BSGF - Earth Sciences Bulletin 2022, 193, 18
© B. Le Bayon *et al.*, Published by EDP Sciences 2022
https://doi.org/10.1051/bsgf/2022017

BSGF
Earth Sciences Bulletin
Available online at:
www.bsgf.fr

The geological-event reference system, a step towards geological data harmonization

Benjamin Le Bayon*, Maxime Padel, Thierry Baudin, Florence Cagnard, Benoit Issautier, Hélène Tissoux, Caroline Prognon, Alexis Plunder, Sandrine Grataloup, Fréderic Lacquement, Aurore Hertout and Juliette Stephan-Perrey

BRGM DGR, BP 36009, 45060 Orléans, France

Received: 9 November 2021 / Accepted: 14 October 2022 / Published online: 14 December 2022

Abstract – The temporal dimension is an inherent component of geology. In this regard, traditional geological maps can represent a few geological events, yet they hardly account for the entire complex rock history whether sedimentary, crystalline or volcanic. Here, using the RGF research program (French Geological Reference platform) we propose a new methodology based on digital technology and the French historical collection of 1:50 000-scale geological maps. This innovative approach consists of describing, organizing and hierarchizing a series of geological events within a reference framework and linking it to GIS map geometries (polygons, faults, points). In this way, the complete history of geological features can be compiled and stored in digital maps, combining distinct geological events and properties. For a single event, all associated transformations can be represented on maps, facilitating the production of real "palaeo-geological" maps that consider not only traditional sedimentary environments but also possible synchronous weathering, metamorphism, and volcanism. We discuss here an example of French orogenic history. The approach demonstrated here on geological maps can be used with other geological data media (boreholes, seismic reflection profiles, etc.) and thus facilitate a 3D-to-4D scale, with a significant ability to address not only academic community needs, but also themes or issues related to applications required by politics, civil engineering, and society itself, to confront challenges such as natural and anthropic risk reduction and subsurface uses.

Keywords: geological history / geological event / reference system / digital geology / geological database / geological maps

Résumé – Le référentiel des événements géologiques, une étape vers l'harmonisation des données géologiques. La dimension temporelle est une composante intrinsèque de la géologie. Les cartes géologiques traditionnelles peuvent représenter quelques événements géologiques, mais elles ne rendent guère compte de toute l'histoire complexe des roches, qu'elles soient sédimentaires, cristallines ou volcaniques. Nous proposons ici, au sein du programme de recherche RGF (Référentiel géologique de France), une nouvelle méthodologie basée sur les technologies numériques en s'appuyant sur les cartes géologiques à l'échelle 50 000. Cette approche innovante consiste à décrire, organiser et hiérarchiser une série d'événements géologiques dans un référentiel et à les relier à des géométries cartographiques SIG (polygones, polylignes, points). De cette façon, l'histoire complète des roches peut être compilée et stockée sur des cartes numériques, combinant des événements et des propriétés géologiques distincts. Pour un même épisode géodynamique, toutes les transformations associées peuvent être représentées sur la carte, facilitant la production de véritables cartes « paléo-géologiques » qui prennent en compte non seulement les environnements sédimentaires traditionnels mais aussi d'éventuelles altérations synchrones, métamorphisme, volcanisme, etc. Nous présentons ici comme exemple l'histoire orogénique de la chaîne des Pyrénées. L'approche démontrée ici sur les cartes géologiques peut être utilisée sur d'autres supports de données géologiques (forages, profils de sismique réflexion, etc.) afin de restituer une donnée cohérente en profondeur utile pour la réalisation de modèles 3D à 4D. Ce nouveau concept de cartographie géologique numérique est appelé « carte géologique évènementielle » et les cartes produites constituent l'un

---

*Correspondence: `b.lebayon@brgm.fr`

des produits innovants du RGF. Cette approche permettra de mettre à disposition à tous les acteurs de la société, une donnée fiable et pertinente sur l'ensemble du territoire, destinée non seulement aux besoins de la communauté académique, mais aussi des thématiques ou problématiques liées aux applications pour faire face à des enjeux tels que la réduction des risques naturels et anthropiques et les usages du sous-sol.

Mots clés : histoire géologique / événement géologique / référentiels / géologie numérique / base de données / carte géologique

1 Introduction

Geological maps appeared simultaneously with the birth of geology (Harrell and Brown, 1992; Ireland, 1943; Ellenberger, 1982; Oldroyd, 2013). One might say that the geological map is the very language of this science. In 1868, Napoleon III signed the decree establishing the French Geological Map Service, headed by Léonce Elie de Beaumont which is undertaking to launch, in the middle of the 19th century, the French geological mapping program (Ellenberger, 1982; Ellenberger, 1983; Medioni, 2002; Savaton, 2007). This program always accompanied geological research, because the two are closely intertwined. In fact, during geological map production, numerous geological data (geochemical, geochronological, petrological, geophysical, etc.) were acquired and published in associated explanatory notes and scientific articles. However, by the end of 1980's, geological research and geologic mapping took different paths (Medioni, 2002), with research becoming more numerical and experimental involving studies of geological processes while mapping continued to seek to describe and quantify specific geologic features based on important field acquisitions. Beginning at this time, additional advances in geological knowledge could not be fully integrated into geological maps. However, as in any other scientific discipline, geology has undergone several paradigm changes that have been analyzed in publications for the purpose of proposing new geological models based on recent field acquisitions and analytical data interpretations. This scientific innovation and its new concepts should have been integrated into geological maps because they are by their nature a summary document that is intended to be the referential basis of national geological knowledge. The common goal of most field research can be summarized as knowledge of geologic events, an event being defined here as a specific process that occurred at a given time and space. Because today's geological maps are digital and connected to databases, it is now possible to introduce the event concept into the information system. The aim of this work is to introduce a new methodology to produce new standard geological documents (maps, boring logs, etc.) based on the geological-event approach.

The present observable state of a rock results from the addition of successive incremental changes acquired during a long and complex history, from their genesis. Representation of these rocks features, and their descriptions in a modern database is still a major challenge. We can assume that a present-day rock is a result of all the transformation events it has undergone since its genesis. These events leave detectable marks in a rock. Thus, the first distinguishable event in a rock's history is its genesis. Rare synthetic maps, as for example the French geological map at 1.000 000 scale (Chantraine *et al.*, 2003) attempts to represent information on both actual state and on protolith of some geological units.

However, traditional geological documents (such as maps, boring logs, cross-sections) usually represent a particular state of the various rock units by showing only few noteworthy events such as a metamorphic or weathering phase. Indeed, documents cannot account for all the numerous geological events that affect rocks during their complex geological history. Such documents generally emphasize the representation of notable events at the expense of all other events. As a result, rock units are primarily represented by their genetic events (nature of the protolith); weathering and metamorphic events are generally underrepresented unless they have completely transformed the rock. For example, (i) most marbles are still often mapped as limestones (as in the geologic maps of the internal Alps), (ii) weathering is often poorly represented, and (iii) metamorphic grades are unsystematically represented (peak metamorphism *versus* retrograde history).

Finally, on geological maps, major but discretely recorded geological events are not represented and those illustrated rely only on the geologist's purposes and perceptions. Nevertheless, it is important to remember that the entire description of a rock's complex geological history can be provided in the map's explanatory note.

This geological-event approach has already been conceptualized in a few data models (*e.g.* GeoSciML[1]). GeoSciML (Sen and Duffy, 2005; Simons *et al.*, 2006; Schiegl *et al.*, 2008) is a model that uses geological features commonly described on geological maps, cross-sections, reports, and databases. It specifies a set of feature-types and supporting structures for information used in the solid-earth geosciences. In the GeoSciML approach, a geologic feature may have a geological history made up of successive geological events (Schiegl *et al.*, 2008; Schuster, 2015; Mantovani *et al.*, 2020). A geological event is described as an identifiable event where one or more geological processes act to modify the geological features (structures, geological unit, measures, analyses etc.). In the GeoSciML model, a geologic event may have a specified event age (numeric range, and/or stage/sub-stage names defining an age range from base to top) and may be specified by one or more event processes and event environments. Various feature types or data types are linked to the geologic event (displacement event, metamorphic description, weathering description) making it possible to attach information to each geological event.

The new geological-event approach we present in this paper, following the GeoSciML[1]/INSPIRE[2] guidelines consists in a production guidance for new types of geological documents (maps, cross-sections, boring logs, 3D models, etc.), that may represent the entire geological history through a

---

[1] http://geosciml.org/.

[2] http://inspire.jrc.ec.europa.eu/documents/Data_Specifications/INSPIRE_DataSpecification_GE_v3.0.pdf.

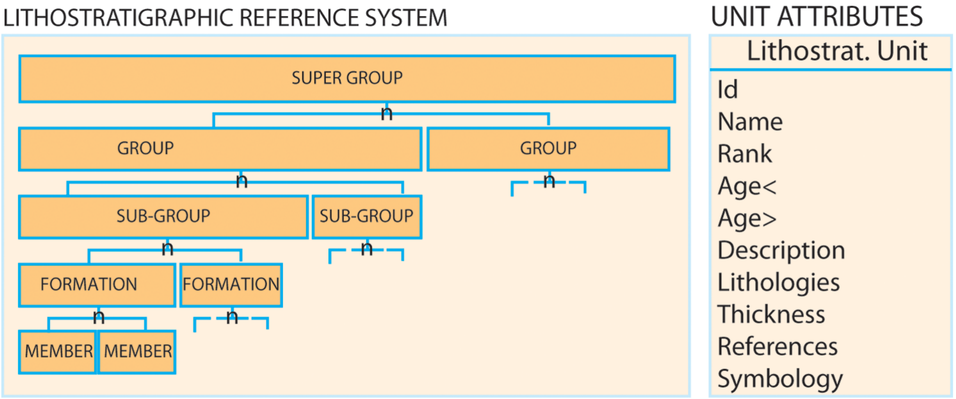

Fig. 1. Overview of the lithostratigraphic reference system architecture and hierarchy, and lithostratigraphic unit attributes.

chronological sequence of geological events. In the present paper, we first describe the geological-event approach, then its central role in linking various geologic information types, and lastly some perspectives this approach may offer for academic and applied geosciences.

2 The “RGF” approach and other geological reference system developments

A primary objective of the Geological Referential of France (RGF) approach is to make available a continuous and coherent layer of geological knowledge for the entire country.

2.1 Lithostratigraphic reference system

A new model of lithostratigraphic reference system was constructed based on existing 1:50 000-scale geological maps and their explanatory notes that have been produced during decades of the French geological mapping program. The first attempt to achieve this type of lithostratigraphic reference system was tested in a RGF demonstration project on the Vosges mountains-Rhine graben area (East of France) (Gabalda *et al.*, 2013), based on two PhD thesis (Skrzypek, 2011; Tabaud, 2012) and this effort was continued and improved on the Pyrenean orogenic belt. It is now expected to extend construction of the lithostratigraphic reference system beyond the Pyrenean geographic area to the entire French metropolitan and overseas territories. The objective of this national lithostratigraphic reference system is to establish a hierarchy (super-group/group/sub-group/formation/member) of all geological units occurring both at the surface and in the subsurface (Fig. 1). The term “lithostratigraphic reference system” as used here also refers to magmatic and metamorphic rocks, as defined by the International Commission on Stratigraphy (ICS) for lithostratigraphic units (Salvador, 1994).

Hierarchization of “lithostratigraphic” units is based on the recognition of major geodynamic cycles that control the basic lithostratigraphic unit grouping. Over time, these hierarchical cycles become more precise and more complete through (i) improved data acquisition as a result of progress in analytical methods, such as geochronological and geochemical data, and (ii) evolution of geological concepts that promote an increased understanding of geodynamic processes and thus a better hierarchization of lithostratigraphic units (for example, recent advances in hyperextended margin concepts). This time-dependent technological and knowledge development may generate disparities in mapping and lithostratigraphic models from one map to another. The hierarchization and harmonization achieved in a lithostratigraphic reference system therefore provides consistency between various geological documents (especially maps and boring logs, but also from literature reviews) that consolidate the models. The lithostratigraphic reference system has benefited from recent updates developed and proposed during the RGF-Pyrénées project and other research projects (*e.g.* Corre *et al.*, 2016; Cochelin *et al.*, 2017; Padel *et al.*, 2018; Angrand *et al.*, 2018; Lemirre *et al.*, 2019; Saspiturry *et al.*, 2019).

Finally, the Pyrenean orogenic belt lithostratigraphic reference system is presented as a hierarchical set of more than 3000 lithostratigraphic units. Each lithostratigraphic unit is defined by unique attributes: a numeric ID, a name, a rank type (member, formation, sub-group, group and super-group), an age range (with a minimum and a maximum age), a generic description, lithologic information, thickness range, references, and a “symbology” (corresponding to a colour used to represent the associated geometries on a document) (Fig. 1).

To characterize Pyrenean lithostratigraphic units, and more particularly the age range of each unit, we produced a modifiable chronostratigraphic chart currently based on existing charts (Gradstein *et al.*, 2020 and references therein), in which we included a new Quaternary chronostratigraphic chart (modified after Tissoux *et al.*, 2020). This chronostratigraphic chart, which contains both international stages and their corresponding regional (French and or European) names, will be used as a chronostratigraphic reference system in the RGF program.

2.2 Structural reference system

A new structural reference system was also created for the Pyrenean belt. The structure of this reference system was developed in line with other similar European initiatives (Hintersberger *et al.*, 2017; Mantovani *et al.*, 2020). This system contains information on geological structures such as

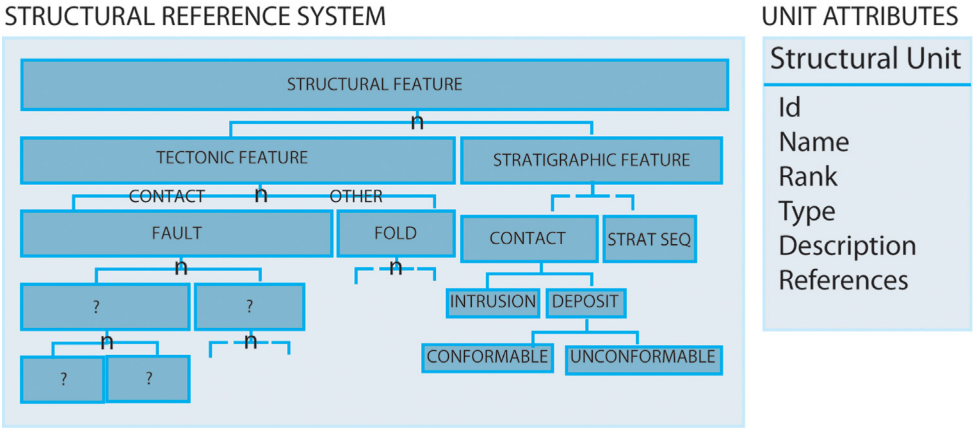

Fig. 2. Overview of the structural reference system architecture, and structural unit attributes.

faults, shear zones, and folds. This structural reference system was built by compilation of information from existing 50 000-scale geological maps, their explanatory notes, and the extensive literature. Hence, each structural feature is defined by multiple attributes (based on CGI vocabularies[3] and BRGM registers[4]) including: a numeric ID, name, rank, type, orientation, dip, fault movement type, deformation style, age, description, references, and a link towards the geological-event reference system (Fig. 2) to attach at least one geological event to each structure. This structural reference system makes it possible to compile and organize information that may be represented by polyline features on maps.

2.3 Geological observations database

In addition to the lithostratigraphic and structural reference systems, a database (called Geofield application) was developed to capitalize all geological observations (observation points) acquired during field campaigns. These field data are categorized as distinct information types to supply various building blocks of the database. The in-house Geofield application makes it possible to manage data from field observations (lithological description) and measurements (structural description), rock sampling, and even a link towards the laboratory analyses (Fig. 3). Each geological description is using the list of terms from the BRGM registers that are standardized and common to different BRGM applications and designed to be compatible with European and international standards (GeoSciML and INSPIRE standards). Most of the terms employed by the Geofield database are compliant with CGI vocabularies registers. Some additional French terms also occur in the BRGM registers but an equivalent term in CGI vocabularies has been identified for each of these French terms.

Each observation point can be associated with one or multiple analytical databases (Fig. 4) of various types (geochronological, geochemical, thermochronological, etc.).

2.4 From data to geological models and geological knowledge

Geologists can reconstruct geological history by identifying successive events that made the rocks what they are today. These events are in fact recognized through specific observations and analytical data. For instance, a given tectono-metamorphic event can be identified and characterized by a specific cleavage marked by its own paragenesis, folding, and its particular age. The main challenge remains to establish the links between all the data sources that define a same event. Different data may be linked by (a) identification of geological events responsible for the characteristics of a geological feature, and (b) establishment of a hierarchized geological event reference frame. This last point is crucial because it makes it possible to produce an infinity of geological models using the same set of factual or interpreted data (Fig. 5).

3 The geological-event approach: concepts and definitions

3.1 Geological history: a chronological sequence of geological events

In its present state, a geological feature is a result of the succession of natural processes that can be discerned from physical and/or chemical evidence observed on a rock (*e.g.* mineral crystallisation, development of geological structures, sedimentary structures, morphological or textural characteristics, etc.). In this way, a geological event is defined as an identifiable event during which one or more geological processes act to modify geological entities (GeoSciML/INSPIRE definition). Thus, the geological history of a geological feature may be described as a sequence of geological events that affected the feature over time (Fig. 6). The events that affect a geological feature are chronologically organized from older to younger, beginning with its genesis. During the “genesis” event (Genesis Event: EG), a geological feature acquires attributes related to the rock formation, such as lithology, chemical composition etc. Various types of “genesis” events are (a) sedimentary deposit, (b) volcano-sedimentary deposit, (c) volcanic deposit, (d) plutonic intrusion, and (e) volcanic intrusion. Within the notion of

---

[3] http://geosciml.org/resource/def/voc/.

[4] https://infoterre.brgm.fr/page/registres-geologiques-brgm.

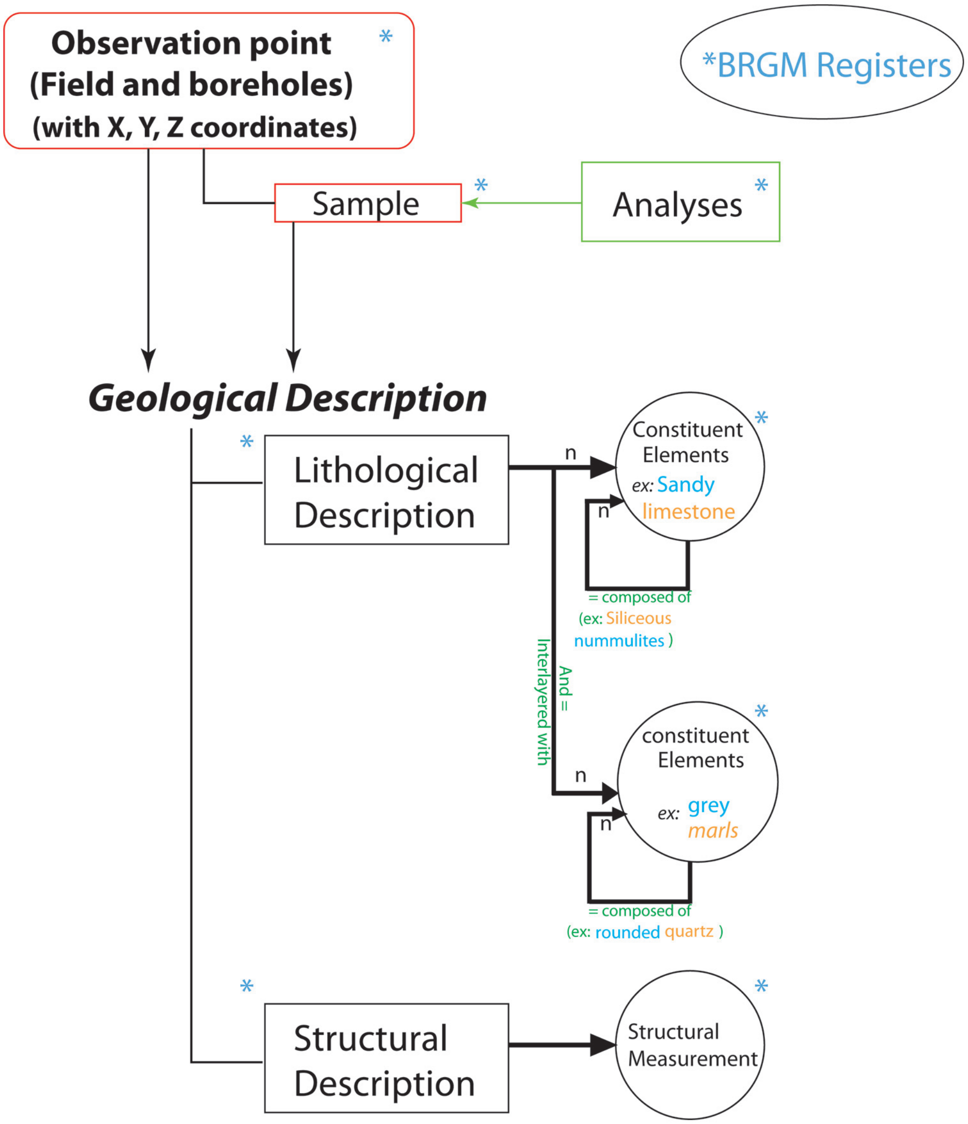

Fig. 3. Diagram showing relationships between observation points and the geological description in the GEOFIELD application. The in-house Geofield application makes it possible to manage data from field observations and measurements, rock sampling, and even laboratory analysis. Each geological feature is described by a list of terms from the BRGM registers that are standardized and common to different BRGM applications, are designed to be compatible with European and international standards (GeoSciML and INSPIRE standards).

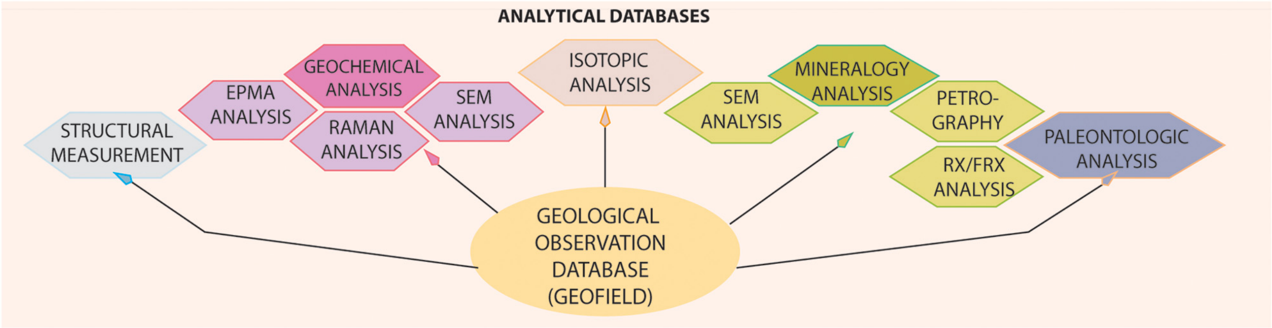

Fig. 4. Schematic relationships between field observations in Geofield and analytical databases.

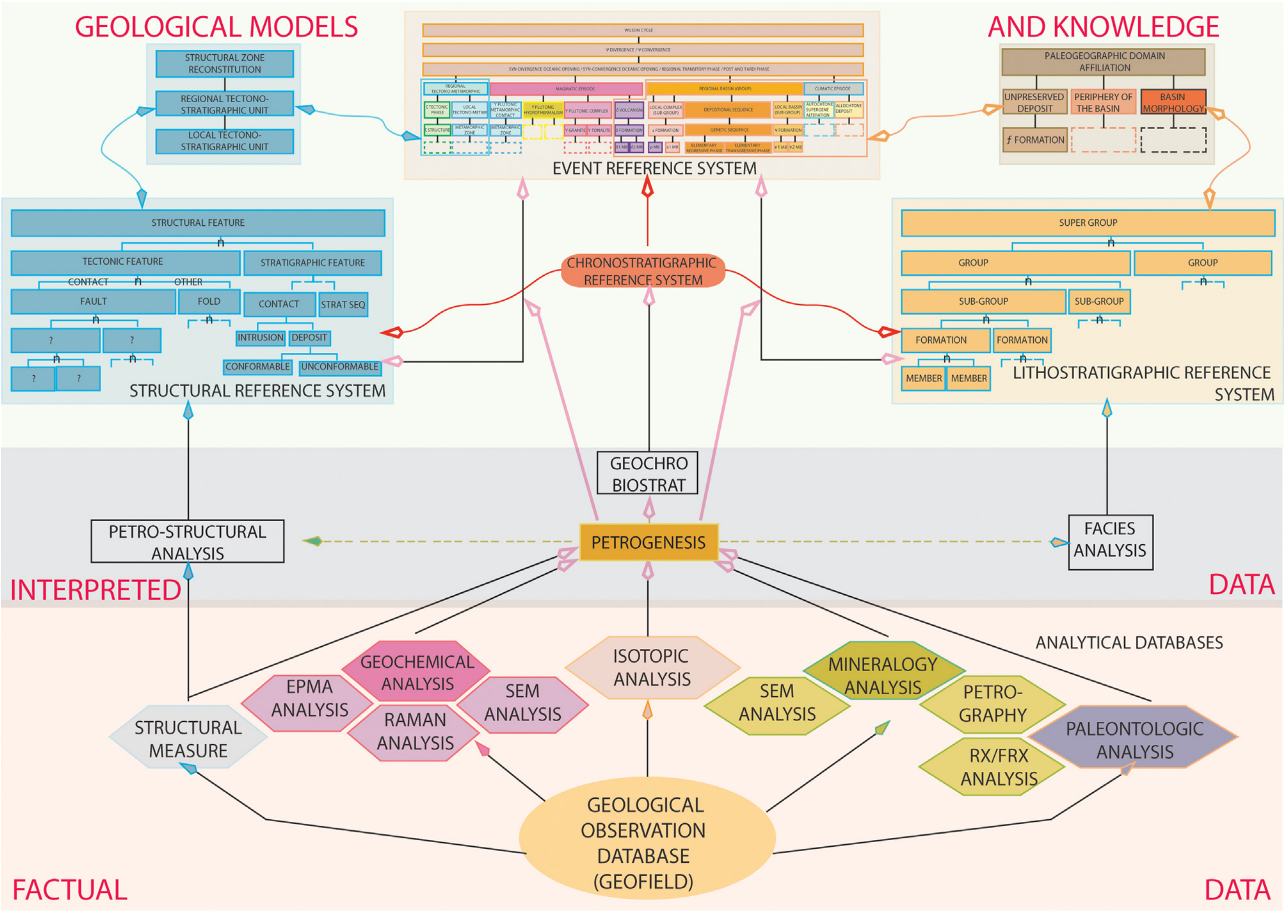

Fig. 5. Schematic relationships between factual and interpreted data and their use in the different reference systems, that are the basis of geological models and knowledge.

genetic event are included processes that immediately follow rock formation, such as solidification of magmatic rocks, or compaction of sedimentary rocks.

Genesis events are generally followed by one or more successive events that affect and modify a geological feature until it achieves its present state. During each transformation event (Transformation Events: ET), the geological feature records changes in mineralogy, texture, aspect, grainsize, etc. Various types of transformation events (ET) are “late” diagenesis (during burial and exhumation, for instance), deformation, metamorphism (contact or regional), metasomatism and weathering (supergene, hydrothermal).

To illustrate this statement, let us consider the example of a geological unit that consists of a clay deposit that was rapidly transformed to a claystone (orange in Fig. 6). This first geological event consists of a “genesis” (EG1) type event, which basically corresponds to the deposition/induration of the sediment. This claystone is then buried and the rock undergoes a tectono-metamorphic event ET1-TM1 (green in Fig. 6). ET1 transforms the claystone into a micaschist as a result of a D1 deformation stage. This is followed by a later geological event characterized by a granitic intrusion (EG2 granite, pink in Fig. 6) into the micaschist associated to a contact metamorphism (ET2). Then, both rocks (micaschist and granite) are involved in a second tectono-metamorphic event (ET3–TM2) that transforms the granite into orthogneiss and deforms (D2) all rocks. The final geological event consists of the progressive exhumation of the rocks (Fig. 6).

3.2 The geological event as a link between geological data

The geological-event approach thus makes it possible to link different types of geological data pertaining to different time and space scales and residing in various databases, for one or more event(s). Geoscientists collect geological information in various ways, in particular in the field (*i.e.* from outcrops) or from cores or well cuttings from boreholes. Using the geological-event approach, different types of data from various observation formats can be linked to the discrete geological events that they define. For example, multiple measurements from a single outcrop can be linked to various deformational stages. Complex mineral assemblages (such as metamorphic parageneses) can be linked to distinct metamorphic geological events observed in a single thin section. Multiple ages within a single mineral may be related to different geological events (Fig. 7). Even if different types of raw data are scattered among separate databases, the geological-event units can be used to create links between

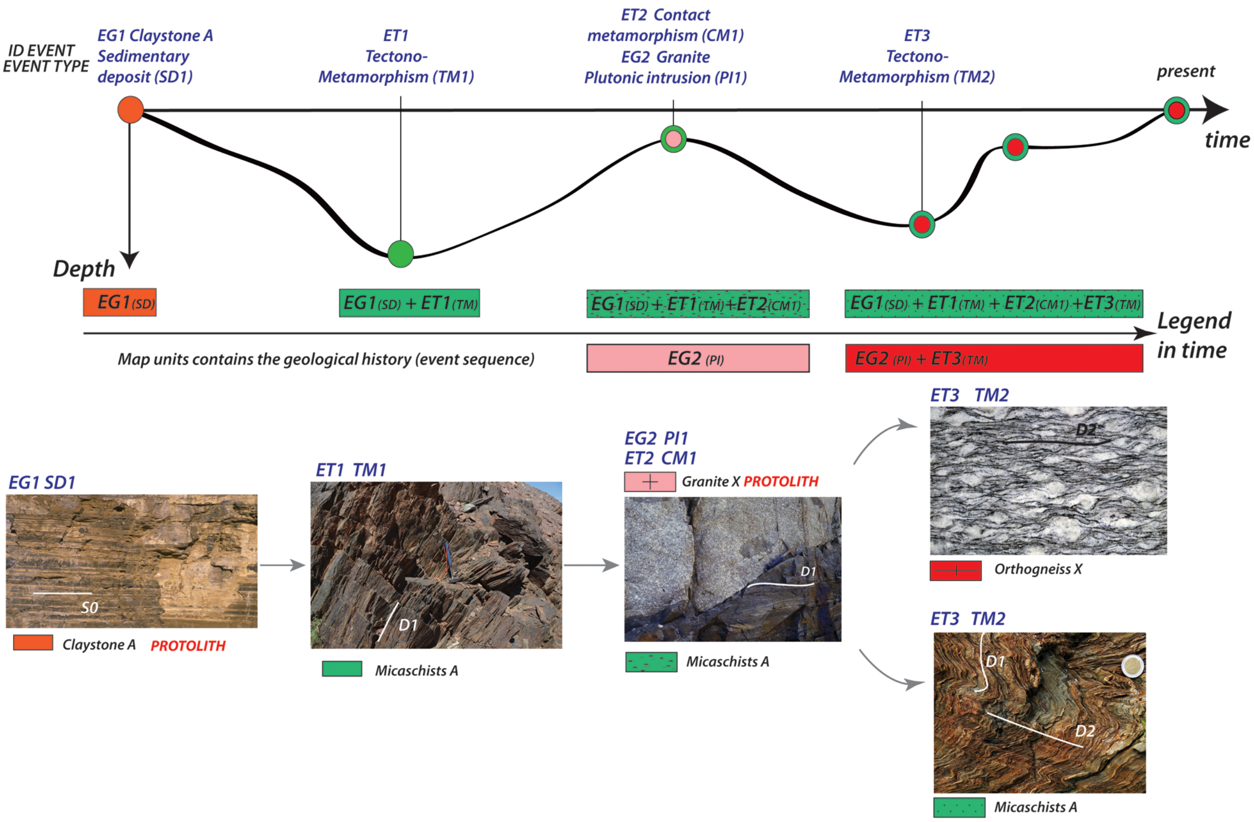

Fig. 6. Geological units are characterized by a complex history due to the overlay of geological events through times. The new geological-event approach links geological events and geological units. For example, the claystone A (in orange), the micaschist A (in green) and the micaschist A (in green and dotted) have the same genesis event EG (EG1) as the sedimentary deposit of claystone A.

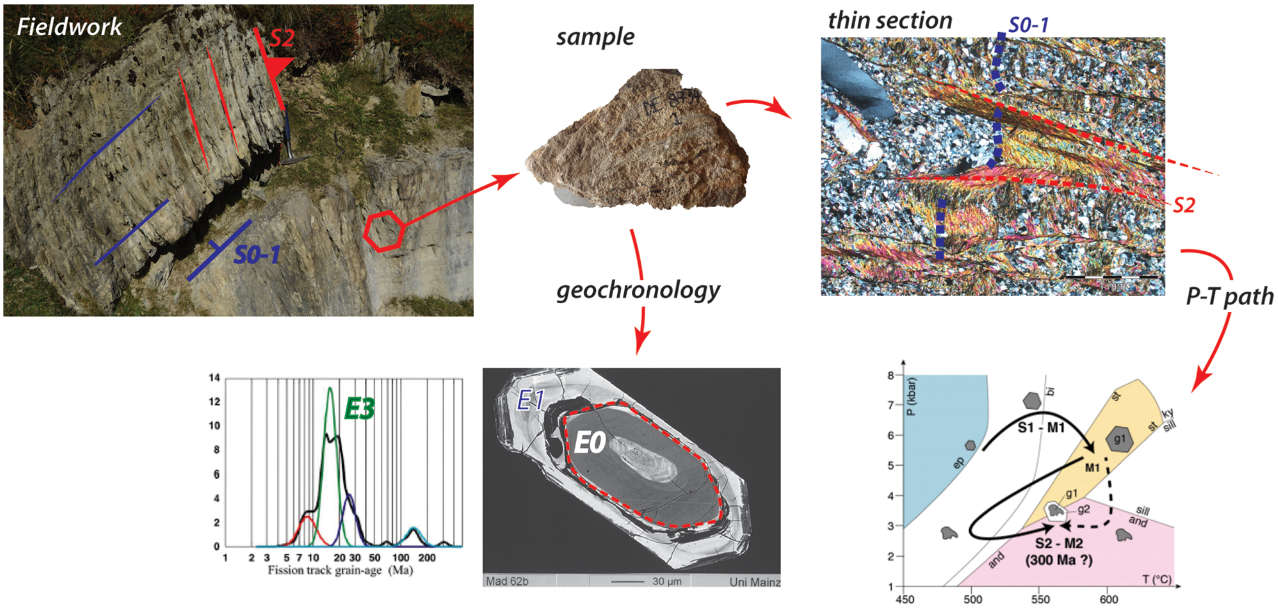

Fig. 7. The geological-event approach makes it possible to link different data associated to the same geological event. Structural measurements recorded in the field can be linked to laboratory analyses (for example, with mineral assemblages characterized by a petrological study, with P–T estimate obtained by a thermobarometric study, and with an age (multi-method geochronological study).

all the data. Figure 7 illustrates a relationship between an assortments of geological data (structural measurements from an outcrop, similar geological structures observed in thin section, associated PTt metamorphic evolution derived from a petrologic rock study) as a result of one or several geological events.

For the RGF project, an innovative database (Geofield, BRGM, see Sect. 2.3) was developed to use data acquired in the field together with a new geochronological database used to store geochronological ages obtained by various methods from multiple minerals. Other databases are currently under construction, (such as a metamorphic database with P–T estimates and facies, a sedimentary database with various depositional environments, a geochemical database, a regolith database for alteration processes, etc.). The links among data from different databases will be made using the event units collected in the geological-event reference system.

The primary challenge now resides in the integration of these events, which are intrinsically interpretative, into geological maps. Because of their print format, paper geological maps necessarily reduced the scope of the information. In fact, a geological formation can be represented by only one colour to show, express the primary lithology and age, sometimes enriched by different hachures, to indicate important events such as metamorphism or weathering. But, since the advent of the digital revolution and particularly GIS, opportunities to integrate new data into geological maps have been multiplied. Geological maps of most countries are today readable through GIS and are sometimes connected to multiple databases, making it possible to consult structural measurement points or analytical data such as chronological ages, geochemical analysis, or P–T estimates. But for the most part, the databases remain isolated and do not provide the event interpretations that they support.

The geological-event, linking all database elements, can now be assigned independently to each geometric features of a geological map (polygon, group of polygons, line or group of lines). These events can also be shown as dots to link them to structural measurements or other analytical data.

4 The hierarchized geological-event reference system

The geological-event reference system, like the lithostratigraphic reference system for lithostratigraphic units, consists of a hierarchical list of identified geological events in a geological area (Fig. 8). In this reference system, each geological event is characterized by a unique identifier, a unique name, an event type, an event process-type, an age range (with minimum and maximum ages), and a hierarchical rank. The identifier consists of a unique numeric ID. The name is free text chosen by the geologist to be validated later by a specialist committee. The age range is bracketed between a minimum (oldest) and a maximum (youngest) age, corresponding to chronostratigraphic ages from the chronological reference system. The age can be either a stage/substage text-name or a numerical age if geochronological data are available to characterize the extent of the geological event.

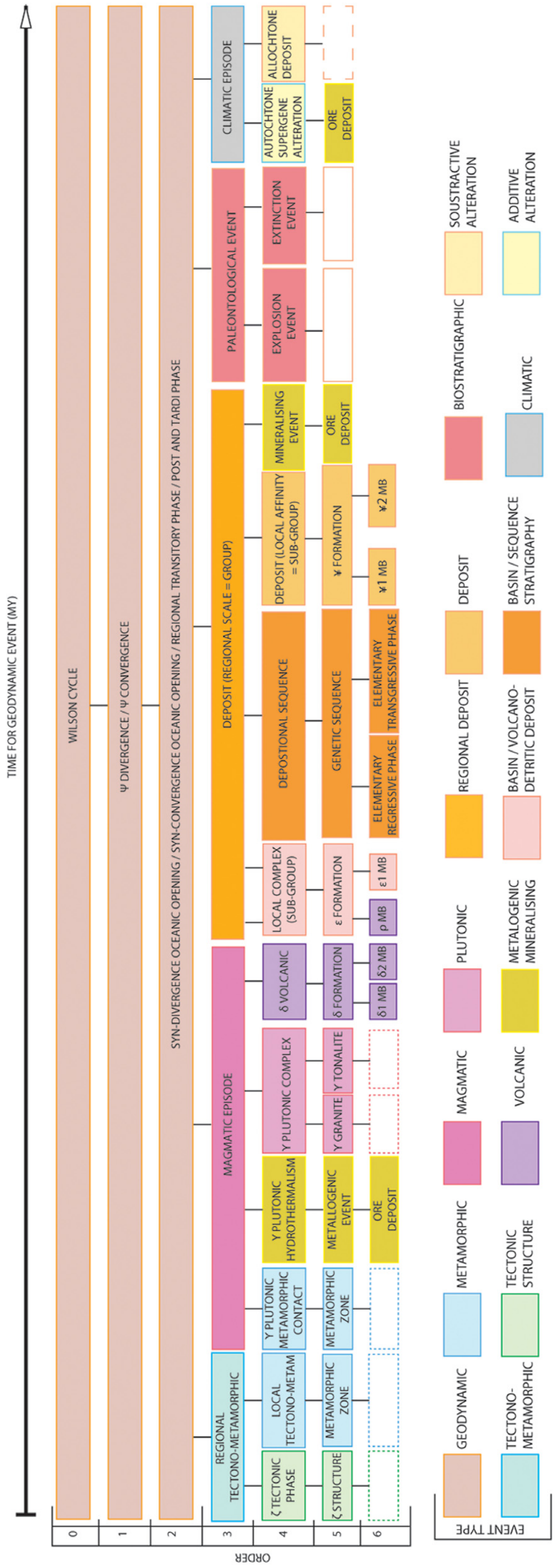

Fig. 8. Overview of the theoretical hierarchical geological-event reference system. The organisation of geological events within the hierarchical geological-event reference system can be represented as a hierarchical tree with various types (different colors) of events for each ranks.

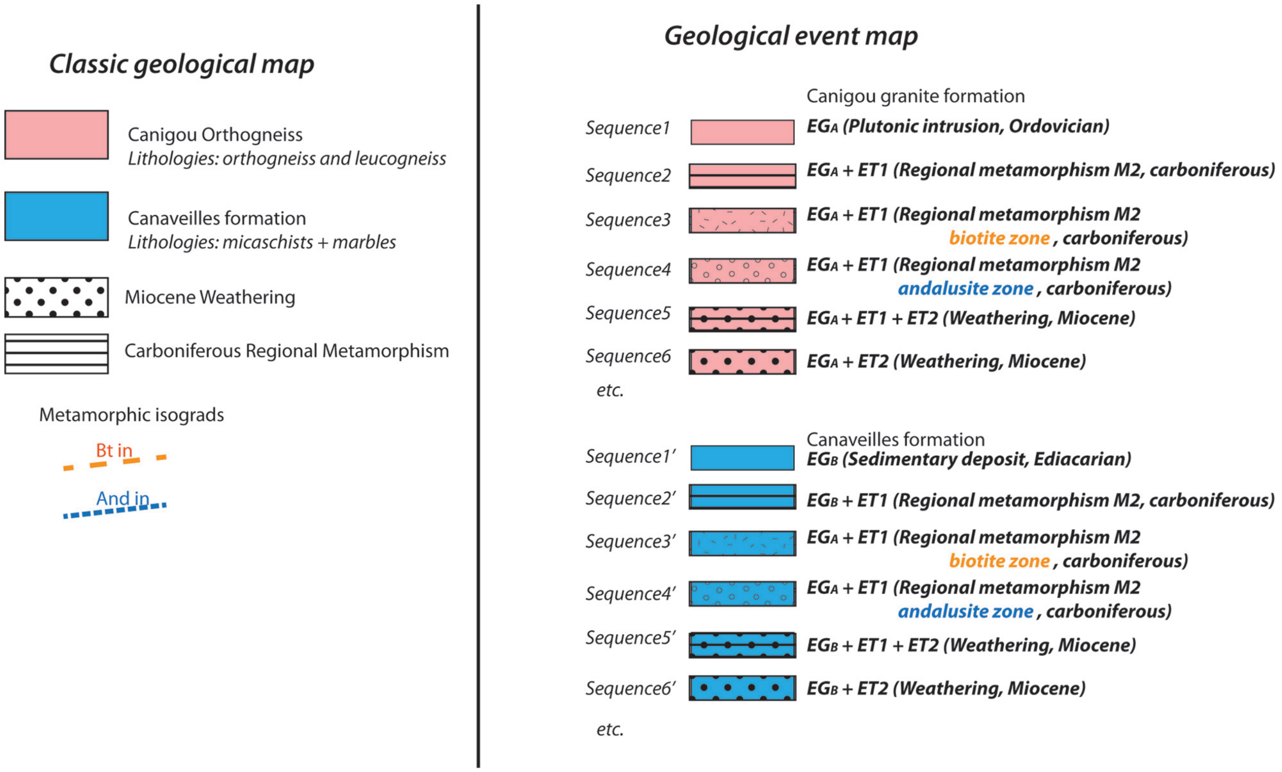

Fig. 9. Example of a geological map legend for a traditional geological map and for a corresponding geological-event map. The genetic events corresponding to (i) the Ordovician plutonic intrusion of the Canigou formation, or (ii) the Ediacarian sedimentary deposit for Canaveilles formation, are respectively common to all polygons that present different event sequences.

Six to seven orders (hierarchic event levels) are used to classify all geological events (Fig. 8). The first rank (rank 0) corresponds to Wilson cycles (*i.e.* Pan-African cycle, Variscan cycle, Alpine Cycle). The duration of these events is ca. 200–600 Ma. Rank 1 corresponds to geodynamical events associated with large-scale divergent or convergent phases within a Wilson cycle (*i.e.* Alpine divergence, Alpine convergence...). These events typically have a duration of about one hundred million years. Rank 2 refers to geodynamical events corresponding to various phases of a large-scale geodynamical event (*i.e.* Variscan orogenic phase, Variscan late-orogenic phase...) with a duration of ca. 50 Ma. Rank 3 events are related to major sedimentary (sedimentary basin filling), magmatic (volcanic, plutonic), tectono-metamorphic, climatic, and weathering episodes (*i.e.* Late-Variscan magmatism, North Pyrenean Metamorphism, North Pyrenean Rift-basins...). Ranks 4, 5, and 6 are assigned to “small-scale” geological events that describe geological features represented on a geological map (*i.e.* rank 4: intrusion of Querigut plutonic complex which contains several rank 5 geological events: intrusion of Querigut granite, intrusion of Querigut granodiorite...). The duration of these lower-order events (ranks 3 to 6) is less than 50 Ma.

The organisation of geological events within the hierarchical geological-event reference system can be represented as a hierarchical tree (Fig. 8), with various types of events for each ranks.

5 From the geological-event reference system to geological representations

5.1 Geological-event maps

The various geometries on geological maps and subsurface data that represent geological features are polygons and polylines. Points indicate structural measurements or analytic data. On a geological-event map, polygons do not only represent lithostratigraphic units, but also include all events associated with geological units. This means that each polygon that belongs to the same lithostratigraphic unit may contain different event sequences (Fig. 9). The primary event, the genetic event, remains common to all polygons that represent the lithostratigraphic unit (Fig. 9).

Even so, different lithostratigraphic units can also undergo the same (or several) event(s). An event is then identified on the geological map as common to all geological units and polygons that were affected by it. This might suggest that an event map differs from a traditional geological map but in fact the event map, by default, maintains the original appearance of the geological map. For example, if the same geological formation is mapped in two lithostratigraphic units because one was metamorphosed, then both units will appear on the event map. But it will then be possible to select the genetic event to highlight only a single original formation. A similar approach can be used with geological map polylines to represent either original contacts between lithostratigraphic units or tectonic contacts.

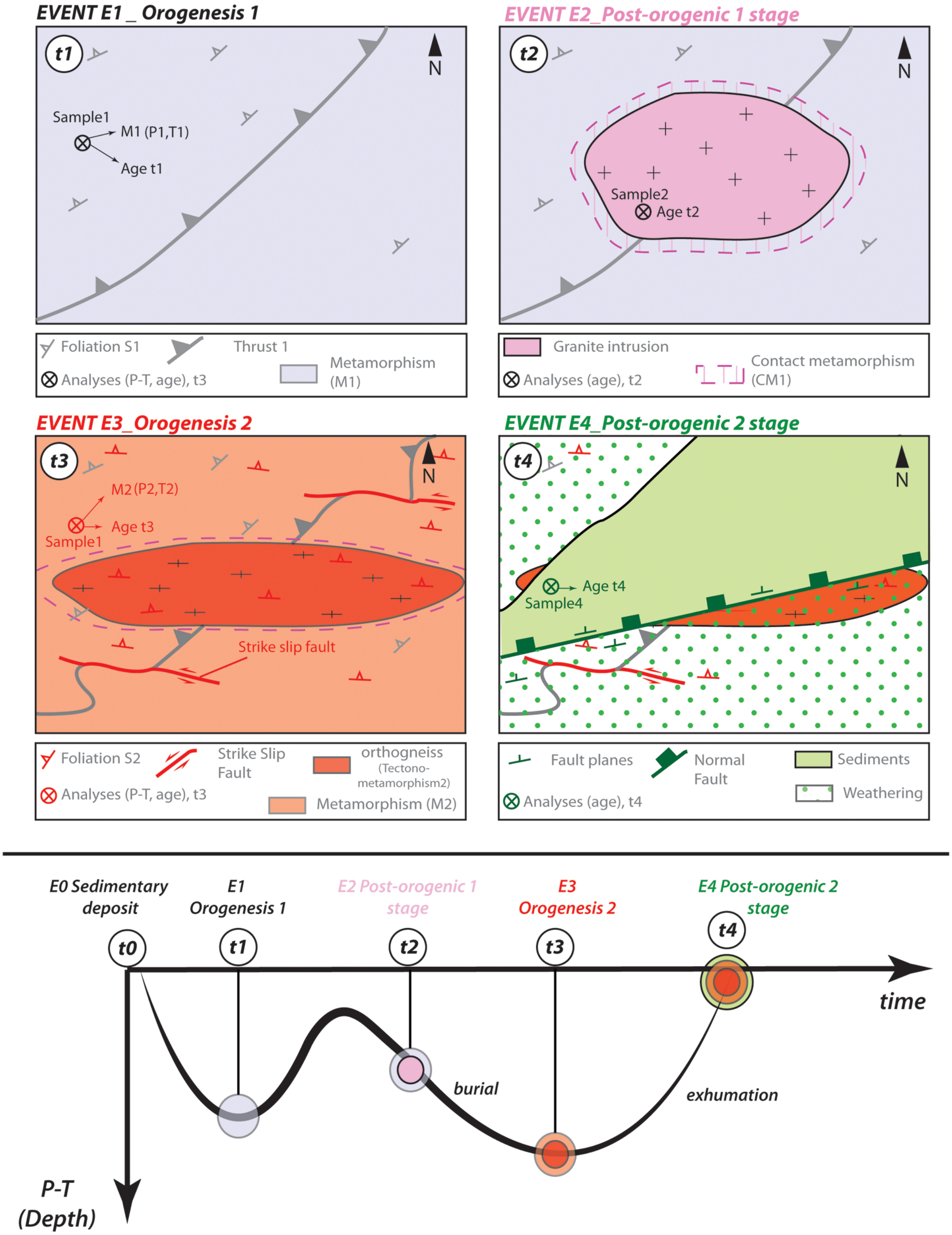

Fig. 10. Schematic successive geological-event maps corresponding to different geological stages. Polygons (geological units), polylines (faults, fold axes, metamorphic isograds, etc.) and points (measurements, analyses, etc.) are linked to different geological events capitalized in the geological-event reference system. All types of mapped features can be linked to a same geological event. This new method makes it possible to provide different digital maps through time.

This methodology is illustrated on Figure 10, which shows a schematic succession of geological events. Event E1 corresponds to an initial orogenesis marked by a tectono-metamorphic event (TM1) associated with development of foliation designated S1, a regional metamorphic stage M1 characterized by pressure (P1), temperature (T1) and age (t1), contemporaneous with the development of a thrust fault (Thrust 1). The E2 event is a post-orogenic stage characterized by a granitic intrusion (pink polygon), with a protolith age for this granite (t2) and coeval development of a contact metamorphic aureole (CM1). Event E3 is a second orogenic phase marked by a tectono-metamorphic event (TM2) associated with the development of foliation S2, a regional metamorphic stage M2 characterized by pressure (P2), temperature (T2) and age (t3), contemporaneous with the development of strike-slip faults. The final event, E4, is a post-orogenic stage with development of normal faults contemporaneous with sedimentary deposits (green on the map) and basement weathering (dotted area on the map).

5.2 Cartographic applications

Geological-event maps obviously have a broad scope of application. Each event can appear on the map independently of lithostratigraphic units. For example, it is possible to display both the intrusion event of a given granitic pluton and its contact metamorphism on the geological-event map. Geochemical and geochronological analyses of the granite are linked to the intrusive event and so mineral paragenesis is associated with the contact metamorphism event. Using the hierarchical level of the event reference system, all related intrusions in an area can be highlighted on the geological map. Regional metamorphism or alteration events (or any event type) are selectable in the same way.

The higher level of the hierarchical referential lexicon relates to geodynamic concepts. This higher level makes it possible to group different event types that integrate global processes. For instance, selection of a "subduction event" on the map can display high-pressure metamorphic rocks, magmatic bodies, tectonic contacts, in addition to frontal trough sediments. Subduction and collision events can then be grouped at the higher level of "convergence event".

Hence, a geological-event map provides the location of various event types at the present-day surface and also through time.

5.3 Generalisation of the event concepts to sequence stratigraphy

With the event approach, the concept of genesis-type event is particularly well suited to sedimentary deposits because it makes it possible to integrate sequence stratigraphy concepts.

Sequence stratigraphy is based on facies description, analysis, depositional environment determination, and correlation of sections through the recognition of key surfaces, to define, identify a synchronous event within the sedimentary basin infill (Salvador, 1994; Catuneanu *et al.*, 2011).

Sequence-stratigraphy principles make it possible to correlate genetic sequences with radically different facies, based on the recognition of isochronous surfaces. This process involves grouping facies deposited synchronously within a single unit that represents a depositional sequence, for example a transgressive phase within a single bounded sequence, well represented by continental deposits (Fig. 11B). Isochronous lines are generally used in borehole interpretation but there is no fundamental difference between geological maps and interpretive sections of drill holes or a seismic sections. A particular section of a boring log can thus be attributed to a lithostratigraphic unit in the same way as a map polygon is (Fig. 11A). Therefore, the drill-hole section can also include event information in terms of sequence stratigraphy (ID temporal notions of regression/transgression) (Fig. 11B). The same goes for the sequence limits corresponding to these isochronous lines. These surfaces are, for example, maximum flooding surfaces (MFS), maximum regressive surfaces (MRS) and erosive surface (ES) or sequence boundaries (SB). The MFS is the most landward shoreline migration denoting a transgression episode (facies retrogradation); the MRS is the most seaward shoreline migration, which denotes a regression episode (facies progradation). The SB marks a sudden acceleration of progradation as indicated by the superimposition of significantly different facies separated by a time gap. An extreme example would be continental deposits overlapping on basin deposits.

The lithostratigraphic and geological-event reference systems used for encoding boring logs or seismic cross-sections are obviously similar to those used on geological maps (Fig. 11D). In this perspective, Figure 11 illustrates how it is possible to come from a classical lithostratigraphical map (Fig. 11A, B) to an event and depositional sequence map (Fig. 11B). Based on information acquired on the field or from a borehole, the sequence stratigraphic interpretation allows to interpolate the key surfaces (MFS, ES) and draw the regressive and transgressive phases between these different key time lines directly on the map (Fig. 11A, B). This approach is of course only possible in relatively well-preserved areas, where sedimentary basins (*e.g.* intracratonic or foreland basins) would be little or not affected by later tectono-metamorphic events.

Section D of the Figure 11 shows how it is possible to identify and hierarchize in the geological event reference system the different geological features used in sequence stratigraphy, whatever it represents key surfaces (MFS or erosive surface) or polygons (transgressive/regressive system tracks) and organize them in each T/R genetic sequences. Finally the geological history resulting from this "Syn-divergence phase 1" (Fig. 11D) represent a sequence of co-genetic events that can be encoded and represented on any geological features.

5.4 Lithotectonic and palaeogeographic domains, derived from the geological-event reference system

Most orogenic belts are commonly subdivided into zones delineated by major tectonic contacts such as thrusts or major strike-slip faults. Similarly, domains are assigned to different palaeogeographies for a given period, as in particular, sedimentary depositional areas in relation to emerged areas. Lithotectonic and palaeographic domains evolve in time and

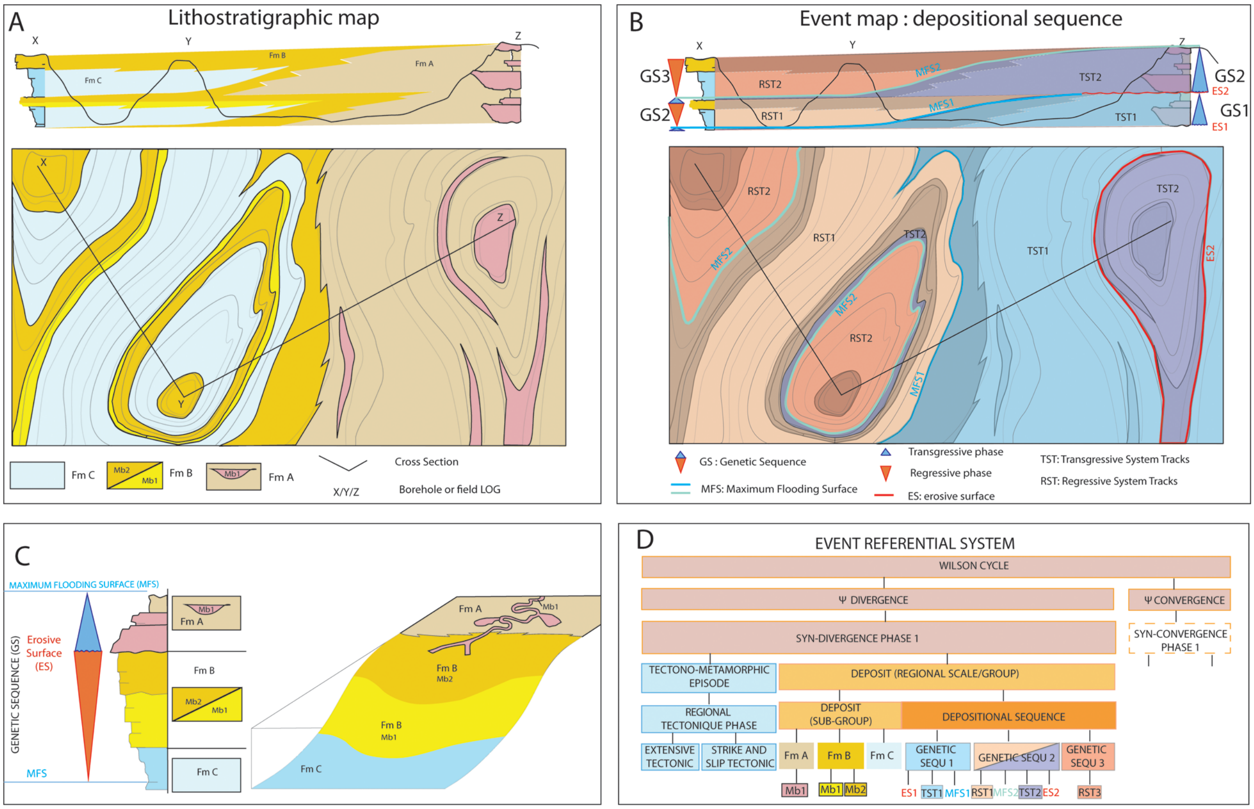

Fig. 11. Schematic illustration for the application of the geological event concept for lithostratigraphy and sequenciel stratigraphy. (A) schematic geologic (lithostratigraphic) map, with cross-section (X/Y/Z) and schematic log from points X and Z, with three principal Formation (Fm A, Fm C, Fm B) and their respective members. Lithostratigraphic boundaries are represented by facies limits corresponding to a certain deposit environment along a transect as illustrate in (C). (B) the same map and cross-section from (A) are analysed and interpreted in term of depositional sequence to represent the different key surface (MFS/ES or SB) and the regressive and transgressive system tracks. These geological features are characteristic of depositional sequences event linked to the deposit of the different formation represented in (A). These two kind of geological event (deposit of the formations and the genetic sequences which are link to them) are registred in the Event Referential System in (D), allowing to proposed a complete sequence of event associated to different process (tectonic, deposit, etc.), to draw the geological history of the syn-divergence phase 1.

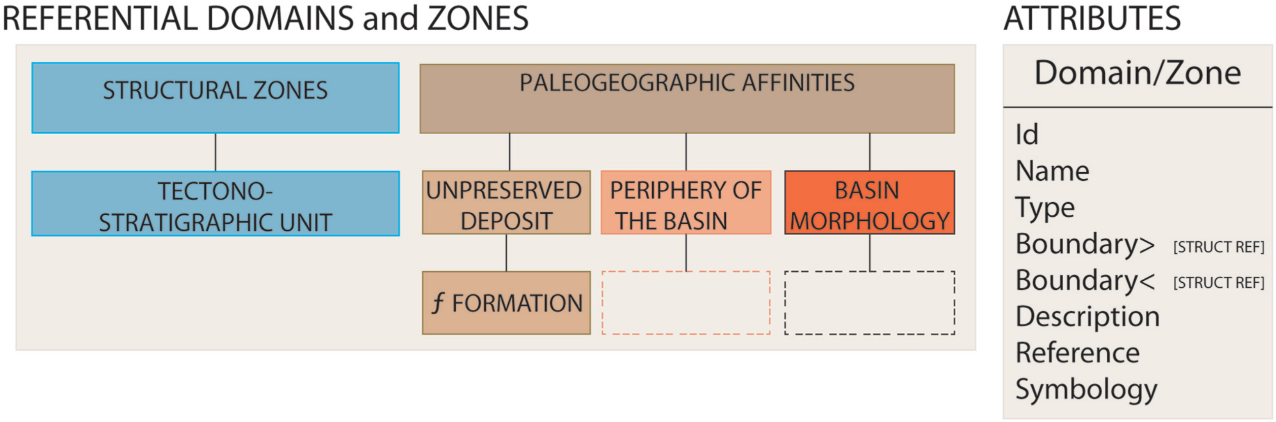

Fig. 12. Overview of the domain/zone reference system architecture, and attributes of the domaine/zone units.

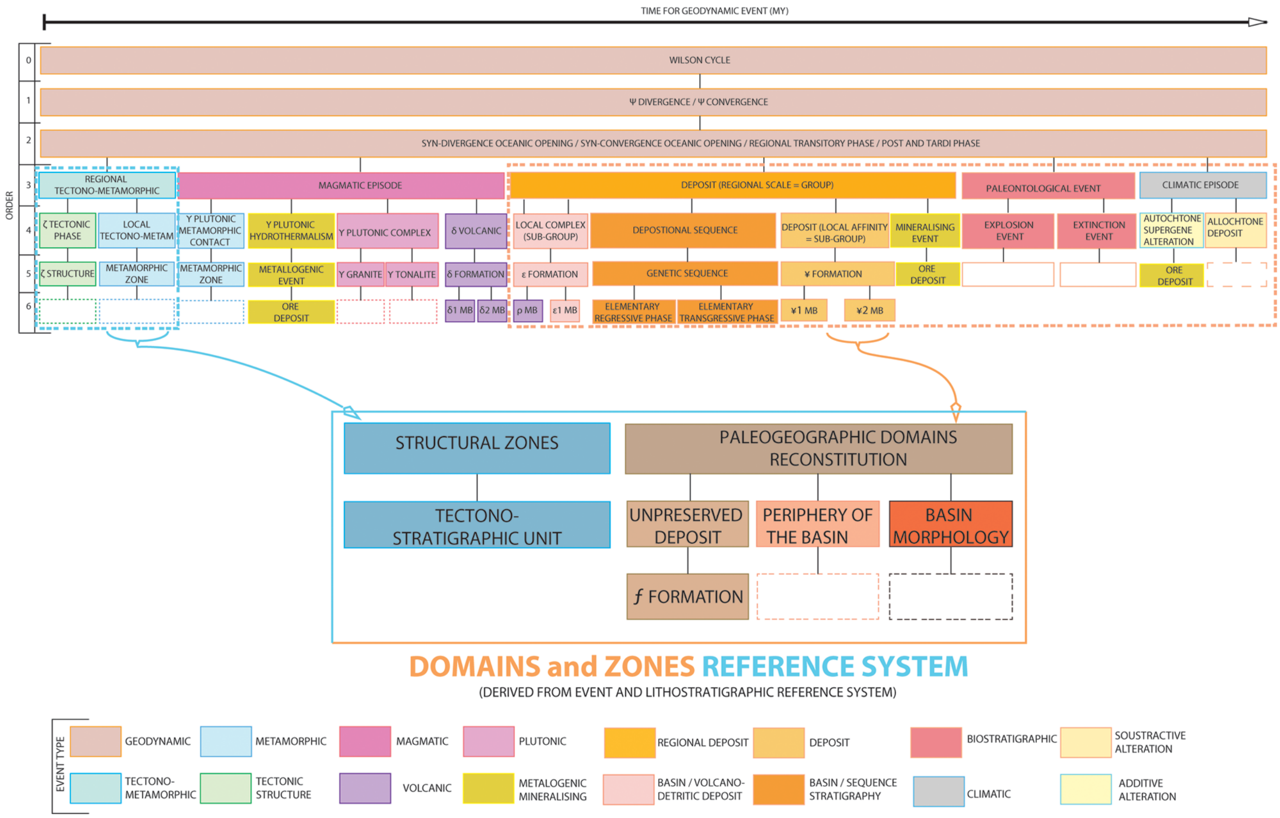

Fig. 13. The domain and zone reference system includes both (a) structural zones with hierarchized tectono-stratigraphic units, and (b) palaeogeographic domains. This reference system is derived from the geological-event reference system.

space and are consequently closely linked to the geological-event approach.

The lithotectonic concept and his place into the database architecture has been largely developed and implemented into GeoSciML and in recent publications (*e.g.* Mantovani *et al.*, 2020).

The term "palaeogeographic domain" is used here to specify a domain where rocks belong to a common palaeogeographic environment, with no initial intent to propose a palaeogeographical restoration map. Likewise, a lithotectonic domain refers to a specific zone where rocks exhibit a common structural and metamorphic environment, but where structural zones are not repositioned in their original position.

The "domains and zones" reference system categorizes tectonic units and palaeogeographic units into coherent sets in space and time (Fig. 12). This reference system includes both (a) structural zones with tectono-stratigraphic units, and (b) palaeogeographic domains. Each unit is then defined by a numeric ID, a name, a type, two structural boundaries (from the structural reference system), a description, a reference and a symbology (Fig. 12).

Once the domain/zone mapping is complete, it is then possible to provide more detailed maps by cross-referencing information from geological-event reference system such as event-type (for example, depositional environments or tectono-metamorphism event) characteristic of various geological units (Fig. 12). Each polygon or line belonging to a specific domain/zone can then be displayed with respect to various criteria of interest, such as depositional environments (external or internal platform, pelagic domain...), structural context (necking zone, hyperextended domain, thrust sheet...) or metamorphic/weathering zonation.

For example, a formation in a rift basin is characterized by local event markers such as sedimentary deposits and structures that show extension (normal or detachment faults) and occasional associated metamorphism or hydrothermal alteration. These local events (in space and time) are grouped within a more unified event named "rift basin opening" that may be associated with a palaeogeographic domain reference system (Fig. 13). In this case, the palaeogeographic domain name is directly linked to a regional event. It shows the geographical location of the regional event, which is limited in time. Similarly, "basin periphery" zones characterized by erosion or weathering events can be identified as elevated domains that supply the basins.

Later, this rift domain may evolve into an oceanic margin and therefore belong to a new palaeogeographic domain. The domain may finally be incorporated into a thrust-sheet zone during a final subduction/collision event. All these domain and/or zone changes that affect a geological unit can be illustrated on geological-event maps through the use of the geological-event reference system. Obviously, palaeogeographic domain maps restore the current geometrical shape of geological units that appear on the geological map. In this sense, these maps will not be strictly "palaeogeographic", but will be particularly useful in the reconstruction required to produce real palaeogeographic maps.

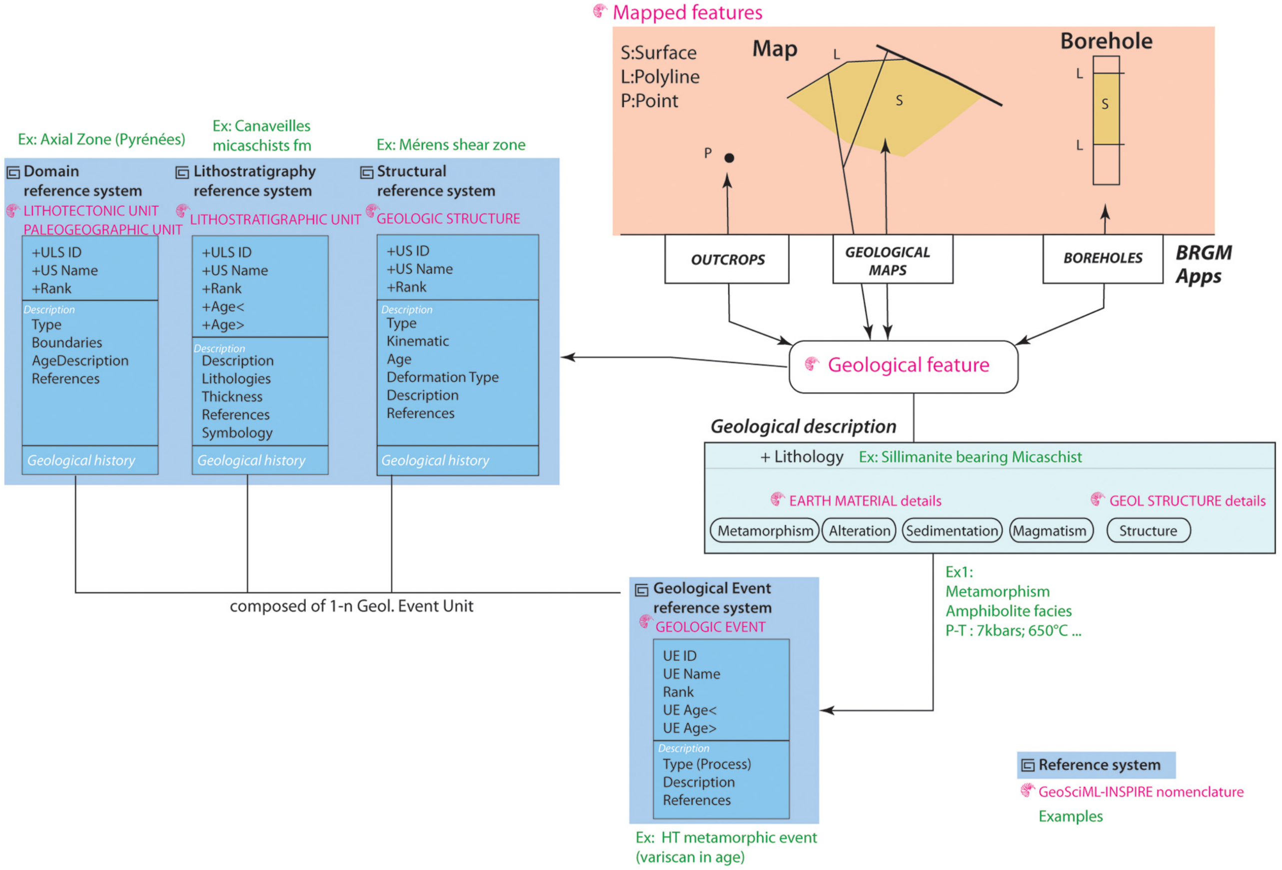

Fig. 14. Overview of the relationships between the reference systems (in blue), geological description of a geological feature, and mapped features. Geometries correspond to different geological features which may be lithotectonic/paleogeographic units (domain reference system) or lithostratigraphic units (lithostratigraphic reference system). A polyline may correspond to a structural unit (structural reference system). The geological events (geological-event reference system) are linked to a geological feature, of which a description of metamorphism/alteration/sedimentation/magmatism/tectonism has to be first realized. In that sense a geological feature can have numerous successive process/environment attributes, that may be linked (or not) to geological events from the reference system.

6 Reference systems relationship and their relation with GeoSciML/INSPIRE data model

The data model of the information system we produced, was expected to be made with respect to INSPIRE and GEoSciML standards. In our model, the geological features are associated to one or several mapped features that may be of different types (points, polygones or polylignes) (Fig. 14). The geological features have a geological description which can be described by different attributes corresponding likely in GeoSciML to EarthMaterialdetails (like RockMaterialDescription, MetamorphicDescription, AlterationDescription, etc.) and part of Geologic Structure details (like FoliationDescription, LineationDescription, FoldDescription, etc.) (Fig. 14). Several BRGM applications have been developed to capitalize geological data acquired on the field, or on a borehole, and related analytical data. Associated cartographic plugins on GIS are still under development in order to link attributes coming from different databases and reference systems to mapped features (polylines, surface and points). The geological-event reference system is the central constituent of the data model because it makes it possible to link the mapped features directly to geological events and it makes also possible to link different reference systems (domain, lithostratigraphic and structural reference systems) to the geological-event reference system (Fig. 14), which differs slightly from the GeoSciML model.

7 Discussion

7.1 Observations *versus* interpretations on geological maps

Most epistemology texts agree that observation and even analytical data are interpretative at different stages in all sciences (Barberousse *et al.*, 2011). Geology is not immune to this assertion and it becomes even more obvious in the production of geological maps.

A geological map records field observations and structural measurements and may be enhanced by geophysical data and laboratory analytical data (geochemical, geochronological, palaeontological, etc.). All data sets used to produce a geological map are considered raw data even if we know they are interpretative in nature. In fact, data can be considered

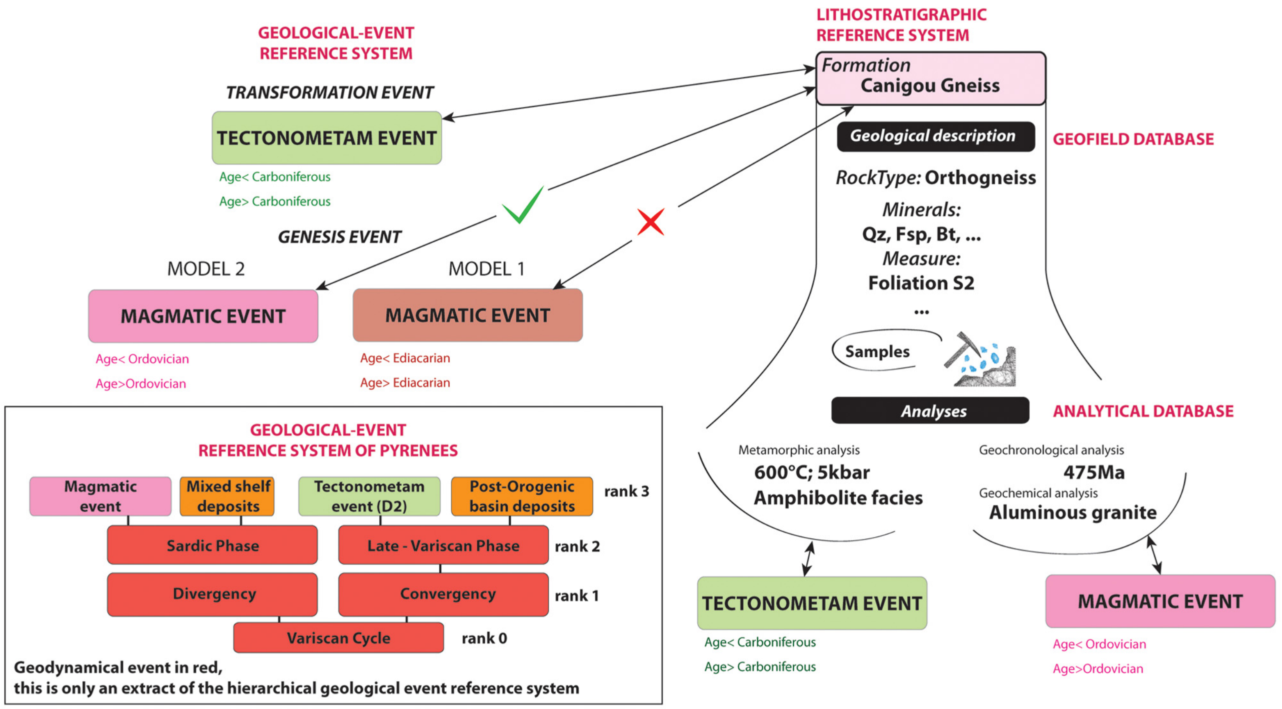

Fig. 15. Example of relationships between field observations, measurements and/or sample analyses allowing to define or refine a geological event. Here, geochronological and geochemical studies make it possible to characterize a genesis event (magmatic event in pink), responsible for a granite emplacement in Ordovician time. Metamorphic studies allow to characterize a transformation event (tectono-metamorphic event in green) as Carboniferous in age; responsible for the transformation of this granite into orthogneiss. These two different geological events are assigned to the lithostratigraphic unit named “Canigou gneiss”. The interpretive geological model is updated, the Canigou gneiss genesis event is the Ordovician magmatic intrusion (model 2) instead of the Ediacarian magmatic intrusion (model 1).

indisputable if they are shared and recognized by all scientists. These datasets are then used by a number of researchers to identify or describe geological events. This approach consists of combining different analytical or observational data to defend a model. This is the essence of geological research. Numerous geological research papers dedicate their discussion/conclusion sections to describing, in narrative style, geological events highlighted in a study area. However, these scientific conclusions remain interpretative compared to factual analytical data and are not accepted by the entire geological community. Thus, geological-event maps and consequently the related geological-event reference system are also interpretative.

7.2 Geological data linked to various geological interpretation models

The division between factual data and interpretative data, which supports the geological-event maps, has obvious advantages. Geologists can establish different links between the data to support his/her, or better: a particular geological model, without modifying the geological data associated with the original geological map. The geological-event reference system then become precious tools in scientific debates for comparing various interpretations from the same geological data set. This possibility can contribute to improve robustness of a model. Indeed, construction of a geological-event map will force the geologist to consider all available data and to leave aside data incompatible with his model.

But the national level requires a consensus vision of global geological knowledge, accepted by the majority, and this task generally falls to state and national geological surveys, assisted by scientific committees.

The method of presenting an official version of historical geology in geological-event map reflects how science functions. Science philosopher T. Kuhn, has claimed that the notion of scientific truth cannot be established at a given time only by objective criteria but that it is also defined by consensus of the scientific community. Moreover, scientific knowledge moves forward with periodic and major "paradigm shifts" (scientific revolutions), rather than in a linear and continuous way (Kuhn, 1970). We think that the Kuhn vision is applicable to geology in general and also specifically to geological-event maps.

In this sense, we can consider geological events that are accepted by a majority of the scientific community, to be one of Kuhn’s paradigms. If a few data pile up in contradiction to a previously accepted geological event, the event will eventually be replaced as a result of majority scientific pressure. An example from the Pyrénées chain illustrates such a paradigm shift (Fig. 15). Several gneissic massifs (*e.g.* the Canigou orthogneiss from eastern Pyrénées) were long considered to be the oldest basement in the chain, Ediacaran in age (Guitard, 1964, 1970), and were mapped as such, despite the existence of a few conflicting radiogenic analyses indicating an Ordovician age (Jäger and Zwart, 1968). The Ordovician age was confirmed and it convinced the geologic community of the existence of an Ordovician magmatic event (Deloule *et al.*, 2002; Cocherie

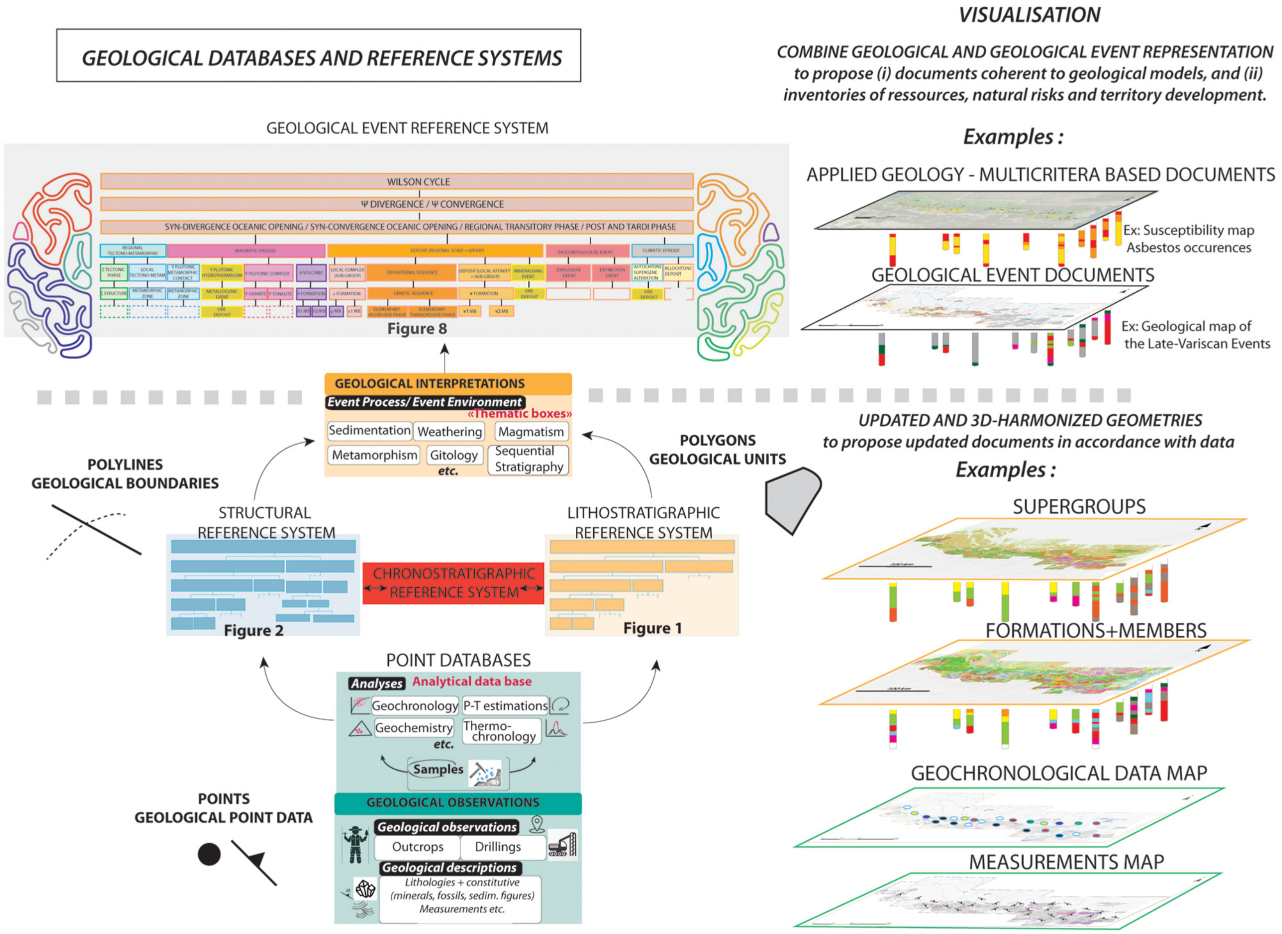

Fig. 16. Overview of the data operating process developed during the RGF-Pyrénées project with the development of databases, reference systems (structural, chronostratigraphic, lithostratigraphic), and the link between them provided by the geological-event reference system. Data from all these sources can be combined to produce different documents, upon request.

et al., 2005; Casas *et al.*, 2010; Liesa *et al.*, 2011). The new data replaced the previous paradigm that had become false (Fig. 15).

Integration of the new paradigm/event into geological-event reference system of the Pyrénées was done without any geological (lithostratigraphic) map correction or factual data changes (such as unit name, petrographic attributes, or analytic data). The granite genesis-event (Ordovician magmatic event), with addition of the new geochronological data, was created without touching other events that later affected this geological unit.

7.3 Geological maps in the service of applied and academic geosciences

Digital event maps will make it easier for non-geologists to read geological maps. Non-geologists will be able to view the complete geological history, which can be read from a rock or a geological unit by consulting a list of different events. This event list could also contain anthropological type events such as ancient quarries or mining works.

Hydrogeology, natural hazards, environmental sciences, natural resource development, and the engineering sciences all need specific geological knowledge adapted to their disciplines. As a result, geologists need to transform scientific geological knowledge into a data set suitable for geo-engineering uses (Fig. 16). This transformation is generally done by assigning physical or chemical parameters (permeability, thermal conductivity, element or ore content...) to a geological unit, either mapped or crosscut in a borehole. But in reality the correlation between a given geological unit and its physical/chemical properties is not so direct. Indeed, as discussed above, a lithostratigraphic unit is defined either by its original description of genesis event type or a notable transformation (metamorphism or alteration). But it is obvious that a rock's physical/chemical property results from all the genesis/transformation events it undergoes and not only from its original state or a single notable event. With the new geological-event approach, it will now be possible to assign a given rock's physical/chemical parameters to an event sequence underwent by rocks rather than to a lithostratigraphic unit, as commonly represented on traditional geological maps (Fig. 17).

This new approach is still in the development phase, but some examples can be used to illustrate the concept. A first example is the production of natural asbestos occurrence susceptibility maps which involve major field sampling campaigns. Asbestos crystallization is initially controlled by

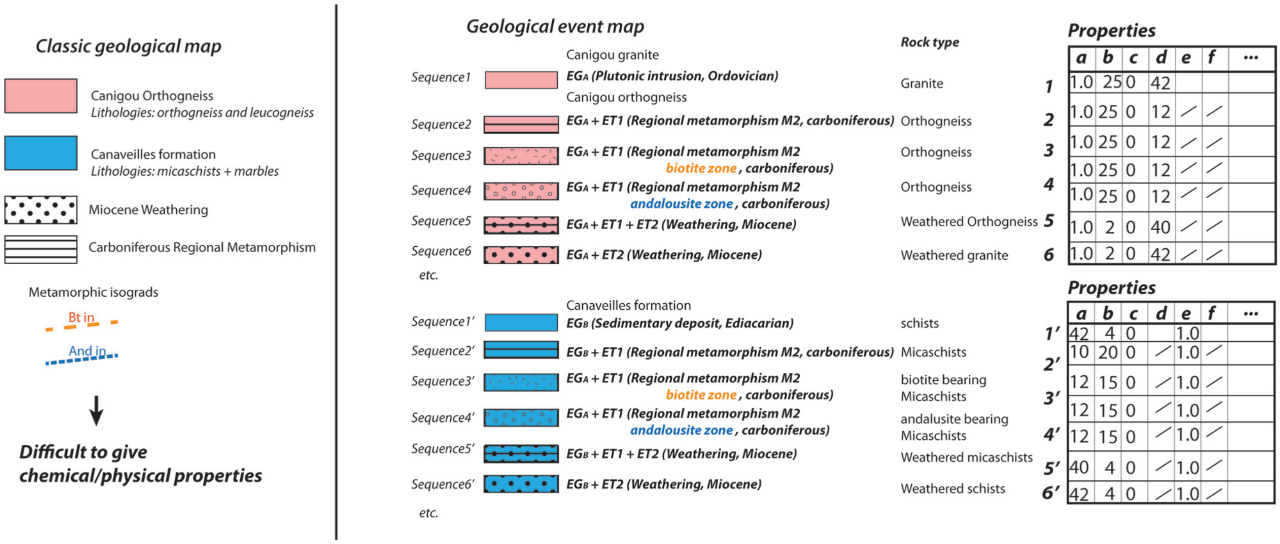

Fig. 17. Example of the legend architecture of a traditional geological map, with geological units and hachures that contain metamorphic and weathering informations, and the legend architecture of a geological event map, with event sequences. A rock unit is characterized by an event sequence. Physical and chemical properties are assigned to this rock unit.

the bulk rock composition and the specific temperature range and associated strain. A geological event map would make it possible to select all mafic or ultra-mafic magmatic events and to cross-check them with tectono-metamorphic events characterized by the temperature range that corresponds to asbestos stability. The resulting map would then be a valuable document for guiding field investigations. In this case the correlation between asbestos occurrences and geological events is direct because it deals with a wellknown causal relationship. This type of approach can be used more broadly in the production of maps or other documents for risk prediction related to geology.

However, very often the effects of an event sequence on the final rock properties are not clearly understood. For example it is difficult to predict how well diagenetic events such as silicification, dolomitization, or vein filling affect permeability, porosity, or thermal conductivity of a rock. Rather than understanding these causal relationships, the better way would be first to establish statistical correlations between rocks properties, when they are available, and the event sequences suffered by the latter. Access to the variability of the rock physical parameters, determined for a given sequence of events, would then make possible to estimate that similar sequences of events of distant rocks have a high probability of having the same physical/chemical properties. Once these relationships are established, it will be easier to predict physical/chemical properties of areas where data are lacking. This feature is particularly advantageous in preliminary studies to estimate potential uses of the subsoil.

8 Conclusions

In this paper, we propose a new geological-event approach based on the description of geological events affecting geological features, allowing to integrate up-to-date knowledge from scientific research. This new approach makes it possible to distinguish raw data from interpretation and to highlight data that conflicts with current paradigms. The event unit allows to link several data coming from different data sets or databases. The associated geological-event maps constitute new products that could be helpful for different applications. The different reference systems (lithostratigraphic, structural, geologicalevent, domains and zones) and associated geometries have now to be shared on an open-source platform to a large scientific community. This involves a significant investment of organizational structure, information technology, and data management as well as a long-term polices to update and maintain such an information system. It supposes also to fix technological issues raised by the complexity of this approach implying the shift from relational databases to ontological formal languages that offer the possibility of encoding the complexity of knowledge production to create geological maps (Mantovani *et al.*, 2020). Results of several studies propose different ways to use this technology to manage similar information (Brodaric, 2004; Balestro and Piana, 2007; Loudon, 2009, 2011: Giboin *et al.*, 2013) that should be considered in future works.

Acknowledgments. Results of this paper were part of a project funded by the BRGM (the RGF-Pyrénées project). The authors thank all the people who believed in this approach and who supported the project team. We thank Patricia Bobeck (DBA Geotechnical Translations) for English revision of this manuscript. We also thank gratefully F. Piana and an anonymous reviewer for their constructive remarks, which made it possible to greatly improve this article. We also thank L. Jolivet and R. Augier for the editorial handling.

References

Angrand P, Ford M, Watts AB. 2018. Lateral variations in foreland flexure of a rifted continental margin: the Aquitaine Basin (SW France). *Tectonics* 37: 430–449. https://doi.org/10.1002/2017TC004670.

Balestro G, Piana F. 2007. The representation of geological knowledge and uncertainty in databases of GIS geological maps. *Boll Soc Geol It (Ital J Geosci)* 126(3): 487–495.

Barberousse A, Kistler M, Ludwig P. 2011. La philosophie des sciences au XX^{e} siècle. Champs-Essais. Flammarion, 352 p.

Brodaric B. 2004. The design of GSC FieldLog: ontology-based software for computer aided geological field mapping. *Comput Geosci* 30: 5–20. https://doi.org/10.1016/j.cageo.2003.08.009.

Casas JM, Castiñeiras P, Navidad M, Liesa M, Carreras J. 2010. New insights into the Late Ordovician magmatism in the Eastern Pyrenees: U-Pb SHRIMP zircon data from the Canigo massif. *Gondwana Research* 17: 317–324. https://doi.org/10.1016/j.gr.2009.10.006.

Catuneanu O, Galloway WE, Kendall C, Miall A, Posamentier W, Strasser A, *et al.* 2011. Sequence stratigraphy: methodology and Nomenclature. *Newsletters on Stratigraphy* 44/3: 173–245.

Cochelin B, Chardon D, Denèle Y, Gumiaux C, Le Bayon B. 2017. Vertical strain partitioning in hot Variscan crust: synconvergence escape of the Pyrenees in the Iberian-Armorican syntax. *Bull Soc Géol Fr* 188: 39. https://doi.org/10.1051/bsgf/2017206.

Cocherie A, Baudin T, Autran A, Guerrot C, Fanning CM, Laumonier B. 2005. U-Pb zircon (ID-TIMS and SHRIMP) evidence for the early Ordovician intrusion of metagranites in the late Proterozoic Canaveilles Group of the Pyrenees and the Montagne Noire (France). *Bull Soc Géol Fr* 176: 269–282.

Corre B, Lagabrielle Y, Labaume P, Fourcade S, Clerc C, Ballèvre M. 2016. Deformation associated with mantle exhumation in a distal, hot passive margin environment: new constraints from the Saraillé Massif (Chaînons Béarnais, North-Pyrenean Zone). *Comptes Rendus Geoscience* 348(3–4): 279–289. https://doi.org/10.1016/j.crte.2015.11.007.

Chantraine J, Autran A, Cavelier C, Alabouvette B, Barféty J-C., Cecca F, *et al.* 2003. Carte géologique de la France à l'échelle du millionième, 6^{e} édition révisée. Orléans: BRGM.

Deloule E, Alexandrov P, Cheilletz A, Laumonier B, Barbey P. 2002. In-situ U-Pb zircon ages for Early Ordovician magmatism in the eastern Pyrenees, France: the Canigou orthogneisses. *Int J Earth Sci* 91: 398–405.

Ellenberger F. 1982. Les premières cartes géologiques en France : projets et réalisations. 1^{e} série, n° 45, 35 p.

Ellenberger F. 1983. Recherches et réflexions sur la naissance de la cartographie géologique en Europe et plus particulièrement en France. *Histoire et Nature* 22–23: 3–54.

Gabalda S. Vernhet Y, Rambourg D, Prognon C, Chevremont P, Capar L, *et al.* 2013. Élaboration d'un chantier RGF : retour d'expérience du chantier pilote Vosges-Fossé Rhénan. Rapport final. BRGM/RP-63008-FR. 238 p.

Giboin A, Grataloup S, Morel O, Durville P. 2013. Building Ontologies for analyzing data expressed in natural language. In Perrin, M., Rainaud, J.F., Shared Earth Modeling – Knowledge driven solutions for building and managing subsurface 3D geological models. Technip edition, IFP energie nouvelle publication.

Gradstein FM, Ogg JG, Schmitz MD, Ogg GM. 2020. Geologic time scale, volume 1 and 2. Elsevier. https://doi.org/10.1016/C2020-1-02369-3.

Guitard G. 1964. Un exemple de structure en nappe de style pennique dans la chaîne hercynienne : les gneiss stratoïdes du Canigou (Pyrénées Orientales). *C R Acad Sci Ser II* 258: 4597–4599.

Guitard G. 1970. Le métamorphisme hercynien mésozonal et les gneiss oeillés du massif du Canigou (Pyrénées-Orientales). *BRGM Mém* 63: 353 p.

Harrell JA, Brown VM. 1992. The world's oldest surviving geological map: the 1150 B.C. Turin Papyrus from Egypt. *Journal of Geology* 100: 3–18.

Hintersberger E, Iglseder C, Schuster R, Huet B. 2017. The new database "Tectonic Boundaries" at the Geological Survey of Austria. *Jahrbuch der Geologischen Bundesanstalt* 157(1–4): 195–207.

Ireland A, 1943. History of the development of geologic maps. *Bulletin of the Geological Society of America* 54: 1227–1280.

Jäger E, Zwart HJ. 1968. Rb-Sr age determinations of some gneisses and granites of the Aston-Hospitalet massif (Pyrenees). *Geologie en Mijnbouw* 47(5): 249–358.

Kuhn Th. 1970. The structure of scientific révolutions, 1962 [Traduction française : La structure des révolutions scientifiques]. Paris: Flammarion.

Lemirre B, Cochelin B, Duchene S, de Saint Blanquat M, Poujol M. 2019. Origin and duration of late orogenic magmatism in the foreland of the Variscan belt (Lesponne—Chiroulet—Neouvielle area, French Pyrenees). *Lithos* 336–337: 183–201. https://doi.org/10.1016/j.lithos.2019.03.037.

Liesa M, Carreras J, Castiñeiras P, Casas JM, Navidad M, Vila M. 2011. U-Pb zircon of Ordovician magmatism in the Albera Massif (Eastern Pyrenees). *Geol Acta* 9: 93–101.

Loudon TV. 2009. Four interacting aspects of a geological survey knowledge system. *Comput Geosci* 35: 700–705. https://doi.org/10.1016/j.cageo.2007.12.009.

Loudon TV. 2011. A Scenario for Systems Geology: Suggestions Concerning the Emerging Geoscience Knowledge System and the Future Geological Map. Nottingham, UK: British Geological Survey, p. 375. RR/11/005.

Mantovani A, Piana F, Lombardo V. 2020. Ontology-driven representation of knowledge for geological maps. *Computers & Geosciences* 139. https://doi.org/10.1016/j.cageo.2020.104446.

Medioni R. 2002. Du service de la carte géologique de la France au Service géologique national. Causes et conséquences de la fusion de 1968. Travaux du Comité français d'Histoire de la Géologie, 3^{e} série (tome 16), pp. 165–175.

Oldroyd D. 2013. Maps as pictures or diagrams: The early development of geological maps. *Geol. Soc. of America Special Paper* 502: 41–101.

Salvador A. 1994. International stratigraphic guide: a guide to stratigraphic classification, terminology, and procedure. 2nd ed. Geol. Soc. America.

Saspiturry N, Razin P, Baudin T, Serrano O, Issautier B, Lasseur E, *et al.* 2019. Symmetry *vs.* asymmetry of a hyper-thinned rift: Example of the Mauléon Basin (Western Pyrenees, France). *Marine and Petroleum Geology* 104: 86–105 https://doi.org/10.1016/j.marpetgeo.2019.03.031.

Padel M, Clausen S, Álvaro J-J, Casas J-M. 2018. Review of the Ediacaran-Lower Ordovician (pre-Sardic) 1 stratigraphic framework of the Eastern Pyrenees, southwestern Europe. *Geologica Acta* 16(4): 339–355. https://doi.org/10.1344/GeologicaActa2018.16.4.1.

Rougier G, Ford M, Christophoul F, Bader A-G. 2016. Stratigraphic and tectonic studies in the central Aquitaine Basin, northern Pyrenees: Constraints on the subsidence and deformation history of a retro-foreland basin. *Geoscience* 348: 224–235. https://doi.org/10.1016/j.crte.2015.12.005.

Savaton P. 2007. The First Detailed Geological Maps of France: Contributions of Local Scientists and Mining Engineers. *Earth Sciences History* 26(1): 55–73.

Schiegl M, Schuster R, Krenmayr H-G., Lipiarski P, Pestal G, Stöckl W, *et al.* 2008. GeoSciML – Ein konzeptionelles Datenmodell fur die Geologie? *Ubersetzung und Erlauterung ausgewahlter Objektklassen von GeoSciML. – Jahrbuch der Geologischen Bundesanstalt* 148/2: 213–226.

Schuster R. 2015. Zur Geologie der Ostalpen. *Abhandlungen der Geologischen Bundesanstalt* 64: 143–165.

Sen M, Duffy T. 2005. GeoSciML: development of a generic geoscience markup language. *Comput Geosci* 31(9): 1095–1103.

Simons BA, Boisvert E, Brodaric B, Cox SJD, Duffy TR, Johnson BR, *et al.* 2006. GeoSciML: Enabling the Exchange of Geological Map Data. *ASEG Ext. Abstr.*: 1–4. https://doi.org/10.1071/ASEG2006ab162.

Skrzypek E. 2011. Structural, petrological and geochronological contribution to intracontinental tectonics of the European Variscan Belt (Sudetes, Vosges Mts). Earth Sciences. Université de Strasbourg, English. tel-00773597.

Tabaud A-S. 2012. Le magmatisme des Vosges : conséquence des subductions paléozoïques (datation, pétrologie, géochimie, ASM). Géochimie. Université de Strasbourg, français. NNT : 2012STRAH003. tel-00755354.

Tissoux H, Ricordel-Prognon C, Prognon F, Lacquement F, Bertran P, Bosq M, *et al.* 2020. Carte au Millionième du Quaternaire de la France métropolitaine. https://doi.org/10.18144/0__bf80ba9f-db3f-455a-9d55-24cadd052db6.

Cite this article as: Le Bayon B, Padel M, Baudin T, Cagnard F, Issautier B, Tissoux H, Prognon C, Plunder A, Grataloup S, Lacquement F, Hertout A, Stephan-Perrey J. 2022. The geological-event reference system, a step towards geological data harmonization, *BSGF - Earth Sciences Bulletin* 193: 18.