TITLE

Old concepts in a new semantic perspective: introducing a geotemporal approach to conceptual definitions in geology

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OLD CONCEPTS IN A NEW SEMANTIC PERSPECTIVE: INTRODUCING A GEOTEMPORAL APPROACH TO CONCEPTUAL DEFINITIONS IN GEOLOGY

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ABSTRACT

Geological units are the fundamental building blocks that help understand regional geological history and architecture. Classifying these correctly is therefore crucial, as is acknowledging how they relate to each other. This is where traditional definitions fall short, which is increasingly becoming evident with the ongoing effort of setting up advanced knowledge systems that rely on semantic grounding. In exploring the way forward for fundamental improvements, we use the foreland basin and related concepts to introduce a geotemporal conceptual approach of defining geological units with relative limits in time and space. This approach closes the semantic gap between definitions in thesauri and formal instantiation in ontologies.

KEYWORDS

Semantic data model

Geoscience ontology

Instantiation

Lithotectonic unit

Lithotectonic limit

Foreland basin

1. INTRODUCTION

In the current context of a global energy transition, there is an increasing demand for accessible and comprehensible geological data to support the development of new low-carbon energy sources. These data are also essential for the sustainable management of natural resources and better use of urban space and the subsurface in general. Significant advances in understanding the Earth system and informed decision-making can only be achieved through better integration of data and knowledge across disciplines and international borders. With an ever-increasing volume of subsurface data being generated, digitalization and standardization are imperative to optimize data use and support future automation.

Traditional geological subsurface data is mostly descriptive with a high level of detail, but rarely in ways compliant with standard vocabularies, and thus leading to some level of ambiguity (Lombardo et al., 2018). Over the last decades, significant progress has been made in the interoperability and standardization of data models suited to capture geological information (e.g., GeoSciML, INSPIRE). However important this step, the terminology currently incorporated in such data models remains confined to vague or subjective definitions.

Automated (machine-learning) technologies can only unlock the full complexities of real geological entities when those are represented and described in full detail in thesauri, which need to be semantically richer than conventional dictionaries to allow for a knowledge infused approach as seen in reasoning engines. Semantic interoperability, or the meaning of data, strongly relies on semantic grounding, on how meaning can be given to concepts. It is therefore considered a core research topic of data-intensive science, as increasing amounts of data need to be supported by more knowledge on how to combine and interpret them (Janowicz and Hitzle, 2012). It has been recognized that one of the primary challenges to the successful deployment of geoscientific database networks is the development of contents for reference or foundational ontologies – including axiomatized, linguistic, and prototypical elements, and their linkage to geospatial, temporal and process ontologies (Brodaric and Gahegan, 2006). This is being translated in recent efforts to revisit geological concepts and their definitions as part of structuring them into scientific ontologies (overview is given in Lombardo et al., 2018; more recent realization e.g., Le Bayon et al., 2022).

Enriching semantic expressions implies that the number of relations between the defined concepts increases (Mazzocchi, 2018). This is a challenge when handling geological data given their intrinsic complexity, with relations between geological entities such as different geological units evolving and changing over time. To optimize interoperability, semantic models for geology must be built from concepts that can represent geological entities as realistically as possible, ideally including the intricacies and unknowns of their relations with each other.

To demonstrate this, we will carefully evaluate the concept of foreland basin, an example of a lithotectonic unit. Lithotectonic unit has two significantly different definitions. We follow the definition included in INSPIRE (URI http://inspire.ec.europa.eu/codelist/GeologicUnitTypeValue/lithotectonicUnit), which differs from the original one that can be found in Neuendorf et al. (2011) that likely goes back to usage within the USGS in the 1970ies or 1980ies. This concept stands out because it is one particular type of sedimentary basin with significant internal complexity, and its evolution takes place within a dynamic setting adjacent to an expanding orogen. Literature on foreland basins is inconsistent due to conflicting use of terminology, for example on how far a foreland basin reaches, what its different elements such as the foredeep or the wedge-top are, and where the foreland basin starts and the orogen ends. Therefore, we use this as a fundamental example, one that most easily forms a template for any lithotectonic structure, because it allows to dig into: how to semantically ground current geological definitions, how to do so while respecting existing understanding of those concepts in literature, how to recognize intrinsic relations and integrate them into the definitions, and finally discuss how those generic definitions provide class-like instantiation of actual concepts. Each of these steps are for us the immediate challenges that stand in the way between converting current geological descriptions into semantic understanding, whether to be grasped by artificial or human reasoning. The foreland basin example therefore is to be seen as proof of concept of a semantic-based approach for geological knowledge organization. For these reasons, this paper focusses on the conceptual process of exploring and shaping an ontology, rather than formalising and implementing it, to demonstrate that such steps should not be taken for granted if the goal is a knowledge system with emergent properties.

2. SHORTCOMINGS OF TRADITIONAL DEFINITIONS

Foreland basins cannot be discussed before examining the broader definition of basins (Dayal, 2017) as used in literature. A sedimentary basin is typically defined as ‘an area where thick sequences of sediments have accumulated' (e.g. Neuendorf et al., 2011). Although this definition is valid for all basin types, it has the pitfall of being too generic and therefore being valid for other geological units that are clearly not basins. One example is the case of the largely obsolete 'post-sedimentary basins' (as late as Einsele, 1992), which represent sediments incidentally preserved in post-sedimentary structural synforms. This is an erroneous attribution that does not follow the principles of basin dynamics (see Ingersoll, 1995) as adopted by, among others, sequence stratigraphy, because there are simply no sedimentary arguments for referring to such a unit as a basin. Although few geologists would still use basin in this meaning, it does confusingly persist in historical names (e.g. pre-Cretaceous sediments of Powder River Basin, Dolton et al., 1990) and it clearly illustrates how generally accepted definitions (as in Neuendorf et al., 2011) may prove unsuitable upon further scrutinization, potentially leading to semantic flaws if integrated in ontologies without correction.

A foreland basin (Fig. 1) is traditionally defined as a sedimentary basin on the continental lithosphere at the outer edge of a mountain belt (Dickinson, 1974; Flemings and Jordan, 1990; Naylor and Sinclair, 2008). It is formed as a result of downward lithospheric deflection in response to a combination of supra- and sublithospheric loads. The lithospheric deflection creates a quickly damped sinusoidal profile that has a large negative flexure directly adjacent to the load (the foredeep), in some cases a positive flexural bulge (the forebulge), and a secondary and distal negative flexure (the back-bulge; DeCelles and Giles, 1996; Catuneanu, 2004). Additionally, wedge-top basins can be developed on top of the accretionary wedge, from which sediments can spill over into the foredeep (DeCelles and Giles, 1996). These definitions are widely used in geoscientific literature, but with many inconsistencies such as mixing foredeep and foreland basin (Neuendorf et al., 2011) or in the ambiguous transition between wedge-top and foredeep (DeCelles, 2012).

Notably, all of these definitions are based on active foreland basins in their present-day geographic configuration (DeCelles, 2012). This means that, at least by approximation, the deformation front forms the boundary between the foreland basin and the current orogenic belt. This leads to a fundamental issue with the current definitions, in that they no longer apply when considering a foreland basin as a dynamically evolving unit. Consider, for example, sediments deposited at an early stage in the foredeep: these clearly belong to the foreland basin, but when the deformation front advances and deforms this early part of the foredeep, should these sediments still be described as part of the basin or rather as part of the orogen? Traditional definitions consider the latter as correct since basins and orogens are regarded as discrete adjacent units. But we will argue that this standpoint fails to convey the complexity of the evolution of this system, and leads to conceptual inconsistencies through geological time.

[insert Figure 1]

3. A GEOTEMPORAL CONCEPTUAL APPROACH TO DEFINITIONS

Scientific definitions should aim to add structure and meaning to any given concept, which can be done through knowledge organization principles that use hierarchical concept schemes. In thesauri, hierarchical relations place a concept between broader, or more generic, and narrower, or more specific, terms. These and other relations refer to how people logically perceive language. A foreland basin is intuitively viewed as a specific type of sedimentary basin, and therefore the conceptual properties of a basin also apply to the foreland basin. Formally embedding such logic assertions upgrades thesauri to an ontology, and enables the expression of higher complexity at the same time allowing for computer reasoning.

We propose a geotemporal conceptual approach to define geological units. In this case, focus on a conceptual definition specifically strives to maximize the level of abstraction. Making the definition also geotemporal means outlining the concept in space and time. In geology, this can be achieved by defining the events that are linked to the start, evolution and finalization of a geological unit. These events correspond to surfaces in the geological record, and we will refer to them as geological limits, because they limit the units in space and relative time.

As limiting events are fundamental concepts, it is important that their definitions are stable, and therefore descriptive rather than genetic, because genetic definitions refer to underlying processes that are, especially in geology, almost always somewhat subjective interpretations of observations. A flooding surface, for example, can be described as a type of unconformity, without making further assumptions about its genesis. Sticking to descriptive definitions and associating events with limits, together essentially underpin the geotemporal approach to conceptual definitions.

Defining regional geological concepts in space as well as time is not new, but rarely emphasized as an explicit and beneficial practice (e.g. Plašienka, 1999). Here we introduce it to come to consistent definitions, where events result in limits that define geological units. Before demonstrating the value of this approach, we will explore how to seamlessly integrate it with our traditional way of defining and understanding relevant geological concepts.

4. GEOTEMPORAL AND CONCEPTUAL EXTENSIONS

Since a foreland basin is a type of sedimentary basin, it is pertinent to define this broader geotemporal concept first. Looking into more detailed definitions of sedimentary basins, one school of thought in geology (from Price, 1973 to DeCelles and Giles, 1996) refer to a basin as a region where current or past prolonged subsidence has created accommodation space for the accumulation of sediments. Following this strictly geomorphological approach, the description includes a process (subsidence) and defines the basin as an empty receptacle, thereby excluding the sediments arriving in it. However, for geological purposes a basin may be better defined as the accumulated sedimentary record. Instead of referring to a process with genetic connotation, the sedimentary basin can be described as resulting from the accommodation of sediments that are more abundant or of different type than in adjacent areas.

This definition is clear near the depositional centre of a basin, while closer to its margins, the sedimentary record may gradually change and become indistinguishable from the sediments outside the accommodation space. There, relative topography becomes a useful indicator, because it allows to define spill points and spill lines. When the sedimentary stack pile reaches above this level, the basin filling spills over and comes into contact with adjacent units; spill lines thus can be regarded as the ultimate basin outline. Introducing them aids to understand how different units conceptually interact as a system, which is more important to build geological understanding than their exact positions.

Although spill lines provide lateral-spatial constraints, they do not define basins in time, or even in depth. That requires the consideration that the base and top of any type of basin correspond to recognizable geological horizons. The base level is usually identifiable as an onlapping unconformity (Christie-Blick, 1990) on top of which the earliest diachronous deposition starts. The top level is represented by sediments of the last basin infill, which may be defined easier conceptually than in reality. Nevertheless, a basin ceases to exist when the sedimentary sequences become indistinguishable in and adjacent to the basin. In practice, because of basin dynamics these often are the layers overlaying a regional erosional surface.

This reasoning is condensed in the geotemporal conceptual definition below that incorporates the traditional understanding and expands to define the event-based limits of a basin. The definition remains valid for narrower, more detailed concepts of specific types of basins.

A ***sedimentary basin*** *occurs where accommodation space exists, and where this space is filled by preferential sedimentation resulting in a thicker or otherwise distinguishable sedimentary record. It is spatially defined by discrete 3D limiting surfaces that correspond to geological events: start of, active sedimentation in, and termination of the basin setting.*

The base of preferential sediments in the accommodation space forms the ***initial limit****. It does not extend beyond the* ***spill line****, which is a topographic feature that marks the areal extent of accommodation space, or the sedimentary divide between adjacent basins.*

In an ***active basin****, the topographic surface forms the* ***current limit****. This limit shifts upward while the basin is receiving new sediments.*

A ***former*** *basin is characterized by a* ***final limit****, which is the top of preferential sedimentation after it is covered by other deposits.*

Note that here also the distinction between active and former basin is introduced, or rather re-introduced, since it once was common to make that distinction (Einsele, 1992), but then fell into disuse. Only the essence of the initial and final limits is given in the definition, although often from their context will be understood that they are identifiable as a sedimentary discontinuity resulting from the initial or final event, such as a hiatus, unconformity, or change in sediment type.

Doing the same for a foreland basin now becomes a matter of defining it as a sedimentary basin (i.e. transitive hierarchical relation), adding what makes it specific and where necessary specifying its particular limits. The position of the spill line (or spill point in cross-sections) is fixed towards the craton side of the foreland basin (Fig. 1), which is in agreement with the definition of a sedimentary basin. Towards the side of the orogen no spill line needs to be defined, since the sedimentary divide of an orogenic range is both obvious and out of reach of any filling stage of the basin. Where and what type of spill line delimits the longitudinal sides of a foreland basin depends on the tectonic setting, but fundamentally in all such settings it is determined by how the initial limit is defined at basin level.

A foreland basin or foreland basin system is defined by a wedge-top, a foredeep and a back-bulge basin (DeCelles and Giles, 1996). We disregard here the forebulge as a sedimentary unit (Fig. 1). There is however a clear distinction between the three basin elements, in that a wedge-top basin can exist independently from, so outside of a foreland basin system, as it can develop in any fold-and-thrust belt. This is not true for a foredeep or backbulge basin, as these are always intrinsic parts of a foreland basin. Semantically this means that the concept of wedge-top is directly linked to sedimentary basin with a type-of relation, while foredeep and back-bulge are hierarchical parts of a foreland basin.

The foredeep basin is the most complex definition in terms of its initial limit; the limit between the wedge-top and foredeep is not defined by a spill line, but rather by the position of the thrust on which the most forward wedge-top basin has formed (Fig. 1). Since these thrusts propagate successively craton-ward, the initial limit jumps each time a new thrust breaks the surface. We propose not to consider blind thrusts, because they do not reach the active level of sedimentation.

This dynamic position of the limit also means that whether sediments belong to the foredeep or the wedge-top basin depends on their location at the time of deposition, and not on their ultimate geometric position within the basin system. Sediments are being deposited in the foredeep up until the wedge-top jumps forward; from then on any subsequent sedimentation orogen-ward of the new thrust is part of the wedge-top basin, while the sediments below always remain part of the foredeep. This is a logical consequence from the conceptual, and especially geotemporal approach taken here and is an important advantage over arbitrarily setting such boundaries, as is traditionally done to separate e.g. the foreland basin and the orogen (see Fig. 2). Considering an orogenic belt is constrained by its deformation fronts, these limits progressively expand as the orogen becomes more pronounced, until they extend into the foreland basin. The deformed basin sediments belong spatially and conceptually both to the foreland basin and to the orogenic belt (Fig. 2). Field observations may leave room for discussion on where the foredeep sediments end, and those of the wedge-top start, but a well-considered semantic approach guarantees the definitions and principles guiding such discussion are robust.

A consideration of the points above result in the following geotemporal conceptual definitions of a foreland basin and its subunits:

A ***foreland basin*** *is a sedimentary basin that forms along an active orogen due to flexural bending of the lithosphere. On the craton side, the spill line corresponds to the edge of crustal flexure.*

A ***wedge-top basin*** *is a sedimentary basin within the orogen where sediments are trapped by outcropping thrust sheets. Its initial limit is the face of a thrust sheet, constrained by the bounding thrusts.*

A ***foredeep basin*** *is the most distinct element of a foreland basin. It is located adjacent to the marginal zone of the orogen, typically a fold-and-thrust belt. Orogen-ward its initial limit is restricted by the most forward outcropping orogenic thrust, implying that blind thrusts can be* *part of a foredeep. Craton-ward this limit either extends as far as the foreland basin, or until the spill line shared with the back-bulge (if present).*

A ***back-bulge basin*** *is the distal part of a foreland basin, separated by a spill line from the foredeep.*

[insert Figure 2]

An important difference from traditional definitions is that event-based limits bear meaning when defined conceptually, even if their exact spatial position is unknown. In the example above, with normal faulting and younger sedimentation partly burying and concealing the foreland basin (Fig. 2), it is clear from a geotemporal conceptual definition that the basin extends beyond the normal fault, as this is only a later, secondary limit, not the defining primary limit (primary limit is used similarly to primary boundary in Kumpulainen, 2017). In this way, uncertainty due to lack of observation is well supported by the newly proposed definitions. This also implies that geological units do not need to be fully encompassed by discrete limits. In the definitions of the basins, the limits do not necessarily meet or crosscut each other. For example, the initial limit in basins extends to the spill line, but no lateral vertical limiting surfaces are introduced to make them meet with a final limit, because those would not have a geological basis. Introducing artificial limits does not add to the description of geology, is therefore unnecessary and hence should be avoided.

The definitions in this section respect how concepts are used in literature, with clarifications only where confusion in literature was present, and now systematically have hierarchical references included. Furthermore, they have been linked to the more formal geotemporal descriptions that specify relations between units and their defining limits. This establishes a generic base of intrinsically related concepts that is ready for further instantiation to be explored next.

5. DEFINITIONS AND KNOWLEDGE SYSTEM PERSPECTIVES

While most of the reasoning up to this point has started from a geological argumentation, there is also a separate line of technical considerations that leads to reconsidering definitions in geology. Most geologist-driven work has focused on building conceptual schemes up to the level of thesauri, in which relations between concepts are mainly broader-narrower hierarchical. Instantiation is often present, but guided by intuitive rather than formal rules (e.g. Hintersberger et al., 2017). This can be improved when the concept scheme is semantically upgraded, and instantiation becomes more formal and explicitly class-based. Taking the geotemporal conceptual definition of foreland basin as an example, this means that an actual geological unit can only be defined as a foreland basin if all of its defining limits are recognized, at least conceptually. This solves inconsistencies that arise from the flexibility and subjectivity of traditional definitions. This is therefore a critical level for conceptual definitions, indicated by a red line in Fig. 3.

We have hinted at transitive and inclusive hierarchical relations, such as the narrower foreland basin concept inheriting the definition of the wider sedimentary basin concept, and also to partitive relations for the foredeep and backbulge relative to a foreland basin. Embedding such relations is further indicative of an ontology, with additional content unfolding from definitions into relations. Formalizing this process based on traditional definitions alone is not straightforward, which is why we have extended them with a limit-based part. This is essential as it establishes a one-on-one match between the textual definition, which will dictate how humans understand a concept, and the explicit semantic relations between concepts, which will guide instantiation and computer (as well as human) reasoning (Fig. 3).

This also leads to a near-mathematical basis for definitions and inference rules, that is formed by a set of non-logical axioms (Table 1). As was introduced in the definition of a sedimentary basin, there are two types of limits that apply to lithotectonic units. The limits linked to the conceptual definitions of units are the primary limits (see axiom 1 in Table 1), and describe how the lithotectonic unit came to be in its pristine state (axiom 2). Since geology is the result of a series of events that rework existing geology, most explicitly for tectonic, metamorphic or intrusive evolution, a lithotectonic unit is likely to have been modified to some degree by more recent events. For some units, such as the foredeep, this happens even before its formation is finished. This does not change its initial conceptual definition (axiom 3), but may alter shape, position and other properties, and are therefore important to describe, and display, the further evolution of a unit. The events associated by overprinting are registered in the geological record as secondary limits (axiom 4). In the simple case of a normal fault, such as in Fig. 2, that fault is a secondary limit to the foreland basin it offsets, but at the same time a primary limit to a fault block (axiom 5). It therefore relates (links) the unit that it overprints, and the one that it defines, allowing for the formulation of logical axioms, such as constraints and inference rules.

Recognizing overprinting relations and embedding these in an ontology is an effective way of retaining the geological significance of lithotectonic units (long) after their initial formation. For example, erosion is the most common way to partly or completely eradicate a unit, especially for naturally elevated units such as wedge-top basins that are rarely preserved outside of their active settings. Eroded or otherwise removed parts of a lithotectonic unit stop being conceptually relevant as a geological building block, so current or past erosional surfaces are practical boundaries of their current volume (and since erosive surfaces are secondary limits, see also axiom 3), which sets them apart from paleogeographic definitions. This illustrates how important it is to scrutinize scientific definitions, especially when reaching beyond the semantic level of a thesaurus, and how it is possible to create embedded links between the real and the conceptualized world. This process of explicit semantic grounding is in our view essential, as well as one of the hardest steps in building ontologies that more than superficially capture the natural world in a semantic frame. Doing this with insight creates a knowledge infused system, different from (but not incompatible with) data driven systems. The benefits of the explicit approach of knowledge systems for certain geological disciplines will come forth from the next discussion.

[insert Table 1]

[insert Figure 3]

6. DEVELOPMENT CONTEXT AND PATHWAY

Structuring concepts hierarchically and with meaning requires understanding fundamental properties specific to the domain of expertise. Geology, especially when geological architecture is involved, is unique and particularly challenging because the geological reality of today is the result of a continuous, long, complex, and often only partly revealed history of processes and episodes during which different geological elements interact, compete and influence each other. Unlike in almost all other disciplines, the present is secondary to the past because geological history is an explicitly visible and structural part of the configuration today. Therefore, the element of time cannot be ignored, especially when defining geological elements.

Traditional geological definitions typically ignore this level of complexity, which is problematic and can upset the organization of geological concepts in a rigorous logical system, weakening hierarchical relations and resulting in definitions with only superficial meaning. Geotemporal conceptual definitions can overcome this issue, as demonstrated for a relatively complex series of concepts related to foreland basins. These new definitions retain their original geological meaning, and therefore respect the community-built knowledge. At the same time, they are in line with the expectations of a reasoning system, in that they are designed to fit hierarchical transitive relation schemes. We consider this to be an absolute requirement for further development into any extensive ontology.

Moreover, these definitions are well-equipped for describing and instantiating geological elements in the real world, which strengthens the link between the theoretical level, abstract level and field descriptions. This is a direct result from linking the description of geological units to their geological limits. Crucially, this automatically leads to embedding an additional layer of meaningful relations that link different geological concepts and concept schemes. 'Automatically’ here does not refer to implicit learning, but rather implies the opposite: expert understanding is embedded in a base layer of relations such that further extension of the concepts become automatically organised to gain meaning. As such, the threshold for developing reasoning schemes and visualizing those in knowledge graphs will readily be crossed.

This generic outline is currently developed to become part of the European Geological Data Infrastructure (EGDI; Tulstrup and Pedersen, 2018; Vidovic et al., 2020) into a data model that is SKOS-based (Isaac and Summers, 2009) with OWL extensions (Hitzler et al., 2012), annotated with a relational database, and linked to a GIS environment for graphical information. Within EGDI the fundamental geological information will be stored together with applied geological information on raw materials, geo-energy and groundwater. EGDI is a stakeholder-driven and policy-oriented infrastructure, with the clear purpose to address real-world needs, such as developing decision support systems that need to combine fundamental and applied geological information, involving machine learning and automatic reasoning. This becomes feasible with a knowledge-infused model, a development path enabled only by underlying robust ontologies such as outlined in this paper.

It is in this context important to properly cite individual ontologies within their larger infrastructure (Lombardo et al., 2018; Zhao et al., 2009; Fig. 4). The semantic characteristics that have been analysed in this paper are of particular importance for the group of lithotectonic units, because these are meaningful units that hold information on geological history, and with the proper rules and relations add up to regional geological evolution. The proposed geotemporal conceptual definitions are highly relevant in this context, but this is not necessarily true for all geological concepts. Therefore, lithotectonic and similar concepts form crucial, but still strongly domain specific ontologies that nest within, and where useful redefine, more generic ontologies. Respecting such structure is important for maintenance and scalability of knowledge infrastructure, but is equally essential for ontologies and thesauri to be exchangeable, reusable (Uschold, 2015) and even shareable between different knowledge applications.

[insert Figure 4]

7. IMPLICATIONS OF CONCEPTUALIZING GEOLOGY

Geotemporal conceptual definitions allow to define geological units, which together add up to a complete, consistent and robust regional framework. Contemporaneous elements defined within the same conceptual scheme and located spatially adjacent to each other, are explicitly sharing well-defined, discrete limits (at least conceptually). In this paper, this is illustrated by the three sub-basins that can occur in a foreland basin. Once sufficiently filled, the foredeep and back-bulge meet at the forebulge spill line. These are adjacent basins that depend on each other to exist and will therefore never overlap, unlike the wedge-top and foredeep where one may outgrow the other and partly bury it (Fig. 1).

However, geological units frequently overprint each other when considering the evolution of a region throughout geological time. Such overlaps are generally ignored in more static, traditional definitions, which was demonstrated for foreland basins, but can be explicitly embedded in geotemporal conceptual definitions since they are based on limiting events. The same applies for other post-sedimentary overprinting, such as normal faults displacing and thereby hiding the full extent of a former (inactive) foreland basin: although partly invisible, its geotemporal conceptual definition remains unchanged, and therefore the extent of the basin should still be defined based on those limiting events (Fig. 2). This example illustrates some of the fundamental rules that need to be respected to correctly summarize regional geology, especially when drafting lithotectonic maps and models. In particular, we illustrate the need to step away from arbitrarily defining concepts, and instead explore the intuitive understanding of a community to identify underlying, fundamental rules, that can be used to come to systemic definitions to guide formal instantiation. In our approach, these summarize to 5 axioms that form the foundation of any lithotectonic unit.

In spite of literature turning away from defining geological units decades ago, we claim that they have become crucially important, now that geological information increasingly becomes part of knowledge systems that ultimately will be adopted for logical reasoning. Therefore, the work presented here springs from a practical rather than theoretical need to define and delimit geological units, and the contradictions and confusions that follow from attempts to use traditional definitions. Introducing geotemporal conceptual definitions will not only lead to more robustly defined geological units, both conceptually and spatially, but automatically define them in their specific regional context, bracketed in relative time by geological events. It makes this approach incredibly powerful as the basis for reasoning through logical assertions, and we present it as a novel and much needed method for building geologically meaningful hierarchical and other relations. Fundamentally, it also sets up integrative levels of complexity, an intrinsic condition for emergent properties. In particular we foresee the capability of providing insights that are not explicitly entered in the system, nor are obvious from looking at individual data, but are possible because of how the knowledge system works as a whole through its relations between concepts, both generic and real-world.

Until implemented at sufficient scale, the foundations of which are being realised in the project GSEU (Hollis et al., 2023), the potential for emergence remains hypothetical. This is not true for the other outlooks that are needed to create communication bridges between geological experts, artificial reasoning systems, and stakeholders outside of the geological community, all of which are imperative for discussing the role of geology in society.

ACKNOWLEDGEMENTS

This work has benefited from the Horizon 2020 project GeoConnect^{3}d of GeoERA under grant agreement number 731166, and the Horizon Europe project GSEU under grant agreement number 101075609, both research and innovation programs of the European Union. Both projects are co-funded by the project partners, and the authors explicitly thank the partners from the GeoConnect^{3}d project and work package 6 of GSEU.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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TABLES AND TABLE CAPTIONS

Table 1. Description of the non-logical axioms that dictate how lithotectonic units and their limits are defined and related. They are the basis of the geotemporal definitions, and embed semantic rules and logic in the definition of the concepts.

Axiom 1	A lithotectonic unit is defined by its primary limits
Axiom 2	A primary limit is a geological testimony of an event that sets the lithotectonic unit apart from others
Axiom 3	As long as a lithotectonic unit remains identifiable, it retains its earliest identity
Axiom 4	A secondary limit is a geological testimony of an overprinting event
Axiom 5	A secondary limit is a primary limit to a more recent lithotectonic unit

FIGURES

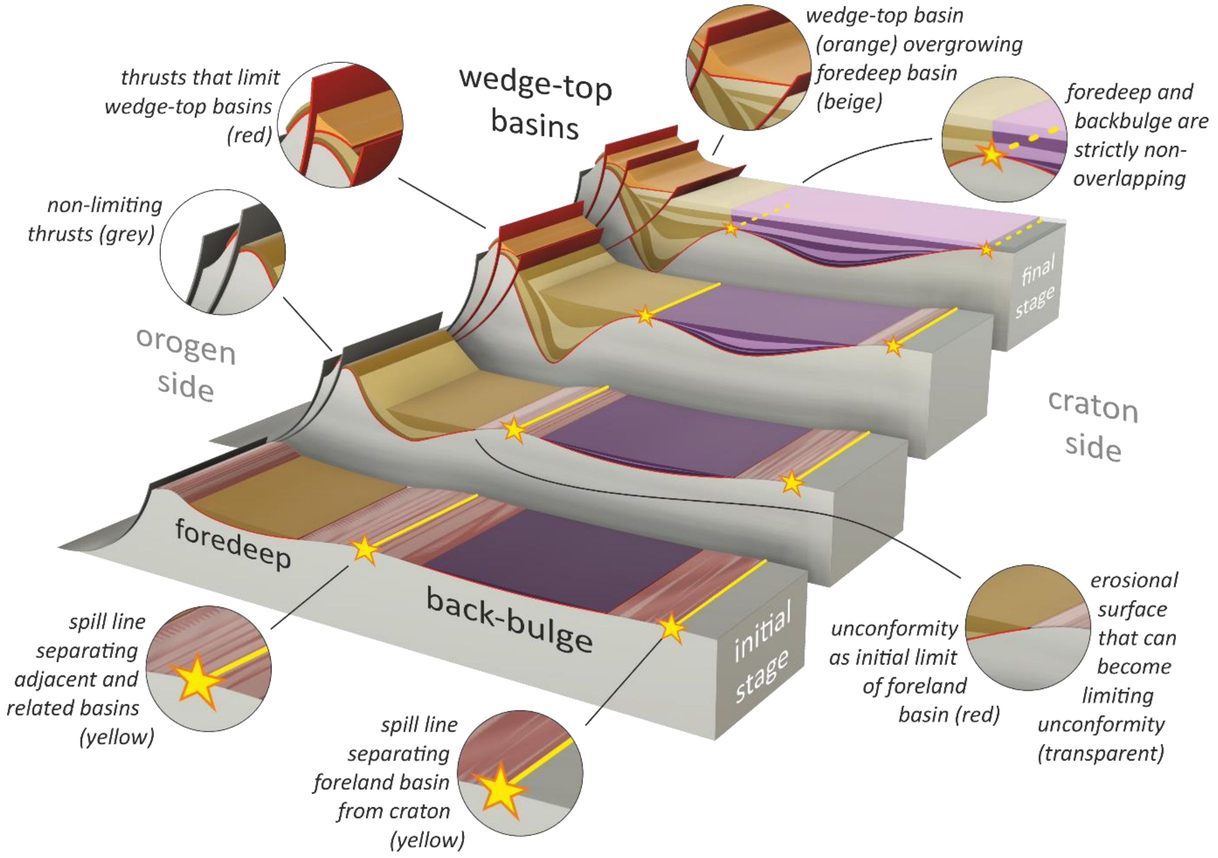

Fig. 1. Evolution of a foreland basin with distinction of different units and defining elements.

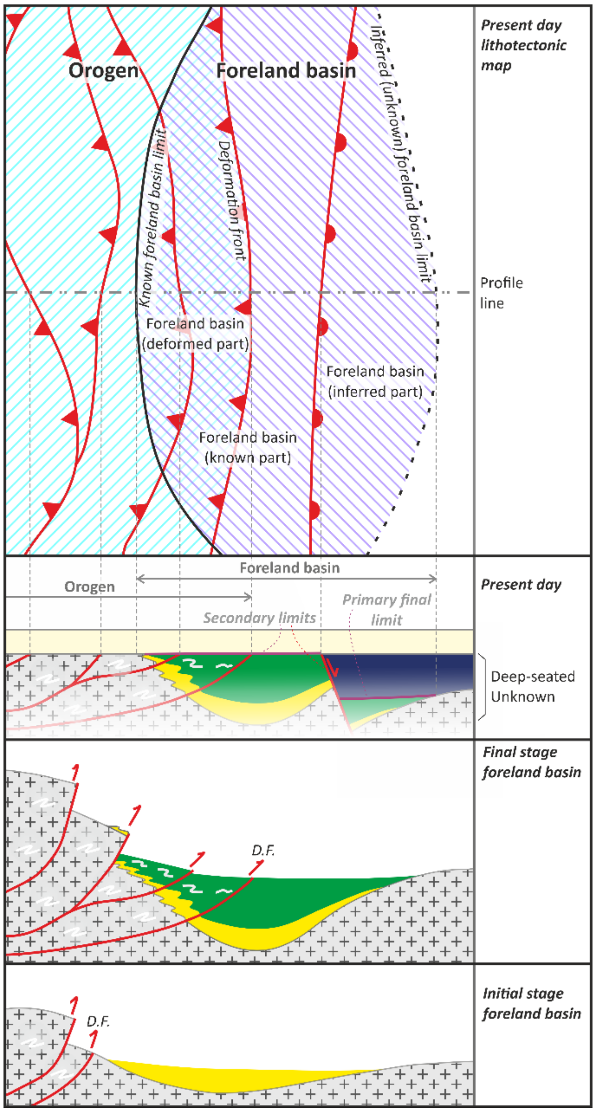

Fig. 2. Schematic evolution of a foreland basin next to an orogen, resulting in overlapping lithotectonic units. D.F.: deformation front.

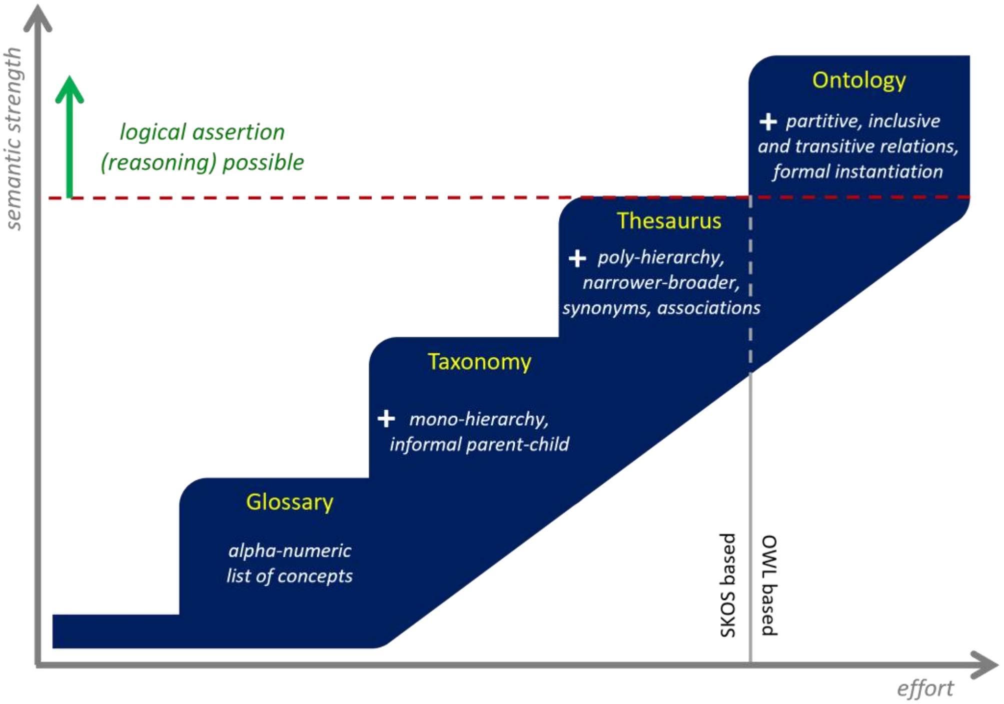

Fig. 3. Concept schemes ranked by richness of semantic expressions, also referred to as knowledge ladder, highlighting the critical levels corresponding to the conceptual scheme at which definitions become the formal basis for instantiation (after Blumauer and Pellegrini, 2006; Goldbeck Gerhard and Simperler Alexandra, 2018; Ma, 2022; Mazzocchi, 2018; McGuinness, 2003; Uschold and Gruninger, 2004).

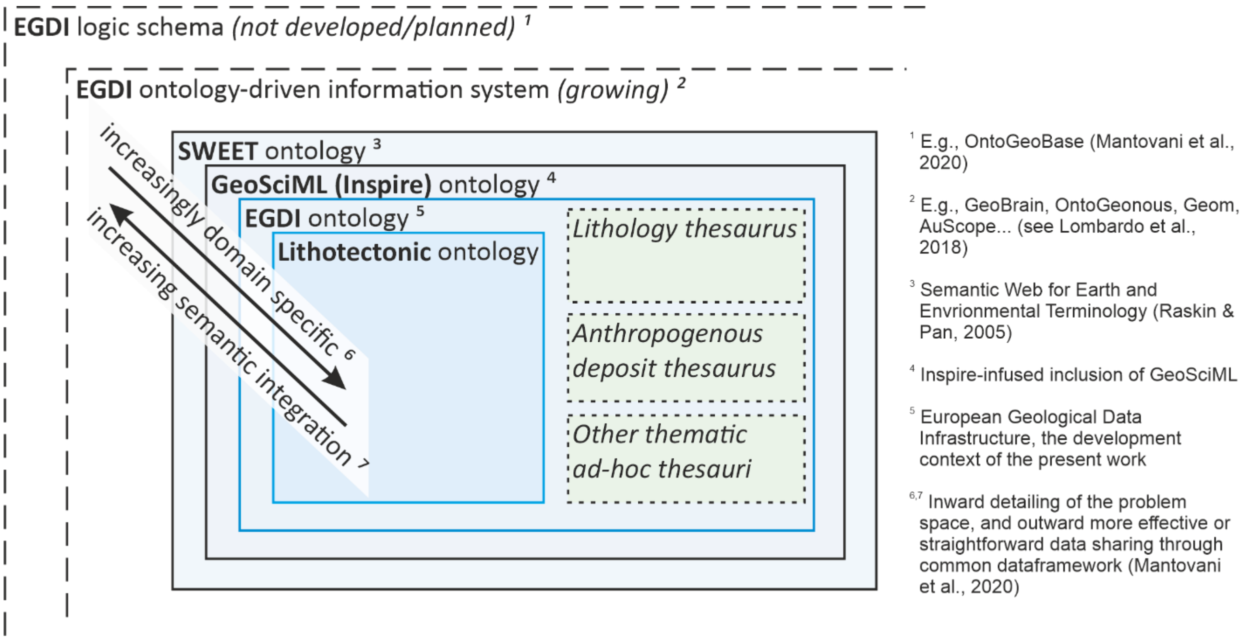

Fig. 4. Loosely-coupled development strategy integrating the views of Zhao et al., 2009 and Lombardo et al., 2018 on connecting new and existing semantic elements. The work on the lithotectonic ontology presented here, contributes directly to the EGDI semantic database (Mantovani et al., 2020; Raskin and Pan, 2005).

FIGURE CAPTIONS (LIST)

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