontologies were mentioned, but it was unclear which one was utilized – these were categorized as “Not Clear”. Meanwhile, an even more significant percentage of articles did not mention top-level ontologies. This lack of mention indicates a possible unfamiliarity or lack of emphasis on the importance of top-level ontologies in managing and connecting lower-level ontologies, a factor that can be crucial in a world moving towards more data interoperability. Hence, it indicates a potential for promoting the understanding and use of top-level ontologies within the projects that aim to develop ontologies for the geological domain.

4.5 Reused Ontologies

We analyzed the 23 papers selected in our study to identify papers that report reusing a ready-constructed ontology in the proposed ontology. Notice that we are not considering top-level ontologies in this category, since top-level ontologies are commonly reused due to their general nature and broad application across various domains, but we analyzed them as a distinct dimension.

In our analysis, we found that a surprisingly low number of 10 papers out of 23 reported reusing some ready-constructed ontology. That is, 56.5% of the studies do not incorporate any form of ontology reuse (excluding top-level ontologies), thus exposing a potential lack of widespread practice or perhaps pointing out the practical challenges in finding suitable ontologies for reuse.

Table 4.6: Reused Ontologies

Ontology	*Set of Papers*
None	13
GeoCore	3
Not clear	2
NASA SWEET	1
Ontology of Physics in Biology	1
Ontology of Computer Aided Process Engineering (OntoCAPE)	1
Ontology of physico-chemical methods and properties	1
Ontology of Experimental Actions, Statistical Methods Ontology	1
Ontology of Biological and Clinical Statistics	1
Geographical Entity Ontology	1
Information Artifact Ontology	1
Relations Ontology	1
"Friend of a Friend" (FOF)	1
GeoScienceML	1
Simple Lithology	1
ICS Geological Time Scale Ontology	1
Fracture Ontology	1
Time Ontology in OWL	1
Temporal Hierarchical Ordinal Reference System(THORS)	1
Ontology from Lorenzatti et al. (2009)	1

Source: The author

Among the utilized ontologies, the most frequently reused ones are showcased in Table 4.6. This also reveals how many articles are featured per particular ontology. As a number of papers might reuse more than a single ontology, the total exceeds the initial 23. Interestingly, the most frequent category happens to be 'None', incorporated by 13 studies. Following this, the GeoCore is mentioned in 3 articles. A mention of 'Not

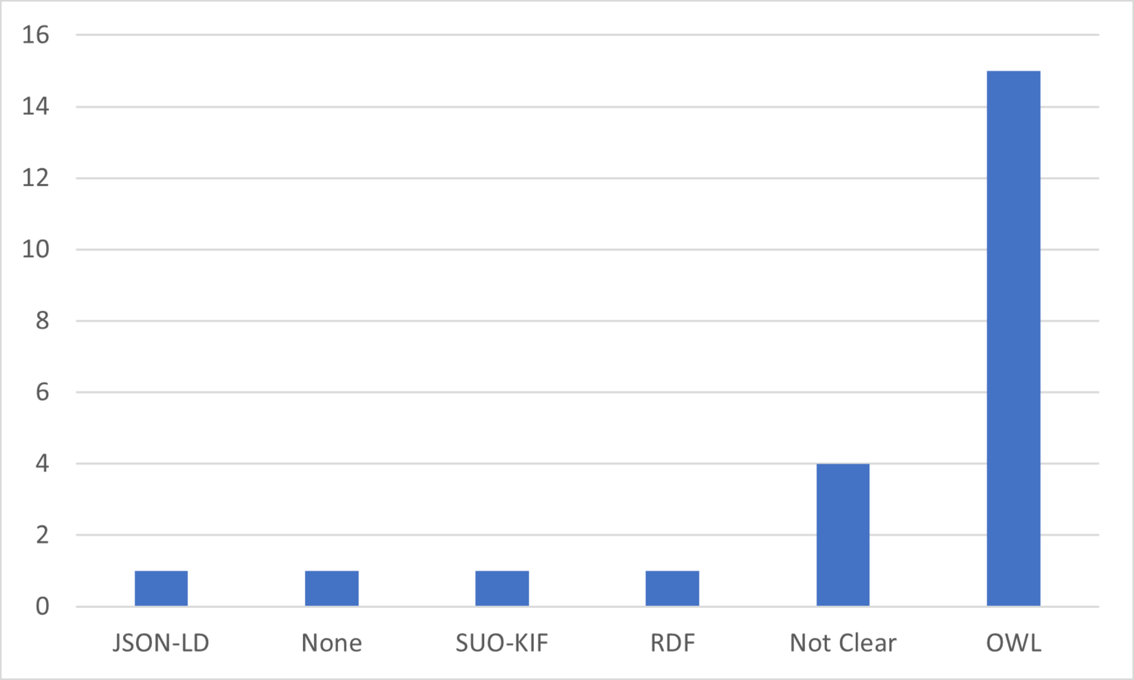
Clear' pops up twice, indicating instances where ontologies were allegedly reused, but the authors neither named the specific ontology nor referenced it.

The remaining reused ontologies are predominantly singular in their occurrence. It is important to note the widespread use of the GeoCore ontology, which stands out among the non-top-level reused ontologies.

4.6 Implementation Languages

The implementation language used for ontology development is a crucial aspect of the ontology creation process. Chart 4.6 illustrates that OWL (Web Ontology Language) is the most widely used implementation language, far surpassing its counterparts. OWL's popularity might be attributed to its expressivity, richness, and the support it receives from various ontology engineering tools. As it is a W3C-recommended ontology language, its use in the scientific community could be deemed as standard practice, reinforcing its prevalence.

Figure 4.6: Languages



Source: The author

However, other lesser-known languages were also found in the chosen articles. For instance, JSON-LD, SUO-KIF, and RDF, each had one occurrence. While these languages are not as popular as OWL, their existence indicates that various other language options are viable, depending on the particular needs or requirements of the ontology creation project (GUIZZARDI, 2005).

There were also some instances where the article describes the ontology and its concepts with images and notations but does not explicitly specify or hint at the language used for development, which suggests that this ontology was just designed on a conceptual model. These instances were categorized as "Not Clear". This ambiguity can lead to difficulty in reusing the ontology, demonstrating the importance of transparency in reporting the implementation language.

Lastly, there was one case where no implementation language was mentioned at all, labeled as "None". This omission could potentially reduce the reuse of the ontology, stressing the need for clearer documentation in ontology publication.

4.7 Applications

During the analysis, one of the focus was the specific applications for which ontologies have been proposed, revealing a vast array of uses across different topics within the field of Geology. From examining Table 4.7, it is evident that these applications are highly diverse, encompassing a variety of fields. This diversity highlights the broad scope and interdisciplinary nature of Geology, which necessitates the integration of complex data sets from numerous sources to form comprehensive, accurate models and analyses.

One of the notable trends visible from Table 4.7 is the applicability of ontologies on semantic search. Semantic search capabilities are critical, as professionals like scientists, economists, and engineers constantly engage in tasks that require the efficient access, integration, and analysis of large datasets (TRAN et al., 2007). Domain ontologies serve a crucial role here by enabling the construction of workflows, primarily by defining workflow components as semantic web services. This capability not only streamlines the data retrieval process but also enhances the overall efficiency of workflow execution, thereby supporting more effective research and analysis (TRAN et al., 2007). Despite the wide range of specific applications, the analysis indicates only two instances of ontology for general use were identified.

Table 4.7: Applicability of ontologies

Paper	*Used for*
[1]	Annotation for named entity recognition.
[2]	Semantic search for querying stratigraphic literature.
[3]	Temporal calculations across different time reference systems.
[4]	Semantic search with query expansion.
[5]	Automatic reconstruction of the relative sea-level curve.
[6]	Semantic query.
[7]	Create a dataset for a question-answering task in the field of Geoscience.
[8]	Identifying geological hazards in images.
[9]	Petrographic description, integrating carbonate microfacies data.
[10]	Data Management.
[11]	Information extraction.
[12]	Description of deep-marine depositional system.
[13]	Geological structure information based on user's sketches.
[14]	Describe and analyze the characteristics of elements in mineral deposit fields.
[15]	General use.
[16]	Software applications in the determination of the physically possible spatial distribution of reservoir geological bodies.
[17]	Semantic-based question understanding and semantic search.
[18]	Question answering, semantic search.
[19]	Interactive visualization for the local geologic time ontology of North America.
[20]	Structure data, information, and knowledge of experimental plastic deformation of poly crystalline rocks.
[21]	Geographical information system.
[22]	General use.
[23]	Description of outcrops, visual interpretation of depositional processes.

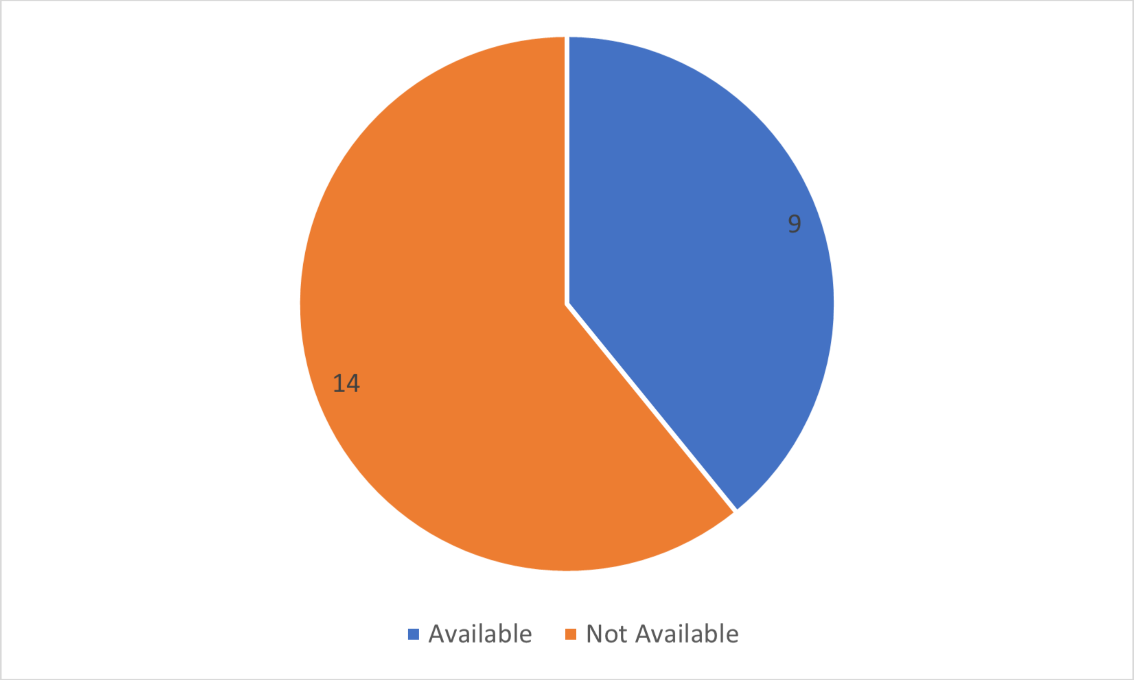
Source: The author

4.8 Availability

The public availability of ontologies is crucial for advancing research in various fields, supporting knowledge sharing, and enhancing the reproducibility of scientific findings. Ontologies, which are formal representations of knowledge within a specific domain, enable researchers to structure and classify information in ways that make it widely accessible and usable by both humans and computers. One of the primary reasons public availability of ontologies is essential is because it fosters collaboration among researchers from different disciplines. By sharing ontologies openly, researchers can benefit from each other's work, avoiding duplication of effort and accelerating the pace of discovery. (D'AQUIN; NOY, 2012)

In our analysis of 23 scientific articles on ontologies, we found that the availability

Figure 4.7: Availability



Source: The author

of ontologies is a concerning issue within the research community. By Figure 4.7 of all the articles examined, only 9 provided direct access to the developed ontologies, with links or references embedded in the articles themselves. This self-contained approach is crucial for enabling researchers to easily access and reuse ontologies in their own work.

Conversely, 13 articles failed to provide accessible links or references to the ontologies they discussed. Additionally, 1 article did feature a link, but it was broken, rendering the ontology effectively unavailable. We opted to categorize this as unavailable for the purposes of this study. This lack of availability hampers the progress of research in ontology development and application, as it restricts the ability of researchers to build upon existing work.

Table 4.8 lists all the papers that have publicly shared their ontologies, including a link for access:

Table 4.8: Available ontologies

Paper	Link
[1]	https://github.com/wangcug/PCDKG/blob/main/Ontology/PCD.ttl
[3]	https://github.com/shuwang8951/Unified-Time-Framework-UTF-ontology
[6]	https://github.com/Nachazel-Tomas/EU-COST-AGITHAR
[7]	https://github.com/BDI-UFRGS/GeoReservoirOntology/releases/tag/1.2.
[8]	https://github.com/BDI-UFRGS/GeoCoreOntology
[9]	https://github.com/xgmachina/geotimeNam/blob/master/Northamerica.json
[11]	https://github.com/vlombard/ontogeonous
[15]	https://github.com/BDI-UFRGS/GeologicalSpatialRelationsOntology
[18]	https://github.com/ontologyportal/sumo/blob/master/GeochronologicTimes.kif

Source: The author

4.9 Discussion

The systematic review begins by addressing RQ-1, which sought to identify the range of ontologies proposed in the field of geology. A comprehensive Table 4.4 summarizing the information gathered showcases a set of ontologies, each designed to focus on different aspects of Geology. This compilation serves as a pivotal foundation for the entire review, as it not only provides a snapshot of the current landscape of ontologies for Geology but also sets the stage for a deeper exploration of each specific ontology's purpose, methodology, and application area.

Regarding RQ-2, the exploration of ontologies in the field of Geology has revealed a diverse landscape of specialized ontologies tailored to various sub-disciplines, such as Geological Hazard, Stratigraphy, and others. However, the lack of frequent occurrences of specific topics beyond the most prevalent ones indicates a potential area for further exploration and development in less-studied sub-fields. The varied topics covered by these ontologies underscore the expanding breadth of geological studies utilizing ontological frameworks, yet it also highlights the challenge of achieving wide coverage across all sub-fields within Geology.

One crucial insight from this review on section 4.3, that answers RQ-3, is the apparent lack of adherence to established ontology-building methodologies. Although it is reasonable to assume that ontologies with high quality can be built without following any established methodology, established methodologies seek to establish a rigorous process that facilitates the development of ontologies while observing good community practices. Many studies prefer custom or vaguely defined methodologies, which can lead to increased complexity, reduced systematic organization, potential negative effects on the ontology's uniformity, and a less reusable final artifact (GRUBER, 1995) of the ontologies developed. These practices could hinder collaborative efforts and the broader acceptance of these ontologies as foundational tools in Geology, as the community lacks a common structured approach to ontology construction.

Furthermore, data related to RQ-4 and RQ-5 was explored in Section 4.4 and 4.5. In our analysis, we observed a notable lack of reuse of both top and non-top ontologies in the field. The use of top ontologies such as SUMO and BFO is surprisingly limited. This lack indicates a potentially underdeveloped culture of sharing and leveraging existing resources within the geological ontology community. Enhancing awareness and encouraging the practice of reusing and adapting existing ontologies could lead to more robust and comprehensive ontology ecosystems in Geology.

The implementation language of the ontologies, mainly OWL, as noted in Section 4.6 underscores its popularity and support due to its expressive power and alignment with web standards answering RQ-6. However, the dominance of OWL also raises questions about whether its prevalent use hinders the exploration of other potentially suitable languages or formats that might better address the unique needs of Geology or a specific application.

To answer RQ-7, the issue of accessibility of these ontologies, highlighted by Section 4.8, presents a significant barrier. The lack of public availability not only stymies the reuse of these resources but also affects the transparency and collaborative progress in the field. Establishing more open-access practices and possibly centralized repositories for geological ontologies could play a pivotal role in overcoming these barriers, fostering a more integrated and innovative research environment in the geological sciences. Such measures would aid not just in the advancement of geological ontology development but also in their practical applications across various related disciplines.

Finally, regarding RQ-8, Section 4.7 shows a gap in the development of more universal ontologies that could potentially serve multiple purposes across various subfields within Geology. Such general-use ontologies could foster greater collaboration and shareability of data and methodologies. The focus, thus far, appears to have been on creating highly specialized ontologies tailored for particular applications, underscoring the immediate needs of the field while also hinting at future opportunities for broader ontology development.

5 CONCLUDING REMARKS

In this systematic literature review, we examined the landscape of ontologies within the field of Geology, addressing several research questions with the ultimate goal of understanding the scenario of ontology development for Geology, and identifying trends, gaps and possible future research. Despite the robust potential of ontologies to offer solutions for data interoperability and knowledge representation, our findings reveal that in the Geology domain, ontologies are still scarcely available for public use. This limitation hinders not only scientific progress but also the broader integration of geological knowledge that could be achieved through more collaborative and open practices.

The review identified a diverse set of ontologies tailored to various geological sub-disciplines, yet the prevalence of ontologies that are accessible and reused is disappointingly low. This lack of availability can stifle innovation and restrict the capacity of researchers to engage in efficient knowledge exchange and refinement through established ontological frameworks.

Many ontologies are not publicly available, limiting their potential for wide adoption and reuse and he prevalence of individualized, non-standardized methodologies in ontology creation creates barriers to interoperability and integration across studies and applications.

Given these challenges, this review underscores a critical call to action for the geological community: to prioritize the publication and availability of ontological resources. Making these resources accessible not only upholds the principles of open science but also significantly amplifies the potential for scientific advancements by offering a shared foundation upon which new research can efficiently build.

In conclusion, this work is a foundation for future research endeavors. The detailed description provided by the ontologies can aid in identifying gaps in various topics of interest, allowing the community to pinpoint novel opportunities for research and development (BRANK; GROBELNIK; MLADENIC, 2005). Additionally, a productive avenue for further inquiry could be a more thorough analysis of the proposed ontologies, assessing their quality using established methodologies from the literature(HLOMANI; STACEY, 2014).

While ontologies hold significant promise as tools for facilitating interoperability and advancing Geology as a science, their impact is currently stifled by issues of availability and methodological inconsistency. We need the community to collaborate to standardize ontology development practices and ensure the open availability of these powerful tools. By doing so, we can unlock a future where geological knowledge is more integrated, accessible, and capable of supporting the complex challenges faced in understanding and managing Earth's dynamic systems.

REFERENCES

ABEL, M. et al. The multiple applications of a mature domain ontology. In: **ONTOBRAS**. [S.l.: s.n.], 2015.

ABEL, M. et al. Ontologies and data models: essential properties and data modeling for petroleum exploration. **Found. J. Prof. Petrol. Data Manag. Assoc.**, v. 3, n. 1, 2016.

ALFAIFI, Y. Ontology development methodology: A systematic review and case study. In: IEEE. **2022 2nd International Conference on Computing and Information Technology (ICCIT)**. [S.l.], 2022. p. 446–450.

ARP, R.; SMITH, B.; SPEAR, A. D. **Building ontologies with basic formal ontology**. [S.l.]: Mit Press, 2015.

BABAIE, H. A.; DAVARPANAH, A. Semantic modeling of plastic deformation of polycrystalline rock. **Computers & Geosciences**, Elsevier, v. 111, p. 213–222, 2018.

BABAIE, H. A. et al. Designing a modular architecture for the structural geology ontology. 2006.

BALASUBRAMANIAN, A. 150 branches of geology (earth science). **Department of Studies in Earth Science, University of Mysore, Mysore-6**, p. 1–47, 2017.

BORGO, S.; MASOLO, C. Ontological foundations of dolce. In: **Theory and applications of ontology: Computer applications**. [S.l.]: Springer, 2010. p. 279–295.

BRANK, J.; GROBELNIK, M.; MLADENIC, D. A survey of ontology evaluation techniques. In: CITESEER. **Proceedings of the conference on data mining and data warehouses (SiKDD 2005)**. [S.l.], 2005. p. 166–170.

BRERETON, P. et al. Lessons from applying the systematic literature review process within the software engineering domain. **Journal of systems and software**, Elsevier, v. 80, n. 4, p. 571–583, 2007.

BRODARIC, B. The geoscience ontology reference. NRCan: Natural Resources Canada, 2021.

CARBONERA, J. L.; ABEL, M.; SCHERER, C. M. Visual interpretation of events in petroleum exploration: An approach supported by well-founded ontologies. **Expert Systems with applications**, Elsevier, v. 42, n. 5, p. 2749–2763, 2015.

CICCONETO, F. et al. A spatial relation ontology for deep-water depositional system description in geology. In: **ONTOBRAS**. [S.l.: s.n.], 2020. p. 35–47.

CICCONETO, F. et al. Georeservoir: An ontology for deep-marine depositional system geometry description. **Computers & Geosciences**, Elsevier, v. 159, p. 105005, 2022.

COMPTON, R. R.; COMPTON, R. **Geology in the Field**. [S.l.]: Wiley New York, 1985.

CONNOLLY, T. M. et al. A systematic literature review of empirical evidence on computer games and serious games. **Computers & education**, Elsevier, v. 59, n. 2, p. 661–686, 2012.

COX, S. J.; RICHARD, S. A geologic timescale ontology and service. **Earth Science Informatics**, Springer, v. 8, p. 5–19, 2015.

COX, S. J.; RICHARD, S. M. A formal model for the geologic time scale and global stratotype section and point, compatible with geospatial information transfer standards. **Geosphere**, Geological Society of America, v. 1, n. 3, p. 119–137, 2005.

CRANE, R. G.; KASTING, J. F.; KUMP, L. R. **The Earth System**. [S.l.]: Prentice Hall, 2010.

D'AQUIN, M.; NOY, N. F. Where to publish and find ontologies? a survey of ontology libraries. **Journal of Web Semantics**, Elsevier, v. 11, p. 96–111, 2012.

FERNÁNDEZ-LÓPEZ, M.; GÓMEZ-PÉREZ, A.; JURISTO, N. Methontology: from ontological art towards ontological engineering. American Asociation for Artificial Intelligence, 1997.

FOX, M. S. The tove project towards a common-sense model of the enterprise. In: SPRINGER. **International Conference on Industrial, Engineering and Other Applications of Applied Intelligent Systems**. [S.l.], 1992. p. 25–34.

GANGEMI, A. et al. Sweetening ontologies with dolce. In: SPRINGER. **International conference on knowledge engineering and knowledge management**. [S.l.], 2002. p. 166–181.

GARCIA, L. F. et al. The geocore ontology: a core ontology for general use in geology. **Computers & Geosciences**, Elsevier, v. 135, p. 104387, 2020.

GARCIA, L. F. et al. What rocks are made of: towards an ontological pattern for material constitution in the geological domain. In: SPRINGER. **Conceptual Modeling: 38th International Conference, ER 2019, Salvador, Brazil, November 4–7, 2019, Proceedings 38**. [S.l.], 2019. p. 275–286.

GEOSIRIS, J. et al. Converting the geology knowledge model embedded in resqml into a well-conformed domain ontology. In: EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS. **Fourth EAGE Digitalization Conference & Exhibition**. [S.l.], 2024. v. 2024, n. 1, p. 1–5.

GÓMEZ-PÉREZ, A.; FERNÁNDEZ-LÓPEZ, M.; CORCHO, O. **Ontological Engineering: with examples from the areas of Knowledge Management, e-Commerce and the Semantic Web**. [S.l.]: Springer Science & Business Media, 2006.

GRUBER, T. R. Toward principles for the design of ontologies used for knowledge sharing? **International journal of human-computer studies**, Elsevier, v. 43, n. 5-6, p. 907–928, 1995.

GUARINO, N.; OBERLE, D.; STAAB, S. What is an ontology? **Handbook on ontologies**, Springer, p. 1–17, 2009.

GUIZZARDI, G. Ontological foundations for structural conceptual models. 2005.

HLOMANI, H.; STACEY, D. Approaches, methods, metrics, measures, and subjectivity in ontology evaluation: A survey. **Semantic Web Journal**, v. 1, n. 5, p. 1–11, 2014.

KITCHENHAM, B.; BRERETON, P. A systematic review of systematic review process research in software engineering. **Information and software technology**, Elsevier, v. 55, n. 12, p. 2049–2075, 2013.

KUO, C.-L.; CHOU, H.-C. An ontology-based framework for semantic geographic information systems development and understanding. **Computers & Geosciences**, Elsevier, v. 181, p. 105462, 2023.

LI, W. et al. Ontology-based question understanding with the constraint of spatio-temporal geological knowledge. **Earth Science Informatics**, Springer, v. 12, p. 599–613, 2019.

LOMBARDO, V.; PIANA, F.; MIMMO, D. Semantics–informed geological maps: Conceptual modeling and knowledge encoding. **Computers & Geosciences**, Elsevier, v. 116, p. 12–22, 2018.

LORENZATTI, A. et al. Ontology for imagistic domains: Combining textual and pictorial primitives. In: SPRINGER. **Advances in Conceptual Modeling-Challenging Perspectives: ER 2009 Workshops CoMoL, ETheCoM, FP-UML, MOST-ONISW, QoIS, RIGiM, SeCoGIS, Gramado, Brazil, November 9-12, 2009. Proceedings 28**. [S.l.], 2009. p. 169–178.

LYELL, C. Principles of geology. In: **British Politics and the Environment in the Long Nineteenth Century**. [S.l.]: Routledge, 2023. p. 41–46.

MARSHAK, S. **Earth: portrait of a planet: 5th international student edition**. [S.l.]: WW Norton & Company, 2015.

MOORES, E. M.; WAHL, F. M. **The art of geology**. [S.l.]: Geological Society of America, 1988.

NILES, I.; PEASE, A. Towards a standard upper ontology. In: **Proceedings of the international conference on Formal Ontology in Information Systems-Volume 2001**. [S.l.: s.n.], 2001. p. 2–9.

NOY, N. F.; MCGUINNESS, D. L. et al. **Ontology development 101: A guide to creating your first ontology**. [S.l.]: Stanford knowledge systems laboratory technical report KSL-01-05 and . . . , 2001.

OWL Semantics Web Standards. <https://www.w3.org/OWL/>. Accessed: 2024-08-14.

PEASE, A.; NILES, I.; LI, J. The suggested upper merged ontology: A large ontology for the semantic web and its applications. In: **Working notes of the AAAI-2002 workshop on ontologies and the semantic web**. [S.l.: s.n.], 2002. v. 28, p. 7–10.

PERRIN, M. et al. Geological time formalization: an improved formal model for describing time successions and their correlation. **Earth Science Informatics**, Springer, v. 4, p. 81–96, 2011.

PONCE, D. et al. Unification of tsunami-related terminology: Ontology engineering perspective. **Computers & Geosciences**, Elsevier, v. 178, p. 105404, 2023.

QIU, Q. et al. Integrating nlp and ontology matching into a unified system for automated information extraction from geological hazard reports. **Journal of Earth Science**, Springer, v. 34, n. 5, p. 1433–1446, 2023.

QU, Y. et al. Geofault: A well-founded fault ontology for interoperability in geological modeling. **Computers & Geosciences**, Elsevier, v. 182, p. 105478, 2024.

QU, Y. et al. Industrial geological information capture with geostructure ontology. In: **SemIIM**. [S.l.: s.n.], 2022.

QUN, Y. et al. Construction of deposit model-oriented knowledge graph. In: IOP PUBLISHING. **IOP Conference Series: Earth and Environmental Science**. [S.l.], 2021. v. 671, n. 1, p. 012034.

RADEMAKER, A. et al. Extending sumo to geological times. In: **Proceedings of the XII Seminar on Ontology Research in Brazil**. [S.l.: s.n.], 2019. v. 2519, p. 70–82.

RASKIN, R. G.; PAN, M. J. Knowledge representation in the semantic web for earth and environmental terminology (sweet). **Computers & geosciences**, Elsevier, v. 31, n. 9, p. 1119–1125, 2005.

RDF Semantics Web Standards. <https://www.w3.org/RDF/>. Accessed: 2024-08-14.

SAMBANDAM, P. et al. Deep attention based optimized bi-lstm for improving geospatial data ontology. **Data & Knowledge Engineering**, Elsevier, v. 144, p. 102123, 2023.

SMITH, P. et al. Biophysical and economic limits to negative co2 emissions. **Nature climate change**, Nature Publishing Group UK London, v. 6, n. 1, p. 42–50, 2016.

STUDER, R.; BENJAMINS, V. R.; FENSEL, D. Knowledge engineering: Principles and methods. **Data & knowledge engineering**, Elsevier, v. 25, n. 1-2, p. 161–197, 1998.

SUÁREZ-FIGUEROA, M. C. et al. **Introduction: Ontology engineering in a networked world**. [S.l.]: Springer, 2012.

SURE, Y.; STAAB, S.; STUDER, R. On-to-knowledge methodology (otkm). **Handbook on ontologies**, Springer, p. 117–132, 2004.

TELFORD, W. M.; GELDART, L. P.; SHERIFF, R. E. **Applied geophysics**. [S.l.]: Cambridge university press, 1990.

TIAN, M. et al. A question answering system based on mineral exploration ontology generation: A deep learning methodology. **Ore Geology Reviews**, Elsevier, v. 153, p. 105294, 2023.

TRAN, T. et al. Ontology-based interpretation of keywords for semantic search. In: SPRINGER. **International semantic web conference**. [S.l.], 2007. p. 523–536.

USCHOLD, M.; KING, M. **Towards a methodology for building ontologies**. [S.l.]: Citeseer, 1995.

WACHE, H. et al. Ontology-based integration of information-a survey of existing approaches. In: **Ois@ ijcai**. [S.l.: s.n.], 2001.

WANG, C. et al. Named entity annotation schema for geological literature mining in the domain of porphyry copper deposits. **Ore Geology Reviews**, Elsevier, v. 152, p. 105243, 2023.

WANG, C.; MA, X.; CHEN, J. Ontology-driven data integration and visualization for exploring regional geologic time and paleontological information. **Computers & geosciences**, Elsevier, v. 115, p. 12–19, 2018.

WANG, H. et al. A knowledge graph for standard carbonate microfacies and its application in the automatical reconstruction of the relative sea-level curve. **Geoscience Frontiers**, Elsevier, v. 14, n. 5, p. 101535, 2023.

WEN, M. et al. Construction and application of a multilevel geohazard domain ontology: A case study of landslide geohazards. **Applied Computing and Geosciences**, Elsevier, v. 20, p. 100134, 2023.

WERLANG, R. et al. Ontological foundations for petroleum application modeling. In: **The Petroleum Network Education Conference, Houston**. [S.l.: s.n.], 2014.

XI, J.; WU, J.; WU, M. Design and construction of lightweight domain ontology of tectonic geomorphology. **Journal of Earth Science**, Springer, v. 34, n. 5, p. 1350–1357, 2023.

XIE, Z. et al. Knowledge graph for identifying geological disasters by integrating computer vision with ontology. **Journal of Earth Science**, Springer, v. 34, n. 5, p. 1418–1432, 2023.

XU, H. et al. A comprehensive construction of the domain ontology for stratigraphy. **Geoscience Frontiers**, Elsevier, v. 14, n. 5, p. 101461, 2023.

XU, Y.; HU, X.; HAN, Z. Carbonate ontology and its application for integrating microfacies data. **Journal of Earth Science**, Springer, v. 34, n. 5, p. 1328–1338, 2023.

YANG, L.; CORMICAN, K.; YU, M. Ontology-based systems engineering: A state-of-the-art review. **Computers in Industry**, Elsevier, v. 111, p. 148–171, 2019.

ZHU, Y. et al. A unified framework of temporal information expression in geosciences knowledge system. **Geoscience Frontiers**, Elsevier, v. 14, n. 5, p. 101465, 2023.