Geological time formalization: an improved formal model for describing time successions and their correlation

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Geological Time Formalization: an improved formal model for describing time successions and their correlation

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Abstract. Geological time description largely rests on an event based chronology based on the *stratigraphical model*. It uses a hierarchy of chronologically ordered *geochronological units and boundaries*. In order to be easily dealt with within large databases used by complex engineering systems, the geological time chronology must be formalized. Stratigraphical time successions should accordingly be described by using adequate semantic tools (ontologies) complemented by a set of logical rules. At present, geological time formalization mainly rests on the GeoSciML model. This model is fit for describing individual geological time scales but does not provide all the necessary tools for comparing various time successions and for operating full stratigraphic correlations. For complementing the GeoSciML model, we define two ontologies for geological time description and for geological dating. They extend the GeoSciML model, so that it becomes possible to fully use the *Allen rules* for operating time correlations between any couple of time scales or stratigraphic successions. We additionally propose a codification resting on the defined ontologies, which allows operating all age identification and correlation by means of simple computation rules.

Keywords: Geological time scales, Geological dating, Ontologies, Codification, Stratigraphic correlation.

1. Introduction

1.1. Geological time description and rock dating

Geology is in many ways a historical science. Information concerning the date in the course of geological times at which some geological process took place or the age of some given geological formation is a significant part of geological information in general, essential in many cases for geologists and for geology users. Geological time is currently described in two different ways. The first one rests on a quantitative chronology based on "absolute ages" expressed in millions years (My), which are established by means of radiometric measurements (Hardenbol & al., 1998). The second one, more frequently used by geologists, uses an event based chronology based on stratigraphic time scales. Event based chronology is commonly used in archaeology and in history. It relies on time scales composed of a succession of time units, each corresponding to the span of time which separates two definite events. Moreover, as shown in figure 1, a period of rank 1 is likely to be recursively divided in sub-periods of higher ranks limited by less important events.

Historically, the main events that were considered for defining stratigraphic time scales were the appearance or disappearance of significant fossil species. However, since adequate fossil occurrence data were not available everywhere, other events were also used for establishing these stratigraphic time scales, such as lithostratigraphic facies occurrences, sequential stratigraphy and geochemistry, palaeomagnetism, solar flux cycles (cf. Ogg & al., 2004). The universal reference for stratigraphic dating is the *International Stratigraphic Scale (ISS).* This standard time sale and the reference rock records on which it rests - formerly stratotypes presently replaced by GSSPs (Global Stratotype Section and Point), each representing the point in time at which a particular stage is starting (Ogg & al., 2004)- are established by the International Commission on Stratigraphy[1] of the International Union of Geological Sciences (IUGS)[2]. Since the ISS can only be used for dating successions containing adequate fossil associations, complementary time scales were defined at the regional scale in various parts of the

[1] http://www.stratigraphy.org/column.php?id=Chart/Time%20Scale
[2] http://www.iugs.org/

world and were correlated with the ISS by all available means. Finally, at local scales, rock dating is currently operated by reference to local stratigraphic successions, whose units are themselves correlated with the ISS or with some regional time scale.

Rank 1 : Period	Rank 2: Dynasty	Rank 3: Pharaoh	Dates (Beginning)
New Kingdom	20th Dynasty		1186 BC
	19th Dynasty	Tausert	1187 BC
		Siptah	1194 BC
		Seti II	1200 BC
		Amenesse	1203 BC
		Merenptah	1213 BC
		Ramesses II	1279 BC
		Seti I	1294 BC
		Ramesses I	1295 BC
	18th Dynasty		1539 BC

Fig1. Example of an event based chronology in the field of history: the Pharaoh dynasties[3]

Compared to the time scales used in history, the peculiarity of the time scales used in geology is the fact that they are based on the *stratigraphic model* (Jackson & Bates, 1997). Used for describing all types of stratigraphic successions, this model is based on the “superposition principle” (Tarbuck et al., 1999). It establishes a correspondence between space and time, considering that any sedimentary succession observed in the field materializes a particular slice of geological time. As pictured in figure 2, each time unit or time boundary belonging to a given time succession, corresponds to a particular geological unit or to a particular geological boundary.

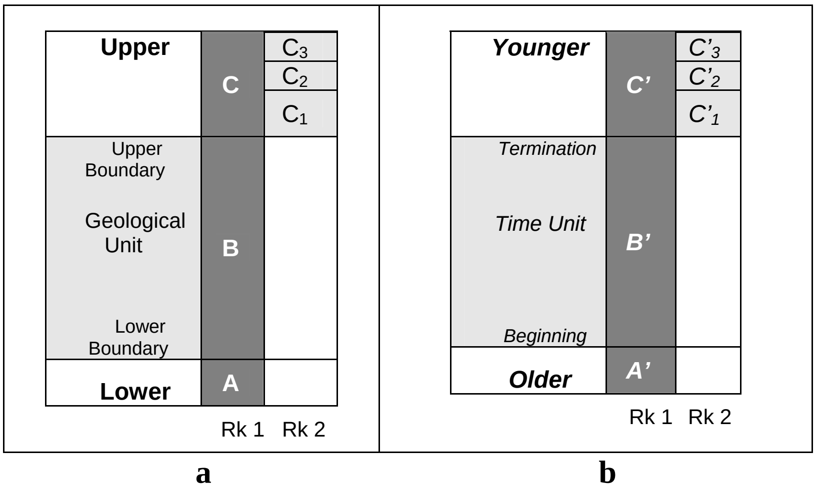

Fig 2. The stratigraphic model: (a) geological succession (b) time succession

The model of time succession pictured in figure 2, rests on the assumption than any time limit corresponds to one atomic time instant in the course of geological times and that, consequently, each time unit begins and terminates at definite time instants. However, this is a drastic simplification of reality since the actual ages of these various limits expressed in My can be determined only with some approximation. One reason for this is the uncertainty attached to radiometric measurements. Another reason, even more important, is the fact that the geological boundaries to which these measurements are related, do not always have one definite age. This notably happens when the geological limits considered are based on lithostratigraphy with no direct reference to fossil occurrences. For these various reasons, rock dating can hardly be seen as a straightforward operation. It always depends in some way on more or less complex geological interpretations, which may generate contradictory solutions. We will further examine how some these difficulties can be taken into account.

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[3] http://www.touregypt.net/kings.htm

1.2. Need of geological time formalization

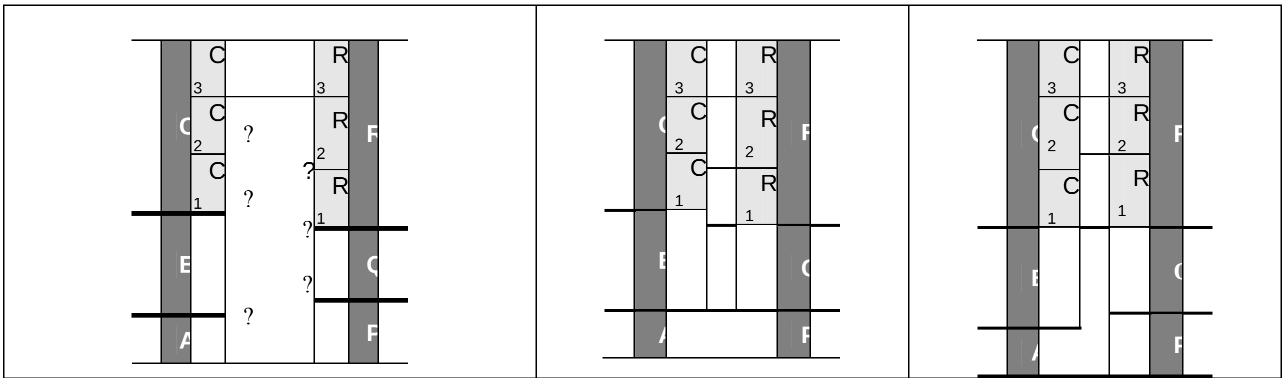
Management and exchange of information within large databases and complex systems is a capital issue in earth sciences as in many other fields. Typical examples concern for instance;

- the edition of geological maps, which synthesize a very large number of atomic field and rock sample observations that need to be periodically incremented, updated and attached to the various geological objects represented on the maps;
- practical activities such as exploration of water or mineral resources, underground waste storage, civil engineering, development planning, which require considering a large number of geology data that must be easily accessed by various kinds of users such as geologists, engineers, decision makers;
- 3D or 4D earth models performed for water or hydrocarbon resource exploration or for underground storage, which result of a complex chain of operations involving data of various kinds: geophysical, geological, petrophysical (Perrin & al. 2005), (Mastella & al., 2007).

In the age of internet, managing the information required for dealing with these problems should be preferably envisaged as a computer-assisted knowledge management activity using web resources. This supposes building research engines and specialized data bases for dealing with geological knowledge. And, as Richard (2006) rightly points out, this further supposes that *"geology as a science* [should be object of] *a greater degree of formalization in order to take advantage of evolving computer-aided knowledge representation and analysis systems"*. Knowledge management thus supposes knowledge formalization

1. 3. Goal of the present paper

Examining the issues related to the formalization of the event based chronology currently used for dating rock successions is the exclusive subject of the present paper. Formalization supposes drastic simplification. For this reason, we will not be concerned here with the complex geological issues related to establishing time scales and more generally stratigraphic successions but only with the formal aspects of their description and of their correlation. For accommodating the uncertainty attached to geological ages, we will just consider that the ages of time boundaries may be determined only with some approximation and that, consequently, the correlation of two stratigraphic successions may eventually be object of contradictory interpretations. This formal issue is illustrated in figure 3.



a) Correlation issues | *b) Interpretation 1* | *c) Interpretation 2*

Fig 3. The stratigraphic correlation issue. Thick lines in (a) indicate correlations that can be established considering lateral continuity or other criteria such as fossil appearance or disappearance while question marks indicate boundaries whose position relative to the other column remains questionable. Boxes (b) and (c) show two possible interpretations for (a).

In the present paper, after having listed the requirements for geological time formalization, we will examine how these requirements are met by the GeoSciML model currently used. We will then propose a few improvements, which open the possibility of not only describing individual time scales but also operating correlations between stratigraphic scales and/or stratigraphic successions in general. We will finally propose a codification method that enables actual stratigraphic successions to be described and correlated.

2. Issues attached to geological time formalization.

We have listed in section 1.2, some fields of activity and some issues for which geological time formalization is required. We should now examine which requirements are attached to these various issues.

2.1. Geochronologic hierarchy

For being accessed within a database, objects need to be classified and, in our view, such a classification should preferably be knowledge based. This supposes considering the semantics of the various objects and attaching them to *concepts*, which must themselves be hierarchically classified. In our case, considering that, within a definite time scale, any geochronologic unit of rank *i* corresponds to a fraction of the time span of the related unit of rank *i*-1, this hierarchy corresponds to a *partonomy* (cf. infra § 3.1). Moreover, since the various units of rank *i* attached to a geochronologic unit of rank *i*-1 are chronologically ordered with respect to each other, this partonomy is *chronologically ordered*.

2.2. Synonymies

A user who searches documents related to a particular geological period, for instance late Triassic, will be wanting to retrieve from the data base, not only the documents, which explicitly mention “late Triassic” but also those containing the word “Keuper”. For a broader research, he/she may also be interested in retrieving documents which contain the word “Triassic” or, on the contrary, documents containing the names of some particular divisions of late Triassic such as “Carnian”, “Norian”, “Rhaetian” or even “Lettenkohle”.

There exists, attached to a given set of geochronologic units, a dual set comprising the associated *time boundaries*. In order to be accessed by users within a database, these various boundaries must also be described and classified by specifying their links with the limiting geochronologic units. This supposes to take into account many synonymies since the top boundary of a given unit is equivalent to the bottom boundary of the unit, which directly overlies it and since a given limit is likely to have different names, depending on the rank of the units to which it is attached. An example is shown in figure 4, where all the listed terms correspond to one same geochronologic boundary corresponding to the beginning of the Triassic period.

Base of	Mesozoic	**Triassic**	Lower Triassic	Indusian	Buntsandstein	Lower Buntsandstein
Top of	Paleozoic	Permian	Lopingian	Changhshingian	Upper Permian (Thuringian)	Tatarian
	Rk2	Rk 3	Rk 4	Rk 5	Rk 4	Rk 5
	International Stratigraphic Scale				Continental Facies Scale (Europe)	

Fig 4. Synonyms for the base of Triassic. The figure shows the various possible names of the boundary corresponding to the beginning of the Triassic in the ISS and in the European continental Triassic stratigraphic scale. Data are extracted from Callec et al. (2006).

2.3 Chronological relationships

Since geochronologic units and boundaries are *chronologically ordered*, it is necessary to specify the temporal relationships, which exist between them. The various possible relationships between time intervals were examined by Allen (1983), who proposed 13 basic relations between two time intervals. Figure 5 illustrates the application of these relations to stratigraphic units and boundaries. This set of relationships will be largely used hereafter in our ontological model and for exploiting the codification of geological scales that we will propose in section 4 of the present paper.

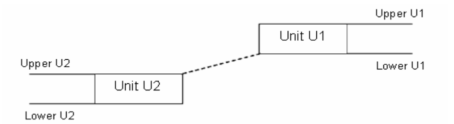
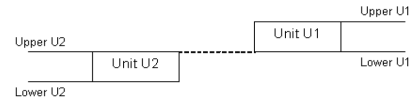
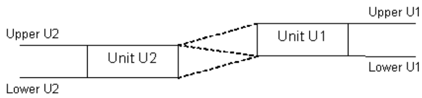
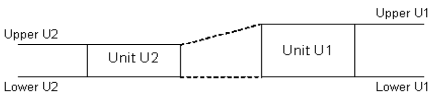
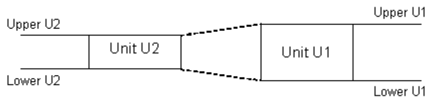
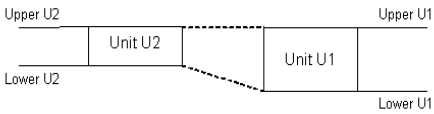
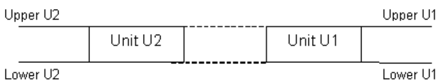
	Unit to Unit relationships	Boundary to Boundary relationships
	U_2 older than U_1	Upper U_2 older than Lower U_1
	U_2 meets U_1	Upper U_2 equivalent to Lower U_1
	U_2 overlaps U_1	Lower U_2 older than Lower U_1 AND Upper U_2 younger than Lower U_1 AND Upper U_2 older than Upper U_1
	U_2 starts U_1	Lower U_2 equivalent to Lower U_1 AND Upper U_2 older than Upper U_1
	U_2 during U_1	Lower U_2 younger than Lower U_1 AND Upper U_2 older than Upper U_1
	U_2 finishes U_1	Lower U_2 younger than Lower U_1 AND Upper U_2 equivalent to Upper U_1
	U_2 equals U_1	Lower U_2 equivalent to Lower U_1 AND Upper U_2 equivalent to Upper U_1

Fig 5. Allen's relationships (Allen, 1983). Seven relationships are shown here. Six additional relationships could be deduced by inverting U1 and U2 in those of the above relationships that are not symmetric (i.e. all relationships except the last one)

2.4. Geological dating

Formally, dating consists in establishing a link between a geological age (stratigraphical or absolute) and some geological object. This supposes that not only geological ages but also geological objects be described in a formal way and that the significance and formats of the established dating links be specified. Geological objects are various and may be simple (for instance: a stratigraphical surface, a single sedimentary strata, an elementary fault,) or complex (for instance a full stratigraphical column, a set of deltaic formations, a fault network). Their formal description supposes that these various objects should be considered as combinations of elementary types defined within some conceptual model (Richard, 2006). .

Specifying the age of a definite object is not always a simple issue since some objects were eventually the results of complicated successions of geological events. In order to avoid all possible ambiguities, it is thus necessary that geologists specify which event(s) the age of a given object should be attached to. We should also consider that the age of a given object may correspond either to a given geological date corresponding to some event considered as "instantaneous" at geological time scale or to a geological time span that begun at a given geological date and ended at another one. Formalization should take into account the above mentioned peculiarities and allow age attribution according to two different time formats, one referring to a quantitative chronology expressed in absolute ages in My and the other to an event based chronology defined in reference to some stratigraphic time scale.

2.5. Accommodating various hypotheses

Since the age of a geological object is not an objective datum but the result of geologists' interpretation, different ages may eventually be attributed to one same geological object. At a larger scale, this is likely to generate different, possibly contradictory versions of the maps and models related to a given geological area. For comparing and evaluating these different versions, a record should be kept of all the elementary interpretations, which generated them (Rainaud, 2005). Consequently, the formalization of geological time that is required should be able to accommodate age uncertainties and to represent many interpretations related to the ages of elementary objects and/or of more or less complex geological assemblages.

3. State of the art of geological time formalization

3.1. Ontologies

Popularized by authors such as Gruber (1993), Uschold and Gruninger (1996), Guarino (1998), Noy and McGuinness (2001) and many others, ontologies have become in two decades a classical AI tool for formalizing technical knowledge. Presently, a widely accepted definition of an ontology in the field of computer science is that given by Gruber (1993): *"an ontology is an explicit specification of a conceptualization"*. In this definition, the word *"conceptualization"* designates an abstract model of things that are assumed to exist in some area of interest (objects, relations) and the expression *"explicit specification"* intends to specify that the concepts and relationships in the abstract model are given explicit names and definitions. So, in contrast to other kinds of models, such as numerical models for instance, an ontology is a symbolic model of the types of objects attached to some domain. It represents a domain conceptualization by means of words and of their meanings. Various ontologies have been defined for earth sciences (cf. Sinha, 2006). Ontologies defined by Richard (2006) and more specifically by Cox & Richard (2005) for the description of knowledge attached to geological time, were at the origin of the GeoSciML model , which is the only significant knowledge formalization presently in use in the field of geosciences.

Before entering into the details of GeoSciML model, it is necessary to recall a few important points concerning ontologies.

i. An ontology is most often built in view of a definite practical goal. For this reason, "*there is no one correct way to model a domain* [but] *there are always viable alternatives*" (Noy & McGuinness, 2001). This is a key point for understanding the choices that were made by the various categories of geoscientists, who have already proposed solutions for geological knowledge formalization.
ii. An ontology is not a software model but merely an abstract model. For using such a model in a software application, it is necessary to formalize it into a logical model with the help of an ontology language (Gomez-Perez & al., 2004). OWL[4] (McGuinness & Van Harmelen, 2004) for instance is the standard language proposed by W3C to formalize knowledge, i.e. make the knowledge from a domain processable by a computer. OWL is based on Description Logics, which is considered one of the most important knowledge representation (KR) formalism, which unify all the well known KR formalisms[5].
iii. In order for end users to check its relevance, the structure of an ontology must be visualized in some way. Since ontology languages such as OWL cannot be easily read by end users, ontologies must be visualized using graphical representations (for instance, the Protégé platform (Noy & al., 2001) for visualizing ontologies expressed in OWL). However, there presently exists no solution allowing end users to visualize ontologies in a fully satisfactory way.

3.2 A formerly developed geological time formalization: the GeoSciML model

Till now, only one significant concept model built by the Arizona Geological Survey (Cox & Richard, 2005) has been proposed for formalizing Geological Time Scales. This same model is presently being reused by the working group GeoSciML, which involves geological surveys from various countries (notably Australia, Canada, France, Italy, UK, USA) with the goal of unifying and formalizing geological knowledge for the sake of geological map editors. The model, which is in free access on the GeoSciML website[6], will be described hereunder as the GeoSciML model for Geological Time Systems or more simply as the GeoSciML model.

[4] http://www.w3.org/TR/owl-ref/
[5] http://dl.kr.org/
[6] http://www.geosciml.org/

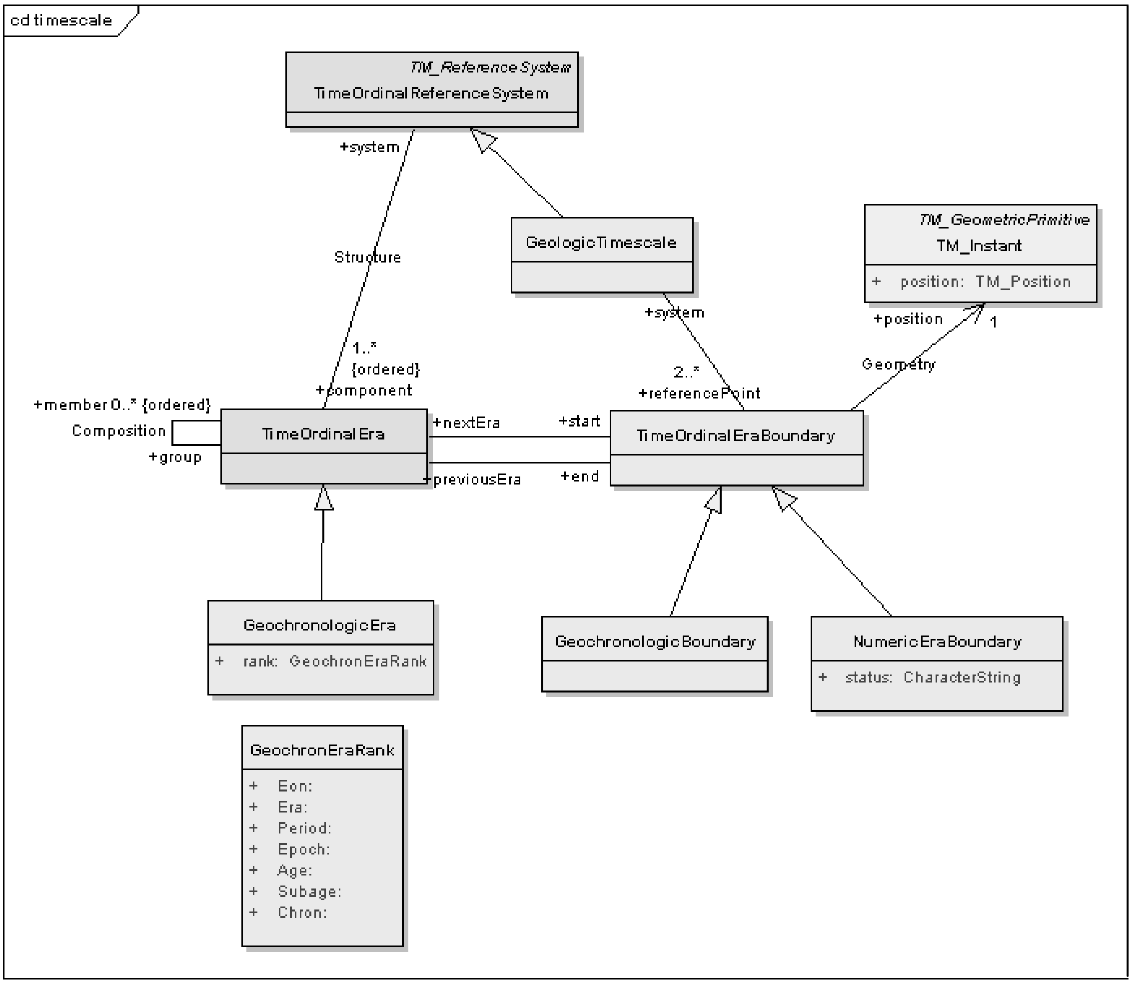


Fig 6. GeoSciML model for Geologic Time Scales (from Cox & Richard, 2005)

The GeoSciML model is written in the UML graphical language and consists of a set of UML diagrams visualized by means of XML representations. The part of the model describing Geological Time Systems refers to the ISO model for Temporal Reference System (ISO 19108) and is thus compatible with geospatial information transfer standards. The ISO 19108 model distinguishes 3 types of reference systems: one based on years, months and days (*TM_Calendar*), one based on hours, minutes and seconds (*TM_Clock*) and one based on named intervals (*TORS* = *TM_OrdinalReferenceSystem*). The latter is of major importance in our case since a *TORS* is composed of an ordered sequence of one or more component *TOE* (*TM_OrdinalEra*) elements (the term *"Era"* having here a generic meaning and being thus different from the geological concept *"Era"*, which refers to geological units of rank 1). A *TOE* can be for instance some geological time interval (such as a geological *Eon*), which can be recursively decomposed into ordered *TOE* elements (*Eras, Periods, Epochs, Ages, Chrons)*. This allows a hierarchical age system to be constructed.

With respect to the ISO 19108 Temporal Reference Model, some variations were introduced into the GeoSciML model represented in figure 6. The major one consists in defining the era limits as *TOEBs* (*TimeOrdinalEraBoundary*), each *TOEB* corresponding to one *TM_Instant*, which is a point in the span of Geological Time. A *Geologic Timescale* is thus a kind of *TORS*, which includes as first-order elements:

1) *GeochronologicEra*, which is a kind of *TOE* with boundaries defined as *TOEBs*. *GeochronologicEra* instances may have names such as Triassic, Oxfordian etc.

2) *TOEB having two specializations:*
   a. *GeochronologicBoundary* defined with reference to some geologic evidence such as, for instance, fossil appearance/disappearance or significant change in local rock lithology.
   b. *NumericEraBoundary* corresponding to geological boundaries dated by absolute age measurements.

The correlation of the timescale elements *GeochronologicBoundary* and *GeochronologicEra* with actual geological records is established by means of the two relationships:

GeochronologicBoundary --- isManifestedBy---> ChronostratigraphicBoundary

GeochronologicEra ------ ---- isManifestedBy---> ChronostratigraphicUnit

The concept of *ChronostratigraphicBoundary* corresponds to an actual reference *Stratigraphic_Boundary* (for instance a GSSP) and that of *ChronostratigraphicUnit* to an actual reference *Geological_Unit* (for instance a stratotype). Moreover the concept of *ChronostratigraphicUnit* may eventually be further characterized as a *LithostratigraphicUnit* with reference to its lithological content.

The GeoSciML model is conceived to record the characteristics of various geological data from which the Geological Time Scale was built, i.e. the data attached to the stratotypes and to the Global Stratotype Sections and Points (Ogg & al., 2004). Generally speaking, a geological object described in the GeoSciML model as a *GeologicalFeature*, can be given an age by using the relations:

GeologicalFeature ---- is linked to -----> GeologicalEvent ---has---> Age

Geological dating thus goes through associating a geological object to the *GeologicalEvent* that generated it. This is a minor difference with respect to the concept model formerly proposed by the Arizona Geological Survey (Richard, 2006), which establishes a direct link:

GeologicalUnit --- has ----> GeologicalAge

3.3. Need of complementing the existing GeoSciML ontology

The main goal of the GeoSciML model for Geological Time Systems is formalizing the knowledge attached to the International Stratigraphic Scale (or possibly to some other Geological Time Scale) and to the geological records, stratotypes and GSSPs, which define it. However, as we mentioned in section 1.2., in their everyday practice, geologists also need to operate correlations between stratigraphic successions by specifying chronological relationships or eventual synonymies between the various items attached to these successions. At present, this cannot be done in a simple way by using the GeoSciML model.

Developing new ontologies or significantly modifying those which already exist is an issue that must be carefully thought about in a field like geology, where significant efforts are being made to unify and formalize vocabulary. But, considering the needs that are not covered by the GeoSciML model and which are of importance for geomodelers like us, we have considered the possibility of proposing improved ontologies for Geological Time description and for Geological Dating. The ontologies that we will hereafter present in section 3 are fully compatible with the GeoSciML model and are in no way redundant or contradictory with this model. Furthermore, these improved ontologies open the possibility of formulating new rules for solving practical issues concerning geological dating and stratigraphic correlation by means of a codification methodology that will be presented in section 4.

4. Proposal for Geological Time Formalization

The ontologies that we present hereafter for geological time description and for geological dating were partly inspired by the GeoSciML model. Their interest is that they open the possibility, which does not exist in GeoSciML, of performing full mutual comparison between stratigraphic successions of any type. A detailed comparison with the GeoSciML model will be presented at the end of the present section. A preliminary version of these ontologies was given in Mastella (2010)[7].

[7] http://pastel.archives-ouvertes.fr/pastel-00005770/fr/

4.1. The Geological Time Ontology

The *Geological Time ontology* was developed for describing the hierarchy of the geological periods of time as it appears in stratigraphical time scales and for further allowing establishing correspondence between different time scales based either on the use of fossils or on absolute ages. The two main concepts that were defined for formalizing the main elements of a geological time scale are *GeochronologicUnit*, which corresponds to a geological time interval, and *GeochronologicBoundary*, which represents a geological time boundary corresponding to an instant having no temporal duration.

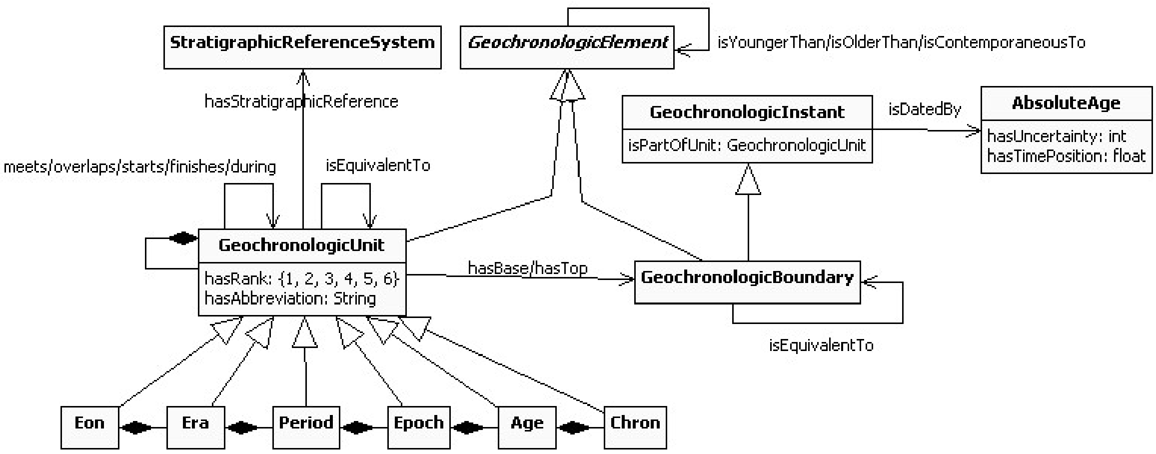


Fig 7. Proposed Geological Time ontology

The Geological Time ontology is represented in figure 7. It can be described in the following way.

i. The abstract concept *GeochronologicElement* is the superclass of *GeochronologicUnit* and *GeochronologicBoundary*.

ii. The class *GeochronologicUnit* is defined by reference to a *StratigraphicReferenceSystem* (a TORS as defined in GeoSciML).

iii. Age relationships between two *GeochronologicElements* of any nature can be established by the relations *isYoungerThan* and *isOlderThan.* This allows specifying the order of occurrence of these elements in the course of geological times, even in the case when they are not attached to the same *StratigraphicReferenceSystem.*

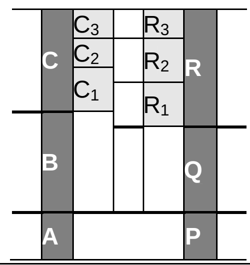
iv. *GeochronologicUnit* instances relate to other *GeochronologicUnit* instances by means of detailed interval relationships (e.g. *overlaps*, *meets*, *starts*, etc.). These relations are those defined by the *Allen's rules* as mentioned in section 2.1.3. As illustrated in figure 8, it is thus possible to precisely describe age relationships between two *GeochronologicUnit*s eventually belonging to different *StratigraphicReferenceSystem*s, notably in the cases when the two units meet or are included one in the other.

v. *GeochronologicUnit* instances (the equivalents to *GeochronologicEra* instances) are organized in a partonomy (i.e. by a *partOf* relation). Units such as *Eon, Era, Period*, etc. are sub-concepts of *GeochronologicUnit* and are organized in specific partonomies: an instance of *Chron* is part of some *Age*, which is part of some *Epoch*. Actual GTS units, such as Triassic, Jurassic, and so on, are represented as instances of the concept *GeochronologicUnit* (in fact, as instances of the concepts *Eon*, *Era*, and so on). Actual boundaries between units are represented as instances of the concept *GeochronologicBoundary.* One can stipulate that definite *GeochronologicBoundaries* correspond to the base or to the top of some *GeochronologicUnit* by using *hasBase* and *hasTop* relationships.

vi. *GeochronologicInstant* is a generalization of *GeochronologicBoundary* representing one particular instant within a GTS, which may correspond or not to a boundary between *GeochronologicUnits*. The age of *GeochronologicInstant* may be expressed by an *AbsoluteAge* (for 1.5 My) or as a stratigraphical age (Lower Pleistocene) or remain purely virtual.

Fig. 8. Examples of relationships between time intervals
(in reference with the interpretation 1 envisaged in figure 3b).

Unit Q begins at the same time as unit B is expressed by the relation: *starts(Q,B)*
Unit R_2 begins after the beginning of unit C and terminates before the termination of unit C is expressed by the relation: *during(R_2,C)*.
Equivalence between units P and A is established by the relation: *isEquivalentTo(P,A)*.



The position of this Geological Time ontology with respect to the GeoSciML model can be appreciated in the following way.

i. The concepts of *GeochronologicUnit* and *GeochronologicBoundary* are respectively equivalent to the GeoSciML classes *GeochronologicEra* and *GeochronologicBoundary*. We prefered the name "Unit" to "Era" in order to avoid any possible confusion with *Geological Era* (= *GeochronologicUnit* of rank 2).

ii. The class *GeochronologicUnit* is more general than the GeoSciML class *Geologic Time Scale*, since it includes stratigraphic successions of any type. The class *StratigraphicReferenceSystem* is a *TM_OrdinalReferenceSystem* (TORS), as defined in GeoSciML.

iii. Relative age relationships between *GeochronologicEra* and/or *GeochronologicBoundary* within a given Time Scale can be established in the GeoSciML model by considering the hierarchy of the *TM_OrdinalReferenceSystem.* This is also possible in our proposed Geological Time ontology. However, the relations *isYoungerThan* and *isOlderThan* completed by the detailed interval relationships issued from *Allen's rules* open the possibility of operating detailed age comparisons between *GeochronologicElements*, which do not belong to the same Time Scale. Such possibility is an original addition with respect to the GeoSciML model.

iv. The partonomy of our *GeochronologicUnits* is strictly equivalent to that of GeoSciML *GeochronologicEras.* The relationships between *GeochronologicBoundary* instances and the associated *GeochronologicUnit* are also strictly equivalent to the GeoSciML relationships: *GeochronologicBoundary ---starts/ends---> GeochronologicEra*.

v. Our class *GeochronologicInstant* is equivalent to the *TM_Instant* class of GeoSciML. However, we proceeded to some simplification by ignoring the GeoSciML concept of *NumericEraBoundary* , which did not appear necessary in view of our goal of stratigraphic correlation and, as a matter of consequence, by also ignoring the concepts of *TimeOrdinalEraBoundary* (TOEB) and *NumericEraBoundary*.

Compared to the GeoSciML model, the main peculiarity of the Geological Time ontology that we have defined is that it can be applied for *geological time correlation*, that is for creating a correspondence between elements of different GTSs. For depicting geologists' interpretations, correlations between units can be created by means of the *time interval relations*.

4.2. Geological dating

4.2.1. Defining geological objects

The *geological dating* procedure consists in assigning an "age" to some geological object. As we explained before, this first supposes that geological objects should be formally defined. For this, we use the ontology of Basic Geology defined by the e_Wok Hub consortium[8] (Aït Ameur & al., 2008), which is represented in figure 9. This simplified model is strictly in accordance with the GeoSciML model.

The Basic Geology ontology is built around the concept *GeologicalObject*, which is constituted by *GeologicalUnits* and *GeologicalBoundaries*. Geological objects are very various (examples among many others are: a stratified sedimentary unit, a reef, a diapir, a fault network etc.) and can be simple or complex. Complex

[8] e_Wok Hub : Environmental Web Ontology Knowledge Hub, http://www.inria.fr/sophia/edelweiss/projects/ewok/

geological objects can be described as associations of a various number of atomic geological objects belonging to two categories:

- 2D objects corresponding to *GeologicalBoundaries* such as erosion surface E, fault F or the upper and lower boundaries b_u and b_l represented in figure 10.
- 3D objects corresponding to *GeologicalUnits* such as the sedimentary unit U limited by the boundaries b_u and b_l in figure 10. The concept *GeologicalUnit* describes a volume of continuous geological matter limited by one or several *GeologicalBoundaries*

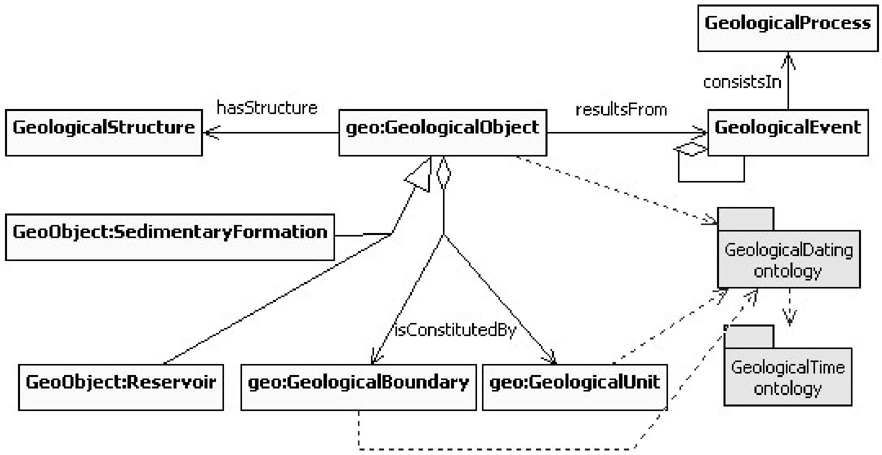


Fig 9. Proposed ontology for Basic Geology

A given geological object is the result of some geological event (represented by the concept *GeologicalEvent*). A geological event may consist of a single geological process (e.g. the deposition of a sedimentary unit) or be composed of multiple geological processes (example: a metamorphic formation deformed by late tectonics). The various specializations of *GeologicalProcess* correspond to thecreation, destruction or transformation of geological matter. They were detailed by the e_Wok Hub consortium in a sub-ontology entitled *Geological Process*. A geological event is also responsible for geological object structures (e.g. Synform Fold, Reverse Fault), which are detailed by the e_Wok Hub consortium in a sub-ontology *Geological structures*.

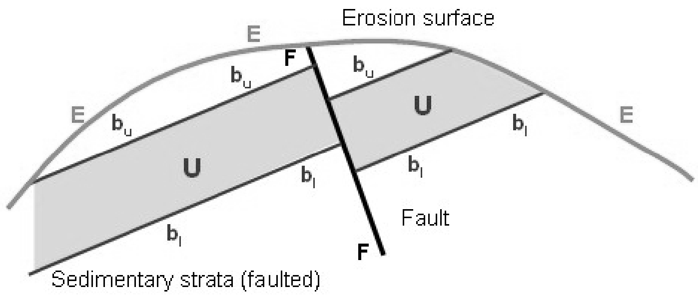


Fig 10. Geological units and boundaries

4.2.2. The Geological Dating Ontology

The *Geological Dating ontology* that we have defined is based on the data model of the Geological Time Scale presented in the *GeoWhen* Database[9]. GeoWhen is a compilation of the main naming schemes for the geologic timescale that appear in the literature. We modified it in many points, and we imported the temporal relations already formalized in the *OWL-Time ontology* (Hobbs and Pan, 2006). The Time Ontology is an ontology of temporal concepts originally developed for describing the temporal content of Web pages and the

[9] http://www.stratigraphy.org/bak/geowhen/index.html

temporal properties of Web services. This ontology can be easily reused for adding temporal aspects to any domain ontology.

Our *Geological Dating ontology* represented in figure 11 allows representing the main characteristics of geological dating and notably the two different ways in which geological ages can be expressed i.e. absolute dating and relative dating using stratigraphic scales. The ontology introduces abstract concepts, which make the link between concepts of the *Geological Time ontology* and of the *Basic Geology ontology*. The concepts imported from the *Geological Time* ontology were given the prefix *GeoTime*, and those imported from the *Basic Geology* ontology the prefix *BasicGeo*.

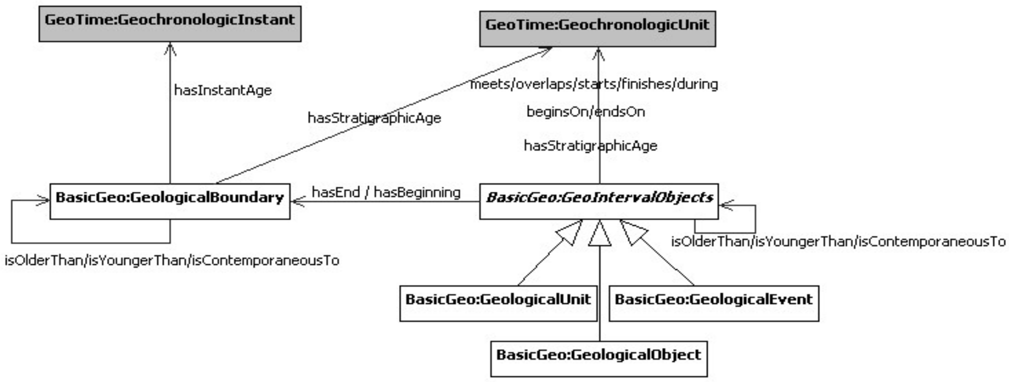


Fig 11. Proposed Geological Dating ontology

The concepts and relationships related to the Geological Dating ontology can be described as follows:

i. The geological objects that can be dated are: *BasicGeo:GeologicalBoundary, BasicGeo:GeologicalUnit, BasicGeo:GeologicalEvent* and *BasicGeo:GeologicalObject.*

Ii All geological objects imported from the *Basic Geology ontology* have a defined stratigraphic age, which is represented by the relation

hasStratigraphicAge with the Geological Time ontology concept *GeoTime:GeochronologicUnit*.

iii. *GeoIntervalObjects* are abstract classes that are superclasses of all interval-like objects imported from the *Basic Geology ontology*. They are related to *GeoTime:GeochronologicUnit* through the relations *meets/overlaps/finishes/during*. These objects also have a *duration*. They can be dated by specifying a stratigraphic age, by defining an interval relation with some *GeoTime:GeochronologicUnit* or by stating that the object begins or ends on some *GeoTime:GeochronologicUnit*.

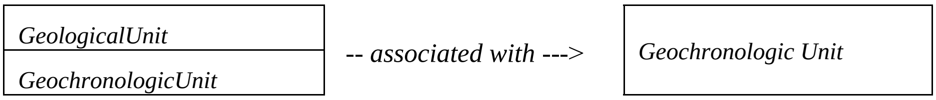
iv. A *GeologicalBoundary* can be also dated by stating a stratigraphic age. Moreover, since it is a boundary, it may be dated by a specific instant in time, represented by the concept *GeoTime:GeochronologicInstant*. This instant can be characterized by an absolute age value or be considered as equivalent to a GTS boundary. It may also remain a purely virtual point in GTS, since *GeoTime:GeochronologicInstant* is a superclass of *GeoTime:GeochronologicBoundary*.

Since we were not concerned by the issue of linking timescale elements to the geological records, which define them, we have defined, in contrast with GeoSciML, geological dating in one simple way:

- by associating any *GeologicalBoundary* to a *GeochronologicInstant*,
- by associating *GeochronologicUnit* to *GeologicalUnits* (or more generally to *GeologicalObjects*) and to *GeologicalEvents*,

This solution allows considering that actual geological objects on the one hand and items belonging to some time scale one the other, can be respectively attached to the same concepts in the following way:

GeologicalBoundary *GeochronlogicBoundary*	*-- associated with --->*	*GeochronologicInstant*



4.3. Conclusion on the proposed formalization

Although being largely inspired by the GeoSciML model and being fully compatible with it, the two ontologies that we developed for formalizing Geological Time and Geological Dating open new possibilities. By introducing a class *GeochronologicUnit* which not only represents time scales but any type of stratigraphic succession and by formally expressing detailed interval relationships issued from Allen's rules, we open the possibility of comparing the ages of *GeochronologicElements* eventually belonging to different time successions. In contrast to the GEoSciML, our improved model thus enables the user to easily operate stratigraphic correlations. The full set of ontologies formalized in OWL language is presented and can be downloaded from the web site of the e-Wok project.[10]

5. Proposal for an Ontology Based Codification of Geological Time

5.1. Introduction

For operating the concepts and properties described by means of the two above defined ontologies, we propose to characterize the various instances of *GeochronologicUnit* and those corresponding to the associated *GeochronologicBoundaries* within one time succession by means of a codification bearing in itself all the information related to these entities. Such a codification should enable one to chronologically classify the various *GeochronologicElements* belonging to one time succession and to determine all the instances associated to a given *GeochronologicInstant.* Moreover, when applied to two time successions, this codification should enable establishing time correlations between these entities.

The codification that we propose, intends to be applicable to any chronological succession based on named intervals i.e. to any *TM_OrdinalReferenceSystem (TORS)* as defined in the ISO 19108 model and in the GeoSciML model. We will describe here the principle of this codification and briefly explain how it can be used for classifying *GeochronologicElements* and for establishing correlations between different time successions

5.2. Codification rules for GeochronologicUnits and GeochronologicBoundaries

The codification that we propose basically rests on a chronologically ordered numbering. Two sets of code numbers are defined one for time units (U_code) and one for time boundaries (B_code). Figure 12 shows how the related concepts can be inserted in the Geological Time ontology.

Let us consider a TORS comprising time units of *n* ranks. The U_code corresponding to some time unit U_i of rank *i* that is a division of a parent time unit U_{i-1} of rank *i*-1 will consist in :

i. a prefix for identifying the considered TORS and for specifying that the code is a U_code. For instance, for a *GeochronologicUnit* belonging to the ISS, this prefix could be ISU = IS (International Scale) + U (U_code).

ii a sequence of *n* pairs of numbers corresponding to the *n* ranks of the considered TORS. The *i-th* pair of numbers ≠ 0 comprises from left to right :

   a. an ID number indicating the position of U_i within the division of the parent unit U_{i-1}
   b. a ND number equal to the total number of divisions of U_{i-1}.

   In a similar way, the *(i-1)th* pair will consist in an ID number describing the position of unit U_{i-1} within the division of the parent unit U_{i-2} and in a ND number equal to the total number of divisions of U_{i-2}.
   In the case when $i < n$, the last *n-i* pairs of numbers of the code are given the values 00. Moreover additional pairs 00 can be eventually added to the code for facilitating time scale correlations as it

[10] http://www-sop.inria.fr/edelweiss/projects/ewok/ontologyview/ontologies.html (in French).

will be explained later in section 4.3.

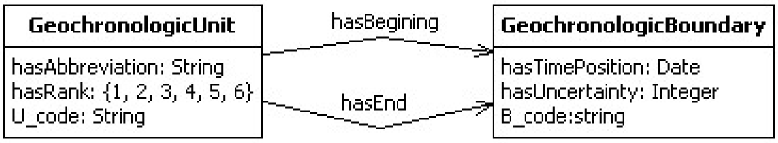


Fig 12. Insertion of the U_code and B_code concepts in the Geological Time ontology

For attributing B_codes to *GeochronologicBoundaries*, we propose to apply two rules. Rule 1 specifies that the B_code attached to the lower time boundary related to any “ultimate” time unit of the TORS, (i.e. to any time unit corresponding to a subdivision, which is not itself divided and which is thus locally the “ultimate” in the partonomy), bears the same number as the ultimate time unit to which it is attached. This B_code will just be differentiated from the U_code to which it is related by the ending of its prefix where the letter U will be replaced by the letter B (the prefix ISU being for instance replaced by the prefix ISB in the case of the ISS).

However, the lower time boundary of some “ultimate” time unit may also be the boundary of time units of lower ranks (i.e. of time units that are not ultimate). In this case, rule 2 specifies that the B_code attached to any boundary possibly related to several time units of different ranks is the one that is defined by considering the ultimate time unit to which this boundary is attached and by applying rule 1. This allows all synonymy problems between boundaries to be easily solved.

Figure 13 illustrates a practical example of codification for a time unit divided into two subunits and seven sub-subunits.

<table>
<tr><td rowspan="7">U ...23 00 00
B ...23 22 33</td><td rowspan="4">U ...23 12 00
B ...23 12 44</td><td>U ...23 12 14</td><td>*B ...23 12 14*</td></tr>
<tr><td>U ...23 12 24</td><td>*B ...23 12 24*</td></tr>
<tr><td>U ...23 12 34</td><td>*B ...23 12 34*</td></tr>
<tr><td>U ...23 12 44</td><td>*B ...23 12 44*</td></tr>
<tr><td rowspan="3">U 23 22 00
B ...23 22 33</td><td>U ...23 22 13</td><td>*B ...23 12 44*</td></tr>
<tr><td>U ...23 22 23</td><td>*B ...23 22 13*</td></tr>
<tr><td>U ...23 22 33</td><td>*B ...23 12 44*</td></tr>
<tr><td>**Rank *n*-2**</td><td>**Rank *n*-1**</td><td colspan="2">**Rank *n***</td></tr>
</table>

Fig 13. Principle of the proposed codification for time units (TM_OrdinalEras) and time boundaries (TimeOrdinalEraBoundaries) in the case of a TORS comprising n ranks.

5.3. Correlation between two time successions

The codification that we have just described applies to any time succession and, more generally, to any TORS. It can also be used for establishing correlations between two time successions.

In the logical frame that we are using for codification based on *GeochronologicUnit* numbering, correlation between two time scales A and B is necessarily an asymmetric procedure. This means that correlation can be established in two different equally valid ways, either by correlating B with A or A with B. Figure 14 illustrates the methodology that we propose in the case of a correlation of a time scale B with a time scale A. We suppose that the two scales were codified as described in section 5.1.2, scale A with a code having the headers AU and AB and scale B with headers BU and BB. We also suppose that the user has determined the time relationships (*youngerThan*/*olderThan*), which exist between any two time boundaries respectively belonging to scale A and scale B, these relationships being eventually the result of his/her interpretation.

Time succession A			Time succession B		
AU 12 00		*AB 12 00 00*	*BB 12 15*	**BU 12 15**	**BU 12 00**
AU 22 00	**AU 22 13**	*AB 12 00 11*	*BB 12 25*	**BU 12 25**	
		AB 22 13 00			
	AU 22 23	*AB 22 13 12*	*BB 12 35*	**BU 12 35**	
		AB 22 13 22	*BB 12 45*	**BU 12 45**	
		AB 22 23 00	*BB 12 55*	**BU 12 55**	
	AU 22 33	AB 22 33 00	*BB 22 00*		**BU 22 00**

Fig 14. Correlation of two time scales A and B

In order to allow the correlation, we first add to the B_codes attached to scale A a pair of numbers, which will be given zero default values. Correlation of B with A then basically consists in solving the two following cases concerning time boundaries:

i. Some time boundary of scale B has the same time position as some boundary of scale A. In this case, the two boundaries are put as equivalent. In figure 14 left, we thus have the equivalences:

BB 22 00 ≡ AB 22 33 00 , BB 12 55 ≡ AB 22 23 00, BB 12 15 ≡ AB 12 00 00

ii. One or several boundaries bB belonging to scale B correspond to *GeochronologicInstants* positioned within a given GeochronologicUnit uA of scale A (which means that boundaries bB are younger than the bottom limit and older than the upper limit of uA). In such a case, we create within scale A additional boundaries that we put equivalent to boundaries bB. The codes of these boundaries will be deduced from the code of the upper boundary of uA by replacing the last ID zero number by numbers 1, 2… in the chronological orders of the bBs from the youngest to the oldest one. Beyond that, the number of additional boundaries must also be set in the corresponding number of subdivisions. Considering the example illustrated in figure 14, the following boundaries can be added to time scale A, as shown on the third column of the left part of the figure:

AB 12 00 11 ≡ BB 12 25, AB 22 13 12 ≡ BB 12 35, AB 22 13 22 ≡ BB 12 45

Having solved the two above issues concerning *GeochronologicBoundaries*, existing relationships between any two time units respectively belonging to scales A and B can then be easily determined by applying the *Allen's rules*.

5.4. Integration of two time successions

Considering the above presented methodology, we can go one step further by operating full integration of the two time scales into one. This is again an asymmetric operation, which can be operated either by integrating B into A or A into B with two different and equally valid results.

Considering the same theoretical case as in section 4.3, our integration methodology is illustrated in figure 15. It consists in considering that the extra *GeochronologicBoundaries* that were added to time scale A for correlating time scale B, correspond to extra divisions of the *GeochronologicUnits* of scale A. If the maximum rank of the scale A divisions was originally n (2 in the case considered in figure 14), it will then become n+1 (i.e. 3 in the case of figure 14). It then suffices to recompute the codification of time scale A according to the rules presented in section 4.1, taking into account these new divisions of rank n+1. The right part of figure 15 shows the result that is obtained for the integrated time scale AB corresponding to the integration of B with A.

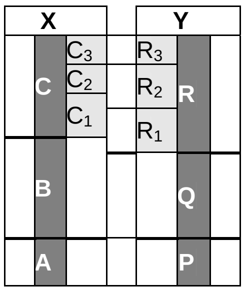
Time succession A		
AU 12 00		*AB 12 00 00*
AU 22 00	**AU 22 13**	*AB 12 00 11*
		AB 22 13 00
	AU 22 23	*AB 22 13 12*
		AB 22 13 22
		AB 22 23 00
	AU 22 33	*AB 22 33 00*

Integrated time succession AB		
ABU 12 00 00 *ABB 12 00 00*		
ABU 22 00 00	**ABU 22 13 00**	**ABU 22 13 12** *ABB 22 13 12*
		ABU 22 13 22 *ABB 22 13 22*
	ABU 22 23 00	**ABU 22 23 13** *ABB 22 23 13*
		ABU 22 23 23 *ABB 22 23 23*
		ABU 22 23 33 *ABB 22 23 33*
	ABU 22 33 00 *ABB 22 33 00*	

Fig 15. Integration of time scale B into time scale A resulting into a time scale A

Figure 16 shows an additional example of stratigraphic correlation and integration corresponding to the example presented above in figure 3b.

Time succession X			Time succession Y	
XU 13 00	XU 13 13	*XY 13 13 00*	YU 13 13	YU 13 00
	XU 13 23	*XY 13 23 00*	YU 13 23	
	XU 13 33	*XY 13 23 11*		
		XY 13 33 00	YU 13 33	
XU 23 00		*XY 13 33 11*		
		XY 23 00 00		YU 23 00
XU 33 00		*XY 33 00 00*		YU 33 00



Time succession XY		
XU 13 00	XU 13 13	
	XU 13 23	
	XU 13 33	XU 13 33 12
		XU 13 33 22
XU 23 00	XU 23 12	
	XU 23 22	
XU 33 00		

Correlation **Integration**

Fig 16. Example of correlation and integration of the two time scales.
The example refers to interpretation 1 of figure 3

5.5. Use of the proposed classification

Thanks to the properties of the proposed classification, it is possible to solve with simple algorithms, all practical questions related to relationships between time units and/or boundaries such as specifying:

- the units of lower ranks into which a given time unit U is inserted and the relationships of U with these units (begins / during / finishes)
- the units of higher ranks inserted in unit U and their relationships with U
- the unit of the same rank immediately laying over U
- the unit of the same rank immediately overlaid by U,
- the time units overlaying or overlaid by a given time boundary B

To take but one example, let us consider the issue of identifying the time units, which overlay a given time boundary B. This problem can be solved by first identifying the ultimate time unit U overlaying B, whose U_code number is the same as the B_code of B and then by identifying all the successive time units of lower ranks, which are begun by U. For finding those, one can apply the rule:

If, in the U_code of a time unit of rank i begun by U, the ID and ND numbers of the last pair of numbers non equal to zero are equal (i.e. have the format kk), this time unit corresponds to the oldest division of the associated time unit of rank i-1, which is itself, consequently, begun by U.

A software application using an OWL version of the ontologies that we defined as well as our proposed codification, is presently being developed at IFP. Software modules have already been realized for enabling the user to interactively build time successions and correlate them. The codes corresponding to time units and boundaries are generated in an automatic way. The correlation of a time succession B with a time succession A and the merging of A and B in one succession AB are simply operated by interactively inserting with the mouse time boundaries belonging to B into time units belonging to A. The codes of the new succession AB are also automatically generated.

These first results already demonstrate that the proposed codification is a flexible tool to easily manage time successions and for correlating and integrating them according to one or eventually to several interpretations. This is likely to help geologists to manage uncertainties attached to the time position of *Geochronologic_Boundaries* by rapidly checking various interpretative hypotheses.

6. Conclusion

At present, many activities using geology rest on large databases and depend on more or less complex engineering systems. One condition for establishing and maintaining such data bases and for efficiently managing the engineering systems, which use them, is adequate knowledge formalization. These issues are the ones which motivated us for reexamining how geologists presently formalize the specific event based chronology that is currently used for geological time description and for dating rock successions and for suggesting some possible improvements

The ISS and the various other event based time successions used in geology rest on the stratigraphic model. Their architectures and mutual relationships depend on the relative chronological order of the various boundaries, which separate time units. For many reasons, mostly geological, the ages of these boundaries can only be determined with some uncertainty. Establishing, maintaining and correlating stratigraphic time scales is thus a difficult task, which rests for a good part on geological interpretation Since formalization supposes drastic simplification, we have decided however not to consider these various geological difficulties but only the formal issues related to the description and correlation of geological time scales and of stratigraphic successions in general.

Considering these formal aspects, we have mentioned that the semantic and logical tools used for describing time scales and stratigraphic successions should enable users:

- to correctly describe the hierarchy of geological time units belonging to any time succession as a partonomy of chronologically ordered elements,
- to take into account the many synonymies between *GeochronologicElements* that exist within a given time scale and notably those related to *GeochronologicBoundaries*,
- to operate a detailed comparison of the relative ages of two *GeochronologicElements* (*GeochronologicUnit* or *GeochronologicBoundary)* possibly issued from two different time successions by operating the *Allen's rules*,
- to operate full chronostratigraphic correlation between two time successions as well as eventual merging of one of them into the other.

For fulfilling these requirements and notably those related to chronostratigraphic correlation, we have shown that there is the need of modifying and complementing the widely used formalization of geological time available within the GeoSciML model. We have thus developed two ontologies for describing *Geological Time* and for operating *Geological Dating*. These ontologies are derived for a good part from the GeoSciML model. With respect to this model, we only have introduced minimum modifications and extensions, which consisted in defining a limited number of new concepts and a full set of relationships resting on *Allen's rules*. The practical result is that geological time scales are now considered as being particular cases of stratigraphic successions.

Any two stratigraphic successions can then be mutually correlated one with another by establishing detailed chronological relationships between the *GeologicalUnits* and *GeologicalBoundaries* related to each of them. The developed ontologies have been expressed as UML schemas and also implemented as OWL code.

A practical tool has also been defined for allowing users to describe time successions and to easily correlate and integrate them by means of software applications. Our proposed codification is applicable to any time scale or stratigraphic succession and more generally to any TM_OrdinalReferenceSystem (TORS). Within a given time scale, the codes attributed to each time unit (U_code) and to each time boundary (B_code) bear in themselves all the age information related to these entities. *GeochronologicalObjects* are described in accordance with the model proposed in the two ontologies that we have defined. By means of simple computation rules operated on code numbers, any *GeochronologicalObject* can be easily retrieved (even when it eventually bears different names) and its age can be easily compared with that of any other *GeochronologicalObject*. In addition, age relationships established by the geologist between two time successions can be expressed as code number relations. These code number relations are used for expressing specific age relationships between *GeochronologicalObjects* respectively belonging to the two successions to be compared and for eventually merging these two successions into one.

The solutions that we propose for describing and formally correlating time scales and stratigraphic successions do not contradict the widely used GeoSciML model but complement it. The cores of the two ontologies that we have defined are in strict adequation with the GeoSciML model and the new concepts that we have introduced are mere generalizations of already existing ones. Our proposed codification itself strictly reflects the existing ontologies available for geological time description and for geological dating, so that it can be used with no major difficulty by most existing systems.

Although we paid no attention to the many geological difficulties that exist for establishing and maintaining usable stratigraphic time scales, the knowledge based tools that have developed present, we think, some interest by allowing geologists to operate easy stratigraphic correlations. Considering this particular issue, we have started studying knowledge based user interfaces that will hopefully help geologists to easily appreciate the practical results of many possibly correlation assumptions and consequently to accommodate in some way the many uncertainties, which affect geological ages.

Considering these various aspects, we hope that our present contribution will be judged acceptable by the geoscience community and useful to many.

Acknowledgments

We wish to thank the many persons, who have been indirectly involved in the work here presented thanks to their participation to joint research projects with the authors (notably the French ANR project e_Wok Hub) or through various informal discussions. We wish to specially thank Mara Abel (UFRGS, Brazil), Jean-François Rainaud (IFP), Beiting Zhu (IFP), Philippe Verney (IFP), Priscille Durville (INRIA), Olivier Corby (INRIA), Sandrine Grataloup (BRGM), Yamine Aït Ameur (ENSMA), Stéphane Jean (ENSMA).

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