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Integrating geological data in Europe to foster multidisciplinary research

Marc Urvois*[,1], Sylvain Grellet[1], Henning Lorenz[2], Rainer Haener[3], Christelle Loiselet[1], Matthew Harrison[1], Matija Krivic[4], Christian Brogaard Pedersen[5], Marianne B. Wiese[5], Amelia Baptie[6], Martin Nayembil[6], James Trench[7], Ivor Marsh[8], Carlo Cipolloni[9], Chiara D'Ambrogi[9], Maria Pia Congi[9]

(1) BRGM, French Geological Survey, Orléans, France
(2) Uppsala University, Department of Earth Sciences, Uppsala, Sweden
(3) GFZ, Helmholtz Centre Potsdam, German Research Centre for Geosciences, Potsdam, Germany
(4) GeoZS, Geological Survey of Slovenia, Ljubljana, Slovenia
(5) GEUS, Geological Survey of Denmark and Greenland, Copenhagen, Denmark
(6) BGS, British Geological Survey, The Lyell Centre, Edinburgh, United Kingdom
(7) GSI, Geological Survey Ireland, Booterstown Hall, Ireland
(8) Marsh Technology, Ireland
(9) ISPRA, Italian Institute for Environmental Protection and Research, Department for The Geological Survey of Italy, Roma, Italy

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Abstract

The European Plate Observing System (EPOS, www.epos-eu.org) is a multidisciplinary pan-European research infrastructure for solid Earth science. It integrates a series of domain-specific service hubs (Thematic Core Service, TCS) such as the Geological Information and Modelling, which provides access to data, data products and services on European boreholes, geological maps, mineral occurrences, mines and 3D models. TCS GIM services are hosted by a group of European Geological Surveys and a couple of national research organizations.
This paper presents novel data discovery and integration, facilitated using borehole logging information with on-demand web services to produce 3D geological structures. This domain interoperability across EPOS was created for the purpose of research, but it is also highly relevant for the response to societal grand challenges such as natural hazards and climate change.
European and international interoperability implementation frameworks are well described and used (e.g., INSPIRE, ISO, OGC, and IUGS/CGI). It can be difficult for data providers to deploy web services that support the full semantic data definition (e.g., OGC Complex Feature) to expose several millions of geological entities through web-enabled data portals as required by pan-European projects. The TCS GIM group implemented and innovatively extended two standardized descriptions, i.e. GeoSciML-Lite and EarthResourceML-Lite, with an important reuse of content from Linked Data Registries. This approach was applied to design and implement the European Borehole Index and associated web services (View-WMS and Discovery-WFS), extended to 3D models, geological maps as well as mineral occurrences and mines.
Results presented here apply the Linked Data approach ensuring optimal semantic description and enriching the data graphs, with complex descriptions and contents. In this way, it is now possible to traverse from one Borehole Index instance to linked richer information such as the borehole

geological log, groundwater levels, rock sample description, analyses, etc. All this detailed information is served following international interoperability standards (Observations & Measurements, GroundWaterML 2.0, GeoSciML4, amongst others).

Key words: EPOS; Geological information; Borehole; FAIR; Linked Data

1. Introduction

Geological data are essential information for different types of users (e.g., scientists, land planners, teachers, construction sector, citizens, etc.) and stakeholders (e.g., policy makers, investors, etc.). Integrated data and product services like harmonized geological maps, boreholes and 3D models facilitate their respective tasks, such as:

- to better understand the major geological characteristics of soil and subsoil within the area of interest (e.g., stratigraphy, lithology, structural elements, geotechnical and hydrogeological properties, etc.), with several applications, such as the assessment of potential georesources [Gourcerol et al., 2019; Gloaguen et al., 2020], and evaluation of geological stability at specific sites [Perrin et al., 2015] as well as groundwater resource monitoring [Vergnes et al., 2020];
- to identify the main factors that have driven the regional geological evolution of the study area in order to point out major active processes that may have implications for the society, e.g., in terms of geohazards [Thiery et al., 2019], with the purpose to develop mitigation plans.

Large amounts of geological data are collected, stored, analyzed and published by the national Geological Surveys as well as universities and regional/national research centres. Through interpretation and processing of the observation data, the value chain produces information, knowledge and predictive models derived from multidisciplinary sources [Habets et al., 2010]. These are used to characterize natural processes, locate underground resources and to predict phenomena and mitigate them. Such tasks require a well-developed data infrastructure that supports cross-domain science. From this perspective, the European Geological Surveys established a common information system called EGDI[1] over recent years [Tulstrup et al., 2016]. Through a series of thematic and data harmonization projects, European geoscientific data and information are now available from a common location, and complying with widely used interoperability standards. EGDI covers onshore and marine geology, mineral resources, geohazards, energy, groundwater and soils [Čápová et al., 2021]. Depending upon the scope of the supporting projects, the geographical extension ranges from pilot study areas to the European continent. As part of the EPOS-IP project (2014-2019)[2] [Cocco et al., 2022; Saleh Contell et al., 2022], the geological information working group selected a subset of these data to be used as reference knowledge and background by the data and products services of other EPOS thematic groups, such as seismology, near fault observatories and volcanoes. These are (i) the geological map of Europe at 1:1,000,000 scale, (ii) boreholes (geotechnical and scientific drilling, underground water, mineral resources exploration), (iii) mineral occurrences and mines and (iv) 3D geological models. As described in section 4 here after, the corresponding thematic web services and interfaces are implemented by the TCS GIM[3] group to serve these data to the EPOS ICS-C [Cocco et al., 2022] and make them accessible through the EPOS Data Portal[4]. Under the umbrella of EuroGeoSurveys[5], the data providers include Geological Surveys from France, U.K., Italy, Denmark, Ireland, Slovenia and Czech Republic as well as the Department of Earth Sciences, Uppsala University, Sweden, bringing its expertise in scientific drilling projects and the Helmholtz Centre Potsdam, German Research Centre for Geosciences, Germany, renowned for its 3D model expertise.

1 European Geological Data Infrastructure: www.europe-geology.eu (last accessed 21/06/2022)

2 https://www.epos-eu.org/ (last accessed 21/06/2022)

3 https://www.epos-eu.org/index.php/tcs/geological-information-and-modeling (last accessed 21/06/2022)

4 https://www.ics-c.epos-eu.org/data/search (last accessed 21/06/2022)

5 The Geological Surveys of Europe http://www.eurogeosurveys.eu/ (last accessed 21/06/2022)

The mineral occurrences and mines are georeferenced as points whereas the geological maps include points, lines and polygons, all being two-dimensional objects. In case of boreholes, these are 2D points with descriptions along a third dimension axis downwards from the ground level. Considering the geographical extension of these national and transnational data sets, it is about managing millions of entities from several data providers and serving them through a one-stop-shop portal.

The aim of the TCS GIM is to design and implement efficient and sustainable access to geological multi-scale data assets through the integration of distributed infrastructure components (nodes) governed by the EPOS Geology domain (geological surveys and research communities). The processing and use of simulation and visualization tools in virtual research environments will subsequently support the integrated analysis and characterization of complex subsurface structures and their inherent dynamic processes. In addition, faster and more comprehensive data discovery and access, and cross-referencing with third party services e.g., sample access, will also benefit traditional research. Altogether, this work will in turn improve research outcomes and facilitate a deeper understanding of complex multi-scale geoscientific questions.

2. Background

For many years, the W3C has been leading a considerable collaborative effort supported worldwide by many actors from both private and public sectors in providing a set of technologies, standards and best practices that constitute the basis for representing, publishing and sharing the data over the Web in a standardized way. The set of technologies and standards proposed by the W3C, also known as the "Semantic Web" technologies (Semantic Web Layercake), are embodied by the four simple principles, known as the "Linked Data" principles [Berners-Lee T., 1989]:

1) Use URIs to name (identify) things.
2) Use HTTP URIs so that these things can be looked up (resolvable, "dereferenceable").
3) Provide useful information about what a name identifies when it is looked up, using open standards.
4) Refer to other things using HTTP URI-based names when publishing data on the Web.

The so-called "Web of Data" results from the adoption of these principles by data providers over the world. It is not intended to be a substitution to the already existing "Web of Documents", but rather to complement it to achieve the original vision of the Web [Berners-Lee T., 1989].

"Data on the Web" working group released its first public draft document in 2015 which became a W3C recommendation [W3C, 2017a]. This set of recommendations aims that 'Data should be discoverable and understandable by humans and machines'. This was then complemented by a second document resulting from the OGC/W3C collaboration initiated in 2014: Spatial Data on the Web Best Practices [W3C, 2017b]. These include the provision of metadata for the datasets, stable identifier in the form of HTTP URI, and linking data through those HTTP URIs.

Adopting them is essential for the geological community as it enhances the discoverability, reuse, and enrichment of datasets of public interest for education, research, knowledge creation, and support of economic activities.

FAIR principles were defined in 2016 to improve the Findability, Accessibility, Interoperability, and Reuse of scientific data both for machines and humans [Wilkinson et al., 2016]. Presently, those principles extend to any other digital assets such as services and software tools [Koers et al., 2020]. The Research Data Alliance also started to work on applying them to Virtual Research Environment[6] (VRE). Open science requires these principles to be implemented. Two of them are worth noting for their formal impact. Interoperability, both technical and semantic, drove dynamics such as the European INSPIRE directive (Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007[7]). The data reusability is clearly included in the European Commission "Directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 on open data and the re-use of public sector information"[8].

6 https://www.rd-alliance.org/groups/fair-virtual-research-environments-wg (last accessed 21/06/2022)

7 https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32007L0002 (last accessed 21/06/2022)

8 https://eur-lex.europa.eu/legalcontent/EN/ALL/?uri=celex:32019L1024 (last accessed 21/06/2022)

The European Geological Surveys have a long history of engagement with these international initiatives. BRGM, France, was represented on the Board of OGC 2009-2021 by François Robida. GeoSciML 1.0.0 was first published in 2005 but importantly brought under the OGC banner at release 4.1. The OGC Geoscience Domain Working Group [Beaufils et al., 2018] was set up to align some of the geoscience standardisation initiatives around the globe in 2017 under the leadership of OGC and IUGS/CGI. In the development of the INSPIRE regulations guidance, the working groups for Geology Annex II, Mineral Resources and Natural Risk Zones [European Commission, 2013; Tomas et al., 2015] in Annex III were each chaired and largely populated by representatives of the national geological surveys. EGDI [Tulstrup et al., 2016] was built by the EuroGeoSurveys to coordinate the FAIR publication of European Commission funded project geoscientific datasets.

During the earlier phase of EPOS [EU H2020; EPOS Implementation Phase Project, 2015-2019], several European Geological Surveys teamed up as a continuation of their respective activities in the standardization and interoperability activities (INSPIRE, IUGS/GCI, OGC). These were national surveys from Denmark (GEUS), Ireland (GSI), Italy (ISPRA), and France (BRGM). In addition, academia were represented by the Department of Earth Sciences, Uppsala University, Sweden, and the Helmholtz Centre Potsdam, German Research Centre for Geosciences, Germany. The Geological Information and Modelling TCS GIM was formally established in 2019 under the umbrella of EuroGeoSurveys (EGS), and through the extension of the initial group. The Geological Surveys of Czech Republic (CGS), Slovenia (GeoZS) and U.K. (BGS) joined. The TCS GIM consortium is chaired by EGS, co-chaired by CGS, and coordinated by BRGM. BGS is in charge of the stakeholder panel. The data and product services are provided under the umbrella of EGS. Three IT contact point representing as many web service end points are in place by BRGM, GEUS and GeoZS.

3. Inter-Linked Data Architecture

During the EPOS-IP project, geological data services of interest for the EPOS geoscientific scope were identified and prioritized in the TCS GIM roadmap. The first services delivered to the ICS-C were the European boreholes, 3D models, the geological map of Europe at 1:1,000,000 scale as well as the mineral occurrences and mines. To follow the path taken internationally by this very same community since 20 years, TCS GIM decided early in the EPOS-IP project that it would base its IT work solely on the ISO, OGC, IUGS/CGI, INSPIRE, W3C and RDA published identified standards and best-practices baseline. This philosophy has applied from this point in the following steps of the EPOS Operational Phase [Cocco et al., 2022; Saleh Contell et al., 2022]. When needed, this work also contributed to the evolution of these standards.

Even though interoperability implementation frameworks are well described and used, it proved to be difficult for several data providers in several earlier pan-European projects to deploy the OGC services with full semantic data definition (OGC/ISO Complex Feature) for the discovery and view of millions of geological entities. TCS GIM decided to take a complementary route. Thus, the way the indices are served is unique compared to previous interoperability projects in which the TCS GIM community took part. Indeed, the entire data architecture revolve around the idea of serving SimpleFeature data. Fully Linked Data-oriented simple data payload provide the relevant link to semantically richer ones. The group reused and enriched specifications (e.g., GeoSciML, EarthResourceML) and previous data collection projects when they were available (EGDI, Minerals4EU). It also complemented the specification (e.g., for Models) and data collection (borehole and 3D model data) landscapes where no previous standard or European data set existed.

As such, the TCS GIM exposes at the central TCS level (i) a metadata description of the available data sets and services, (ii) a number of SimpleFeature “index services” towards the EPOS ICS-C, (iii) a code list registry and (iv) a Linked Data resolver. These allow EPOS end users to search and locate boreholes, geological maps and features, 3D models, etc., based on the information referenced by the index services.

Information indices have been set up for data types that require data compilation for EPOS (e.g., Model Index) as well as for data types where such data were collected during previous European projects (e.g., GeologicalUnits by EGDI, GeoResources by Minerals4EU and Mintell4EU). In this Linked Data approach, the data instances are associated with URIs and point to other information resources also using URIs. The Linked Data principles ensure the best semantic description (e.g., URIs to shared code list registries entries) and also enrich an initial “information seed” (e.g., a set of Borehole entries matching a search) with more content (e.g., URIs to richer information in a ComplexFeature data flow). As a result, this pattern of SimpleFeature service with Linked Data has a positive effect on the IT architecture: interoperable services are simpler and faster to deploy (thus by more data providers) and there is no need to harvest a full OGC ComplexFeature data set. The architecture is also more sustainable and scalable.

The European Geological Services code list registries were enriched with new vocabularies as part of the broader European Geoscience Registry[9]. In compliance with the relevant European INSPIRE rules, this registry is now part of the INSPIRE Register Federation, the central access point to the repository for vocabulary and resources. The European Geoscience Registry is available for reuse and extension by other geoscientific projects.

As stated above, European geological data are exposed with a Linked Data approach. The borehole index gives access to the location and a limited number of descriptors whereas the comprehensive data include full information on the borehole and samples for scientific research. The full sample material (drill core) information is available by linked third party services as a reference with an International Geo Sample Number (IGSN) [Conze et al., 2017]. As an example, consider boreholes used to monitor groundwater levels equipped with sensors, data from measurements are collected over time. These are stored in separate information systems. They can be made accessible to the end users through the Linked Data architecture being progressively set up by TCS GIM data providers (Fig. 1). The full semantic consistency of the underlying data was assured with the Borehole Conceptual Model, which is based on GeoSciML, GroundWaterML2.0, Observations & Measurements and the INSPIRE Environmental Monitoring Facility Data Specification.

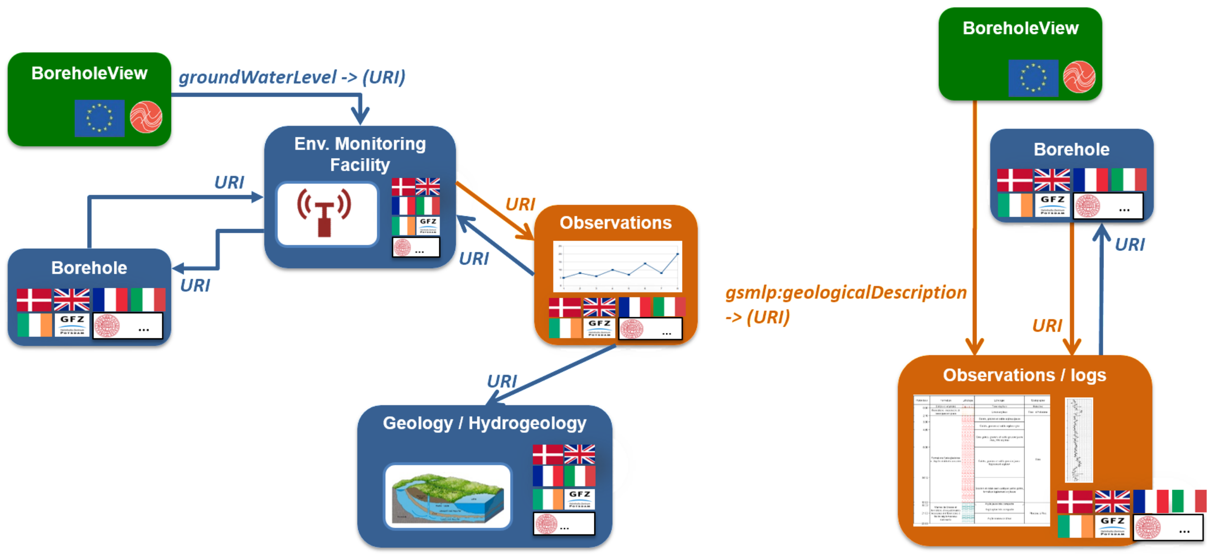

Figure 1. Example of the borehole-related data sets linked with URIs through a dynamic graph. Each arrow represents the link between instances, e.g., from one borehole description to the environmental monitoring facility (sensor) deployed there, then to the measurements acquired and to the description of the hydrogeological unit(s) being monitored.

Each instance is associated with a URI and points to other information resources also using URIs.

Another significant input to the user community is achieved by effectively establishing interdisciplinary collaboration across national, domain, and system boundaries. This collaboration between largely heterogeneous geoscientific communities is mainly based on interoperable services that provide standardized data. In addition, these can be seamlessly integrated into scientific workflows or collaborative environments such as Jupyter[10] Notebooks.

9 https://data.geoscience.earth/ncl/ (last accessed 21/06/2022)

10 https://jupyter.org/ (last accessed 21/06/2022)

4. TCS GIM services

As mentioned above, the Thematic Core Service implemented by the Geological Information and Modelling group represents a selection of basic geological topics useful for other TCS communities (Fig. 2).

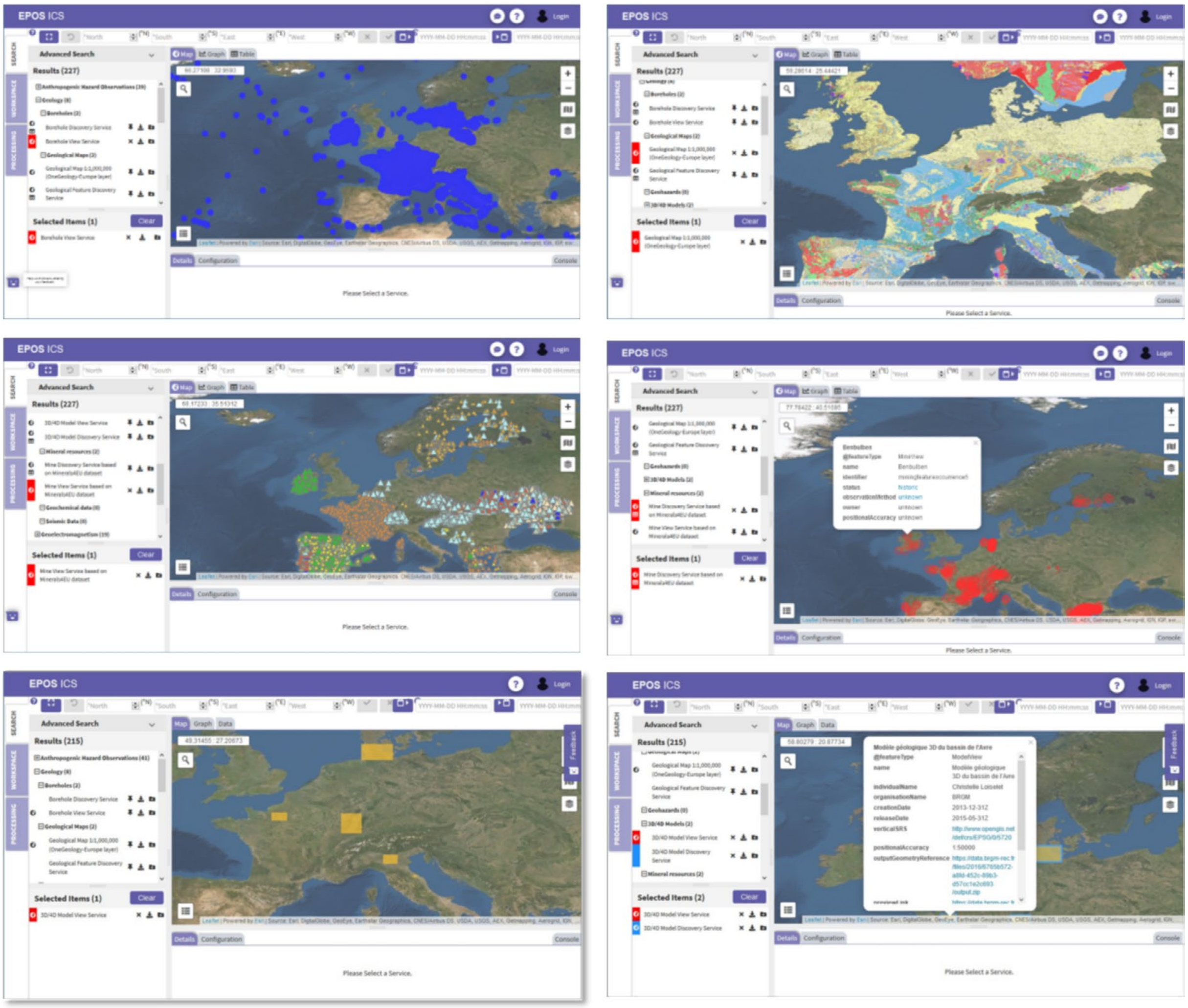

Figure 2. TCS GIM services on the EPOS Data Portal: Boreholes, Geological map at 1:1,000,000, Mineral resources and 3D models.

4.1 Geological map

One of the main missions of the geological survey organizations is focused on the knowledge of the subsurface. It is then made available through the geological maps at local, regional, national scales. The pan-European surface geology at 1:1,000,000 scale is a transnational map provided by EGDI and harvested from INSPIRE-compliant national web feature services on GeologicUnit.

Two services are offered to the users:

- Map View Service (OGC WMS): the surface geology entities are described as geological units forming a continuous map across Europe on the EPOS Data Portal,
- Feature Index Discovery Service (OGC WFS): enables the user to search for GeologicUnit by matching a set of criteria such as location and other properties that are defined in the specification based on GeoSciML-Lite (e.g., lithology, age…), INSPIRE code lists are used.

4.2 Boreholes

The data set exposed in EPOS includes onshore and offshore boreholes made available by the TCS GIM members (over 2.2 million boreholes as on 31/12/2021). It includes both scientific and commercial boreholes. The regional and national geological surveys expose national data sets as part of their public service mission, often comprising several millions of boreholes.

Most boreholes drilled for the purpose of scientific research are located in areas that are of particular interest for understanding the structure and composition of the subsurface and which are not sufficiently explored by commercial wells. Therefore, data from scientific drillings are of particular interest for the solid Earth science community despite their marginal number when compared to the data sets that contain millions of commercial boreholes. The Department of Earth Sciences of Uppsala University provides a data set compiled from projects and expeditions of the International Continental Scientific Drilling and International Ocean Discovery Programs (ICDP/IODP).

Index data services are exposed by each data provider according to the TCS GIM specifications (EPOS-GeoSciML-Lite profile[11]). They are in-turn harvested at the TCS GIM central node level for quality check, European consolidation and exposition to EPOS ICS-C.

Two services are offered to the users:
- The Map View Service enables the user to discover and interact on a map with the available boreholes. A click on a Borehole provides the user with a set of descriptors that are defined in EPOS GeoSciML-Lite profile (e.g., depth, purpose, drilling method, availability of borehole logs, link to monitoring equipment, etc.),
- The Feature Index Discovery Service enables the user to search for boreholes matching a set of criteria such as location, and many other properties that are defined in the specification based on GeoSciML-Lite (e.g., drilling method, core length, access to the physical core, to logs, to water level, etc.). When code list registries were not available from INSPIRE and/or the Commission for the Management and Application of Geoscience Information of the International Union of Geological Sciences (IUGS/CGI) level, specific entries were added in the European Geoscience Registry.

The data providers expose OGC ComplexFeature services where such rich information is available. These services are directly interfaced from the index service as Linked Data, i.e. they are not routed through the EPOS TCS or ICS infrastructures. This is the perfect example of the benefits of a fully Linked Data approach. Those datasets/services are still integrated in EPOS in the sense that are described using the common metadata semantics agree on in EPOS while still being hosted as close as possible to the Data Provider which is important for data maintenance. Another benefit of such a fully Linked Data approach is the capacity to dynamically enrich the data content handled by a software when a user is using it without asking him to go back again in a data catalogue to search for the second dataset that will enrich the first. This is feasible in tools such as QGIS GIS with its “GML Application Schema Toolbox” plugin[12]. This feasibility has been implemented as a demonstrator[13].

4.3 Mineral resources

This data set was compiled over more than 15 years in a series of European mineral inventory projects (e.g., ProMine, Minerals4EU, Mintell4EU). Most geological surveys host data on raw materials, however, data are typically organized in different ways from one country to another based on different geological traditions, legal frameworks, etc. The latest Mintell4EU project [Flindt Jørgensen et al., 2021] built on previous projects to collect a selection of these national/regional raw material data, to store them in a central database, and finally to offer a visualization in a harmonized way at the European Geological Data Infrastructure (EGDI). This Minerals Inventory database [Kumelj et al., 2021] includes, among other assets, the location of individual mineral occurrences and

11 https://gitlab.brgm.fr/brgm/epos/epos-tcs-gim/-/tree/master/Documents/EPOS_GeoSciML_Lite_Profile (last accessed 07/06/2022)

12 https://plugins.qgis.org/plugins/gml_application_schema_toolbox/ (last accessed 07/06/2022)

13 https://github.com/BRGM/gml_application_schema_toolbox/tree/master/docs/presentations/2018_EGU (last accessed 07/06/2022)

mines, aggregated statistical data at national level on production, trade, resources and reserves compiled in the electronic Minerals Yearbook.

The corresponding harvesting system for collecting and validating these European mineral resources data is operational, and technical routines are in place during the harvesting phase to ensure a rigorous control of the data quality. As of 31/12/2021, the data collection involves 36 providers from 31 countries. It includes 143,537 mineral occurrences and 58,910 mines.

Two services are offered to the users:
- Map View Service: the European mineral occurrences and mines are displayed using a first set of descriptors (name, status, activities and associated products, citation),
- Feature Index Discovery Service: in addition to the geographical search provided by the EPOS Data Portal interface, the user can interact with the mineral occurrences and mines with dedicated descriptors (e.g., commodity, geologic history, type of mineral occurrence type, etc.).

4.4 3D models

This data set is an inventory of 3D models available at the data provider level. Presently, the 3D Model Index includes a first selection of models exposed by the geological surveys of France (Vosges-Rhine Graben), Denmark (South Jutland-Schleswig) and Italy (Central Po Plain and Fossombrone area). TCS GIM developed an *ad hoc* semantic specification[14], as no previous one was available. Based on these four examples, the development process already produced two versions of the 3D Model and associated representation specifications in conjunction with the OGC Geoscience Domain Working Group[15].

Two services are offered to the users:
- Map View Service (OGC WMS): to discover the available models through a first set of descriptors, i.e. location, name, description, positional accuracy, online resource,
- Feature Index Discovery Service (OGC WFS): to interact with the proposed models through the new entries in the new code list registries, i.e. area of interest, purpose, status, modelled feature, discretization type used, etc.

5. Vocabulary registry and resolver

The TCS GIM utilizes the European Geoscience Registry, which was set up as the reference code list registry to consolidate and share controlled vocabularies throughout the various thematic projects and data infrastructures in which EuroGeoSurveys members participate. The TCS GIM activities aim at avoiding the single use of project code lists while building on the knowledge and enriching reusable European vocabulary registries on Boreholes, Models and associated Representations. Each registry and its entries are identified by a URI that can be addressed in data flows when needed. The system provides human and machine-readable representations of these vocabularies.

Along with the resolver, each information element (e.g., data, service, metadata…) served from TCS GIM to the EPOS ICS-C is assigned a URI under the same URI[16] base, which allows:
- fine grained identification,
- external systems to refer to them and dereference the content when needed,
- guarantee access to those information resource to external systems without impacting when a resource provider changes within the TCS.

14 https://gitlab.brgm.fr/brgm/epos/epos-tcs-gim/-/tree/master/Documents/EPOS_Lite (last accessed 07/06/2022)

15 https://external.opengeospatial.org/twiki_public/GeoScienceDWG/WebHome (last accessed 07/06/2022)

16 https://data.geoscience.earth/ (last accessed 21/06/2022)

6. Discussion

Essential base information for all disciplines in solid Earth science, whatever they describe, is geology or is a property that depends on geology or is an interpretation of such properties. Thus, geological data are the baseline in all Earth Sciences research. They are essential for increasing our multidisciplinary knowledge about the planet Earth and the transformation of this knowledge into innovation, i.e. value that supports a sustainable society. How this is done or could be approached is discussed with the help of examples from the TCS GIM achievements.

6.1 Serving multidisciplinary scientific drilling data

In-situ subsurface information is the least accessible part of geoscience information. However, it is very valuable for interpreting complex data sets and building relevant models of the solid Earth. Although drillings can only penetrate the uppermost curst, this is the deepest in-situ information that is accessible, and it is from the part that is of most importance for society.

A scientific borehole usually produces substantial sample material (drill core) supplemented by a geological description, image documentation and geophysical downhole logs. In special cases, time series data will be available from downhole sensors (e.g., downhole seismometers installed after drilling an active fault zone; piezometers in aquifers). A wide range of research can benefit from such data, like modelling groundwater flow patterns, heat flow and geothermal potential; rock mechanical testing and modelling for subsurface construction; and estimating the risk for seismic hazards to a settlement, mine or water reservoir close to a drilled fault zone. Data discovery for multidisciplinary data sets in the EPOS Portal provides an overview over the scientific (and other) boreholes of the area. Already at this stage- provided by the View-WMS of the European Borehole Index- information about the availability of data sets is available and the geological description can be dereferenced either directly or via the complex borehole service. This facilitates the scientists' selection of relevant objects. The complex service also provides information on whether the borehole is accessible for complimentary studies, its dimensions and last known conditions (where specified) and collected drill core samples. References to the International Geo Sample Numbers of the borehole and samples provide the opportunity to interface IGSN services from the EPOS GIM borehole service that allow scientists to screen the entire drill core virtually for further assessment of the borehole's relevance to the topic or require access to the physical samples in the core archive. In this way, for example, seismologists and rock physicists can discover and access sensor data from a fault zone that was penetrated by the borehole, combine it with downhole logging data and compare results with images of the drill core (on an IGSN service) before they sample the optimal pieces of core for laboratory measurements and, eventually, add new research data to EPOS services. In the larger picture, data from the EPOS GIM borehole service would add an additional dimension to the regional model that is based on surface geology and seismological data, InSAR satellite and GNSS data for surface motion and tectonic analysis, and existing laboratory data on rock samples from the area – all discovered and provided by EPOS community services.

6.2 Groundwater monitoring

From a Borehole Index entry, one can access the hydrogeological logs available along with the description of (i) the monitoring facility, e.g., piezometer, (ii) the aquifer being monitored and (iii) the observations/measurements acquired by the monitoring facility (Fig. 3). All the elements in this data graph are described according to well-established international interoperability standards (such as OGC/ISO Observations & Measurement, OGC GeoSciML, INSPIRE Data Specifications, etc.).

Figure 3 exemplifies how such a fully Linked Data approach improves multidisciplinary science. Currently in many Geological Surveys legacy systems, each “box” shown on this figure is “siloed” in its own information system. In such a context, the end user must have an intimate knowledge of where are all the corresponding datasets/services, how to connect to them and search the data of interest within each database. A fully Linked Data approach allows to go all across those siloes from one object description (e.g., one borehole) to another (one geological log).

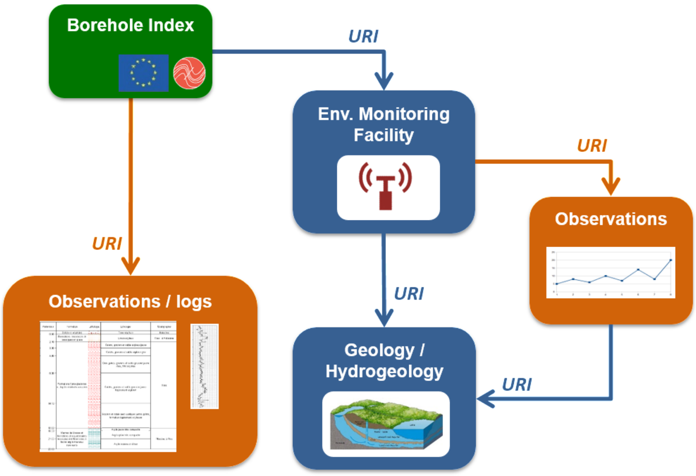

Figure 3. Simplified representation of the data graph. Each arrow represents the link from one instance to another. From one borehole description selected in the index, one can access the environmental monitoring facility (sensor), the observations acquired and the description of the concerned hydrogeological unit(s). In addition, the various geology/hydrogeology logs available at the borehole are also accessible.

Building on this approach that utilizes pre-existing open source libraries, interoperable client tools can be deployed in a generic way. For example, an open source desktop GIS software such as QGIS[17] can be used to ingest and interact with the interoperable data (Fig. 4).

The Linked Data approach allows the end user to walk within and across data silos using features provided by a community (e.g., a geologic fault, a borehole, etc.) as a reference, without being the original data provider of that feature and without requiring additional data integration mechanics. This fosters multidisciplinary work as the access to relevant and useful data content is direct and immediate.

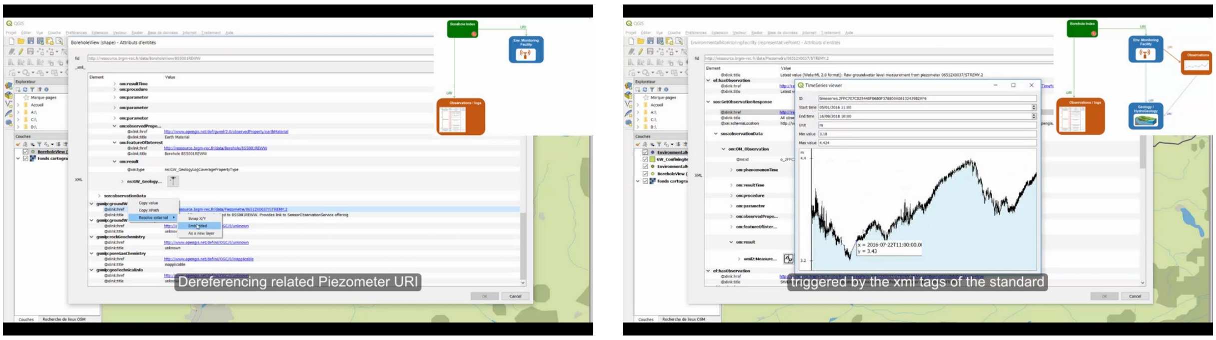

Figure 4. Discovery of borehole Linked Data using QGIS GML Application Schema Toolbox.

Figure 5 illustrates another example of interaction within TCS GIM data graph via the interaction of the EPOS Data Portal with the Borehole Index services. Starting from the web map service to spatially scope the search (millions of boreholes on the map), it is then narrowed down to a limited data set and the web feature service is used to identify the Borehole Index entries relevant to a given need. After an entry is selected, more content (code list definition, logs) are accessed by fetching Linked Data content.

17 https://www.qgis.org (last accessed 07/06/2022)

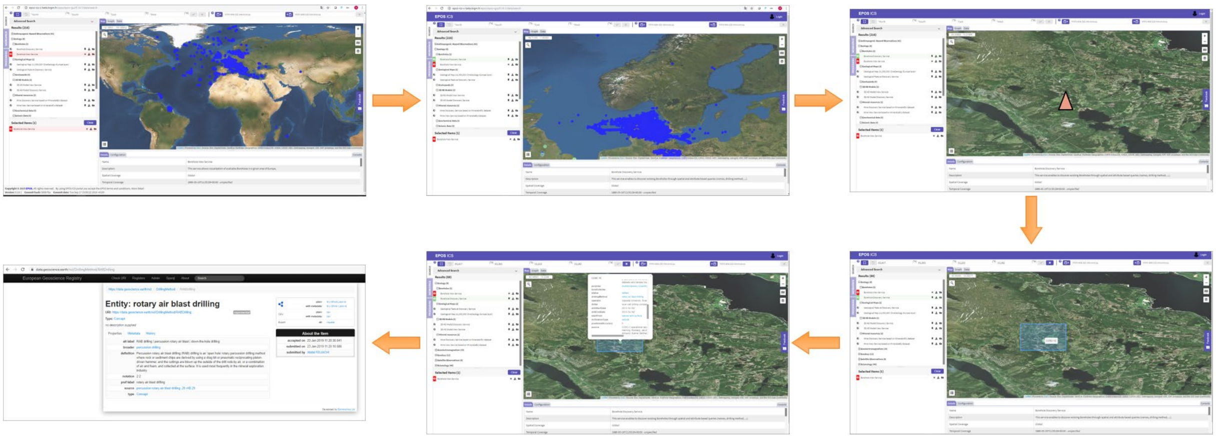

Figure 5. Working sequence using the EPOS Data Portal to access detailed borehole information.

The subsequent steps are either data download for local analysis on the end user's system or triggering the borehole visualization tools in the EPOS Data Portal using TCS GIM dedicated libraries. This way, the user interacts with the data served by the EPOS platform, including the possibility of "bookmarking" the data URIs for later use or passing the data payload to a distributed processing system, the EPOS ICS-D [Cocco et al., 2022].

6.3 Data integration using borehole logging information for 3D modelling of geological structures

Beyond the correlation of borehole logs and existing geological models, Figure 6 illustrates the application of a web-based fusion of information from 3D modelling, neural network analysis and borehole logs. Such integration will enhance the definition of geological horizons, both spatially by control points and physically by information

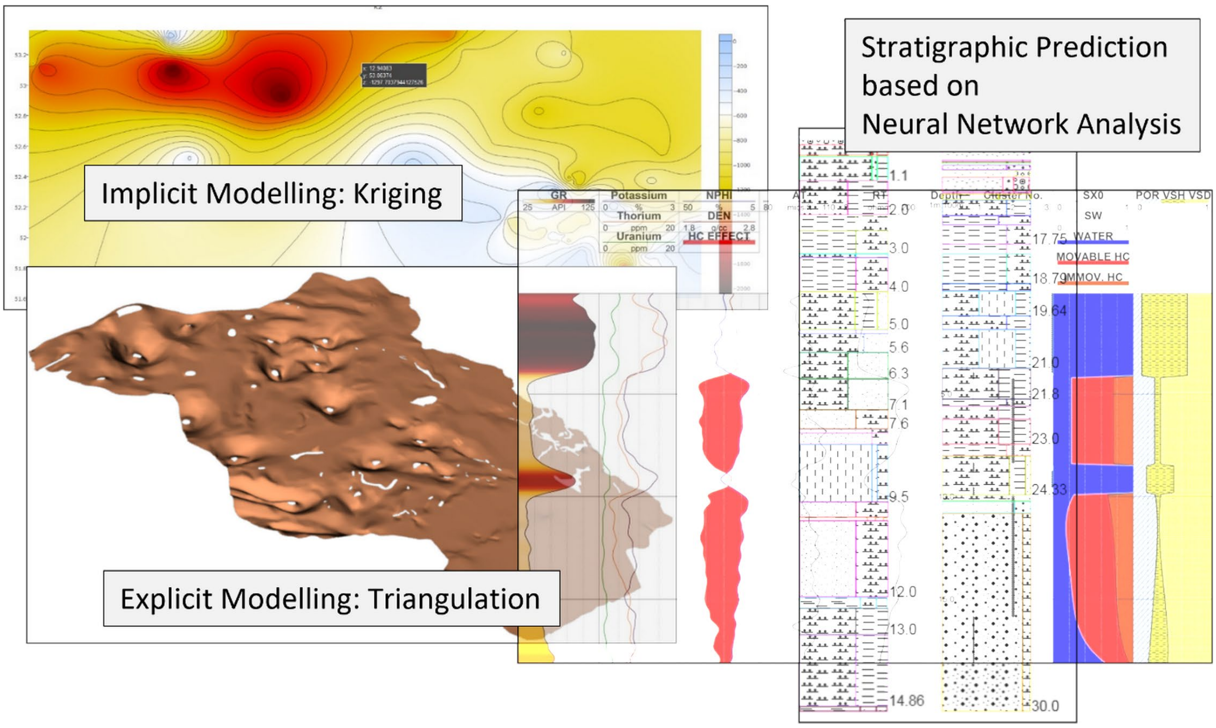

Figure 6. Correlation of borehole logs and geological models. Improvement with depth information of geological interfaces (point-clouds) derived from the analysis (e.g., visual or AI-based, evaluation) of borehole-logs and cores.

about composition and physical properties, and thus, substantially improve 3D models that encompass such horizons and information. The corresponding modelling processes can take place both in a collaborative environment such as a web-based application (Fig. 7 and Fig. 8) or a Jupyter Notebooks (Fig. 9). The improved models are relevant to a multitude of topics, from subsurface construction and critical infrastructure via groundwater, raw materials and energy to risk assessment of natural and anthropogenic hazards.

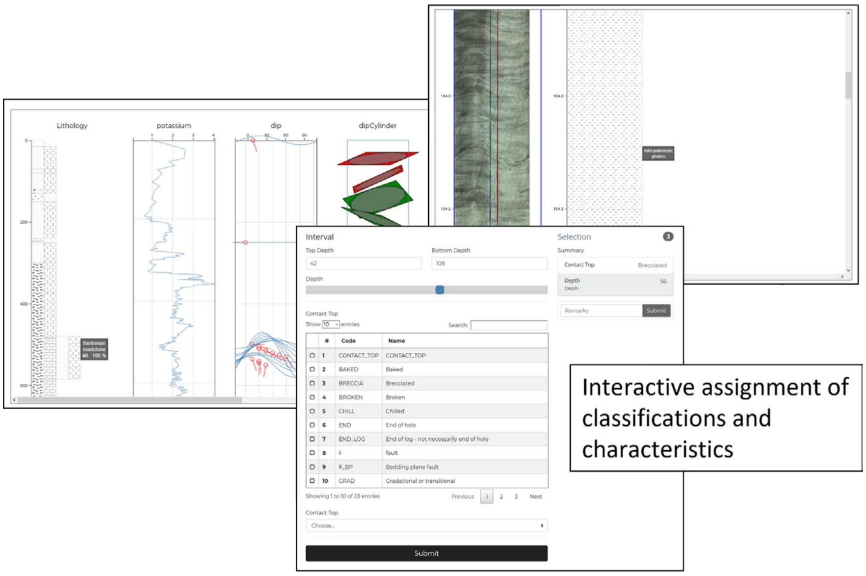

Figure 7. Interactive and web-based well log analysis. While visualizing borehole logs, the geologist can classify and distinguish geological structures, units, or formations together in a collaborative environment (e.g., Jupyter notebook) that provides all standard domain controlled vocabularies.

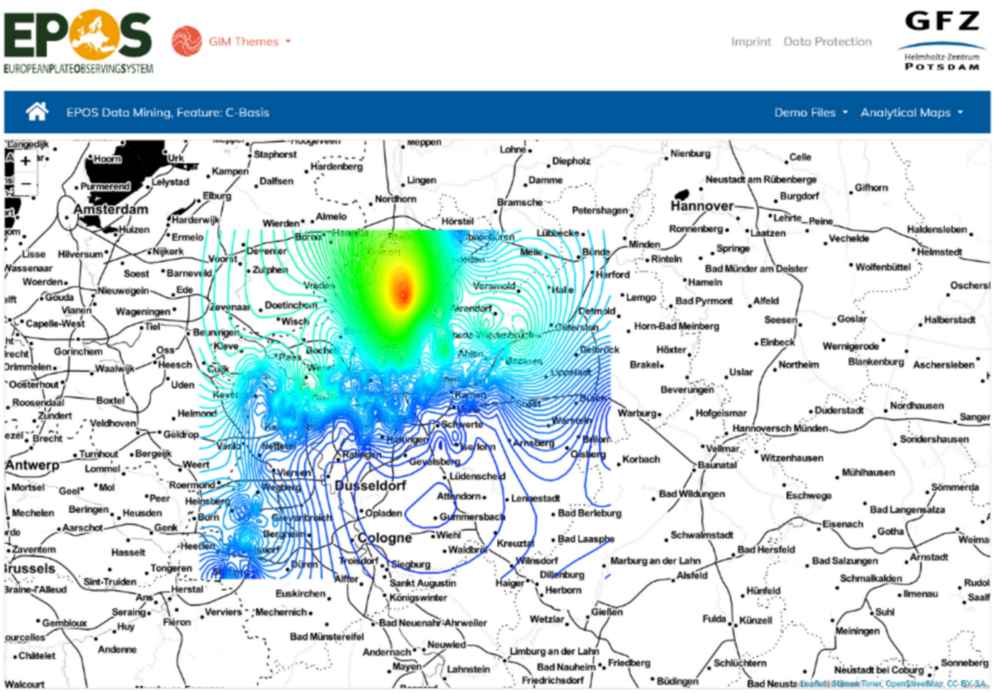

Figure 8. On-demand modelling of the bottom of a geological interface. Boreholes with lithostratigraphic logs provided by EPOS are used to either trigger services that compute (e.g., kriging) a 3D surface from a point cloud of depth information or interactively process the information in a Jupyter Notebook.

Another prominent example is the on-demand and web-based modelling of geological structures on the basis of logging information from boreholes provided by web services. Figure 9 illustrates the web-based modelling (kriging) of a geological horizon based on stratigraphic information from borehole logs provided by web services. As a major objective of the EPOS research infrastructure, this data mining and fusion process joins the power of data integration and modelling in one tool and provides it to the end user.

6.4 Data integration using a notebook in Iceland

The collaboration between largely heterogeneous geoscientific communities is facilitated by the adoption of interoperable services that provide standardized data. In return, these can be seamlessly integrated into scientific workflows or collaborative environments such as a Jupyter Notebook.

Figure 9. Snapshot of an animated earthquake visualization related to a plate boundary (Observable Notebook).

Figure 9 illustrates a use case on how the temporal development of earthquakes can be related to geological structures (plate boundary, in this case) and outlined by geological modelling. The example shows a working notebook application[18] correlating information from different domains. All the required information is searched for and retrieved through the data assets discovered thanks to the EPOS ICS-C metadata catalogue. Although this is a simple example, it perfectly illustrates how scientists can collaborate in a common environment by interactively processing heterogeneous information in a cross-domain manner.

6.5 Geological information to address societal questions

One of the main interests of a research infrastructure such as EPOS is the high-level disciplinary and cross-disciplinary interoperable services offered to scientists, the public and private stakeholders. Beyond a better understanding of the Earth system, also societal questions can be addressed such as the impact of anthropogenic hazards and the adaptation to climate change. A recently started research project (Geo-INQUIRE) [Cotton et al., 2022] aims to complement multi-scale approaches of anthropogenic hazard episodes. This interdisciplinary research will take advantage of the synergy between TCS GIM and TCS AH (Anthropogenic Hazard) [Orlecka-Sikora et al., 2020]

18 https://observablehq.com/@rhaener/japan-earthquakes-2011 (last accessed 21/06/2022)

data and product services through both the EPOS Data Portal and the EPISODES platform[19]. Extended access will then be improved to a wide range of multi-disciplinary data sets, e.g., geology, subsurface structures and hydrogeology information from boreholes, geophysical and broadband monitoring data, as well as technological data describing the cause of the man-induced hazards. In relation to the low carbon emission, a part of this project is about improving the CO2 storage. Geological characterization, geophysical data and water table monitoring data in combination with data from in-situ equipment (injection wells, laboratory facilities) shall improve underground CO2 storage. The result of this research on the gas-water-rock interaction will benefit from EPOS and ECCSEL[20] research infrastructures and contribute to develop the next generation of CCUS[21] technologies in an efficient and structured way, and help to enable the low to zero CO2 emissions goals of industry and power generation to combat global climate change.

6.6 Challenges

The fundamental challenge for a research infrastructure like EPOS is to provide more and richer data, as an ever increasing accuracy is a major trait of the present age. Computations can be increasingly complex and thus, include and produce more detail, and observations/analyses are increasing in resolution on the specimen level. However, this cannot be readily transferred to a complex and inhomogeneous system like the Earth, where observations on properties are comparatively few and unequally distributed, and with the perspective that this will not change in the foreseeable future.

Against this background, a first challenge is to increase geographical coverage. This was expected and thus, addressed from the very beginning by including a low cost of entry into the service design, with the intention that a high ratio between added value and costs to participate would encourage potential data providers to join the TCS GIM efforts.

The second challenge is to increase the granularity of the data where this is possible and viable, because the adaptation and preparation of data becomes more complex with increasing granularity, and the required effort increases. In addition, it has to be ensured that the underlying services, and the standards they rely on, are capable of dealing with the higher data granularity.

The third challenge in this context is to include new data types by extending the existing data models and services while keeping them fully interoperable and compliant with standards (e.g. diverse geophysical downhole logs in the borehole service). This is the least controversial challenge, as it follows needs defined by the community and is mainly limited by the available workpower/funding.

Much legacy data exist, but these are often only available in legacy formats and dispersed across diverse more or less well organized data stores. In general, it is not possible without a major financial and community effort to prepare such data for services like those of TCS GIM. However, new data are usually collected in a structured way and could be available without much delay, if this is supported by the communities.

7. Conclusion

The TCS GIM data models and services reuse and enhance well-established semantic and technical interoperability standards (ISO, OGC, IUGS/CGI, INSPIRE). With a unique Linked Data approach, consistent geoscience data are served for cross-disciplinary research. As such, this work improves standards and practices of the OGC and RDA communities. The consequent utilization of open source software and libraries facilitates the implementation and development of TCS GIM services in the community, and provides for easy adaptation to other purposes. The combination of these technologies guarantees that the services can be interfaced and digested by other services and end users, utilizing both, open source and proprietary software.

19 EPISODES: https://tcs.ah-epos.eu/ (last accessed 08/06/022)

20 https://eccsel.org (last accessed 08/06/022)

21 CCUS: CO2 Capture, Use, Transport and Storage

TCS GIM addresses the challenge of providing more and increasingly detailed data with a continued development towards new data types and with a high added-value to cost ratio, in order to attract new data providers and in this way increase geographic coverage and data density. Thus, community outreach is a major task for the coming years.

With this approach, EPOS TCS GIM and its services further multidisciplinary Earth sciences research, which is essential to maximize the gain in new knowledge and its transformation to value for a sustainable society.

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References

Beaufils M., Kemp C. (2018). OGC GeoScience Domain Working Group: A forum to enhance and organize geoscience data standardization. Resources for Future Generations – RFG2018, Jun 2018, Vancouver, Canada. ⟨hal-01753163⟩.

Čápová D., J. Šinigoj, M. Urvois, M. Harrison, P. Bell, M. Sanabria, J. Hernández Manchado, M. Pedersen, J. Tulstrup (2021). Geodata management in a European perspective – The European Geological Data Infrastructure (EGDI), In GeoKarlsruhe 2021 Conference Abstracts.

Cocco M., C. Freda, K. Atakan, D. Bailo, K. Saleh Contell, O. Lange and J. Michalek (2022). The EPOS Research Infrastructure: a federated approach to integrate solid Earth science data and services. Ann. Geophys., 65, 2, https://doi.org/10.4401/ag-8756.

Cotton F., A. Strollo, K. Fleming, G. Festa, S. Murphy, M. Majdański, F. Haslinger, S. Wiemer, H. Pedersen, H. Crowley, M. Urvois, M. Harrison, S. Lorito, A. Babeyko1, D. Bailo, O. Lange (2022). Geo-INQUIRE – a new opportunity for exploiting European geoscience infrastructure for curiosity-driven research through test sites and training, In Il Convegno Nazionale del Gruppo Nazionale di Geofisica della Terra Solida.

Conze, R., Lorenz, H., Ulbricht, D., Elger, K., and Gorgas, T.: Utilizing the International Geo Sample Number Concept in Continental Scientific Drilling During ICDP Expedition COSC-1, 16, https://doi.org/10.5334/dsj-2017-002, 2017.

D. de Oliveira D., M. João Ferreira, M. Sadeghi, N. Arvanitidis, G. Bertrand, S. Decrée, H. Gautneb, E. Gloaguen, T. Törmänen, H. Reginiussen, H. Sievers, L. Quental, A. Wittenberg (2021). FRAME's (Forecasting and Assessing Europe's Strategic Raw Materials Needs) innovative research in mineral raw materials on the eve of the EU's "Green Deal", In GeoKarlsruhe 2021 Conference Abstracts.

Discovery-WFS: https://www.ogc.org/standards/wfs (last accessed 07/06/2022).

European Commission (2013). Data specification on Natural Risk Zones – Technical guidelines. European Commission, Joint Research Centre, D2.8.III.12_v3.0, 135.

Flindt Jørgensen L., E. Deady, Š. Kumelj, K. Aslaksen Aasly, M. Urvois, J. Tulstrup, M. Pedersen (2021). Harmonised data on European raw materials, the creation and content of the MIN4EU database, In GeoKarlsruhe 2021 Conference Abstracts.

EarthResourceML-Lite: https://cgi-iugs.org/project/earthresourceml/ (last accessed 07/06/2022).

EGDI: European Geological Data Infrastructure: www.europe-geology.eu (last accessed 07/06/2022).

EPOS Data Portal: https://www.ics-c.epos-eu.org/data/search (last accessed 07/06/2022).

EPOS-IP project: https://www.epos-eu.org/ (last accessed 07/06/2022).

EPOS-GeoSciML-Lite profile: https://gitlab.brgm.fr/brgm/epos/epos-tcs-gim/-/tree/master/Documents/EPOS_GeoSciML_Lite_Profile (last accessed 07/06/2022).

EuroGeoSurveys: Association of the Geological Surveys of Europe: http://www.eurogeosurveys.eu/ (last accessed 07/06/2022).

European Geoscience Registry: https://data.geoscience.earth/ncl/ (last accessed 07/06/2022).

Gloaguen E., P. Higueras, G.Iacono-Marziano, A. Lima, D. Pierre, et al. (2020). ERA-MIN2 AUREOLE project: Targeting EU critical metals (Sb, W) and predictibility of Sb-As-Hg environmental issues, EGU General Assembly Conference Abstracts, https://hal-brgm.archives-ouvertes.fr/hal-02594902.

GeoSciML4: https://www.ogc.org/standards/geosciml (last accessed 07/06/2022).

GeoSciML-Lite: OGC 16-008: https://docs.opengeospatial.org/is/16-008/16-008.html (last accessed 07/06/2022)

Gourcerol B., E. Gloaguen, J. Melleton, J. Tuduri, X. Galiègue (2019). Re-assessing the European lithium resource potential – A review of hard-rock resources and metallogeny, Ore Geol. Rev., 10.1016/j.oregeorev.2019.04.015.

GroundWaterML 2.0: https://www.ogc.org/standards/gwml2 (last accessed 07/06/2022).

Habets F., S. Gascoin, S. Korkmaz, D. Thiéry, M. Zribi, et al. (2010). Multi-model comparison of a major flood in the groundwater-fed basin of the Somme River (France), Hydrol. Earth Sys. Sci., Europ. Geosci. Union, 14, 99-117, 10.5194/hess-14-99-2010.

Haener R., S. Grellet, H. Lorenz (2019). Establishing a knowledge management for the interdisciplinary exchange of geoscientific information and models, In EGU General Assembly Conference Abstracts, 5565.

Haener R., H. Lorenz, S. Grellet, S. Hameau, F. Robida, J. Waechter (2018). Architectural patterns for web-based information processing in scientific infrastructures, In EGU General Assembly Conference Abstracts, 13680.

ICDP (International Continental Scientific Drilling Program): www.icdp-online.org (last accessed 10/06/2022).

IGSN (International Geo Sample Number): https://www.igsn.org/ (last accessed 07/06/2022).

INSPIRE (Infrastructure for spatial information in Europe) https://inspire.ec.europa.eu/ (last accessed 07/06/2022).

INSPIRE Register Federation: https://inspire.ec.europa.eu/register-federation/help.jsp (last accessed 07/06/2022).

IODP (International Ocean Discovery Program): https://www.iodp.org (last accessed 07/06/2022)

ISO 191xx Standards https://doi.org/10.1007/978-0-387-35973-1_811 (last accessed 10/06/2022).

ISO 19156:2011 / OGC 10-004r3 https://www.iso.org/standard/32574.html (last accessed 07/06/2022).

IUGS/CGI (Commission for the Management and Application of Geoscience Information of the International Union of Geological Sciences) https://cgi-iugs.org/ (last accessed 07/06/2022)

IUGS/GCI GTWG (Geoscience Terminology Working Group) https://cgi-iugs.org/project/geoscienceterminology (last accessed 07/06/2022).

Jupyter: https://jupyter.org/ (last accessed 07/06/2022).

Koers, H., D. Bangert, E. Hermans, R. van Horik, M. de Jong and M. Mokrane (2020). Recommendations for Services in a FAIR Data Ecosystem, Patterns, 1, 5, https://doi.org/10.1016/j.patter.2020.100058.

Kumelj Š., L. Flindt Jørgensen, F. Schjøth, A. Vihtelič, B.Bahar, K. Hribernik (2021). Collecting, sharing, and visualising harmonised data on European raw materials occurrences and mines – success or failure?, In GeoKarlsruhe 2021 Conference Abstracts.

Minerals4EU: http://www.minerals4eu.eu/ (last accessed 07/06/2022).

Mintell4EU: https://geoera.eu/projects/mintell4eu7/ (last accessed 07/06/2022).

Observations & Measurements: https://www.ogc.org/standards/om (last accessed 07/06/2022)

OGC Open Geospatial Consortium: https://www.osgeo.org/ (last accessed 07/06/2022).

OGC GeoScience Domain Working Group: https://external.opengeospatial.org/twiki_public/GeoScienceDWG/WebHome (last accessed 07/06/2022).

OGC/ISO Complex Feature: https://www.iso.org/committee/54904/x/catalogue/ (last accessed 07/06/2022).

OGC10-100r3: Geography Markup Language (GML) simple features profile: https://portal.ogc.org/files/?artifact_id=42729 (last accessed 08/06/2022).

OGC Geoscience Markup Language 4.1 (GeoSciML). OGC 16-008. GeoSciML Modelling Team. Wayland, MA, USA, Open Geospatial Consortium Inc.

Orlecka-Sikora, B., S. Lasocki, J. Kocot et al. (2020). An open data infrastructure for the study of anthropogenic hazards linked to georesource exploitation, Sci. Data, 7, 89, https://doi.org/10.1038/s41597-020-0429-3.

Perrin J., C. Cartannaz, G. Noury, E. Vanoudheusden (2015). A multicriteria approach to karst subsidence hazard mapping supported by weights-of-evidence analysis, Engin. Geol., 10.1016/j.enggeo.2015.09.001

ProMine: http://promine.gtk.fi/ (last accessed 07/06/2022).

RDA: Research data Alliance – Vocabulary Services Interest Group: https://www.rd-alliance.org/groups/vocabulary-services-interest-group.html (last accessed 07/06/2022).

Saleh Contell K., K. Karlzén, H. Pedersen, M. Cocco, K. Atakan, D. Bailo, O. Lange, Mercurio D., G. Maracchia, A. Sangianantoni, D. Piras, M. Fredella and C. Freda (2022). Long-term sustainability of a distributed RI: the EPOS case, Ann. Geophys., 65, 2, https://doi.org/10.4401/ag-8786

TCS GIM: https://www.epos-eu.org/index.php/tcs/geological-information-and-modeling (last accessed 07/06/2022).

Semantic Web Layercake: https://www.w3.org/2007/03/layerCake.svg (last accessed 08/06/2022).

Berners-Lee T. (1989). Information Management: A Proposal, https://www.w3.org/History/1989/proposal.html (last accessed 08/062022).

Thiery Y., F. Lacquement, N. Marcot (2019). Landslides triggered in weathered crystalline rocks of moderate latitudes: A case study in Mediterranean environment (The Maures Massif, France), Engin. Geol., https//doi./10.1016/j/enggeo.2018.12.002.

Tulstrup, J., A. Tellez-Arenas, M. Pedersen, F. Robida, B. Pjetursson and C. Delfini (2016). The European Geological Data Infrastructure EGDI, in 35th International Geological Congress: IGC 2016.

Tomas R., M. Harrison, J.-I. Barredo, F. Thomas, I. M. Llorente, M. Pfeiffer, O. Čerba (2015). , Nat. Hazards, 78, 3, 1545-1563, https://doi.org/10.1007/s11069-015-1786-7.

URI (Uniform Resource Identifier): IETF rfc3986: Generic Syntax https://datatracker.ietf.org/doc/html/rfc3986 (last accessed 07/06/2022).

Urvois, M., S. Grellet, A. Feliachi, H. Lorenz, R. Haener, C. Brogaard Pedersen, M. Hansen, L. Guerrieri, C. Cipolloni, M. Carter (2020). Open access to geological information and 3D modelling data sets in the European Plate Observing System platform (EPOS), In EGU General Assembly Conference Abstracts, 5131, https://doi.org/10.5194/egusphere-egu2020-5131.

Vergnes J.-P., N. Roux, F. Habets, P. Ackerer, N. Amraoui, et al. (2020). The AquiFR hydrometeorological modelling platform as a tool for improving groundwater resource monitoring over France: evaluation over a 60-year period, Hydrol. Earth Sys. Sci., 24, 633-654, 10.5194/hess-24-633-2020.

View-WMS: https://www.ogc.org/standards/wms (last accessed 07/06/2022).

W3C (2017a). World Wide Web Consortium recommendations: Data on the Web Best Practices, https://www.w3.org/TR/dwbp/ (last accessed 08/06/2022).

W3C (2017b). World Wide Web Consortium Working Group Note: Spatial Data on the Web Best Practices, https://www.w3.org/TR/sdw-bp/ (last accessed 08/06/2022).

Wilkinson, M. D., M. Dumontier, J. Ij.Aalbersberg, G. Appleton, M. Axton, A. Baak, et al. (2016). The FAIR guiding principles for scientific data management and stewardship, Sci. Data, 3, 160018, https://doi.org/10.1038/sdata.2016.18.

World Wide Web Consortium – Data on the Web Best Practices: https://www.w3.org/TR/dwbp/ (last accessed 07/06/2022).

World Wide Web Consortium – Spatial Data on the Web Best Practices: https://www.w3.org/TR/sdw-bp/ (last accessed 07/06/2022).

***CORRESPONDING AUTHOR: Marc URVOIS**,
BRGM, French Geological Survey, 45100 Orléans, France
e-mail: m.urvois@brgm.fr

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APPENDIX TO

INTEGRATING GEOLOGICAL DATA IN EUROPE TO FOSTER MULTIDISCIPLINARY RESEARCH

Marc Urvois[1], Sylvain Grellet[1], Henning Lorenz[2], Rainer Haener[3], Christelle Loiselet[1], Matthew Harrison[1], Matija Krivic[4], Christian Brogaard Pedersen[5], Marianne B. Wiese[5], Amelia Baptie[6], Martin Nayembil[6], James Trench[7], Ivor Marsh[8], Carlo Cipolloni[9], Chiara D'Ambrogi[9], Maria Pia Congi[9]

[1] BRGM, French Geological Survey, Orléans, France
[2] Uppsala University, Department of Earth Sciences, Uppsala, Sweden
[3] GFZ, Helmholtz Centre Potsdam, German Research Centre for Geosciences, Potsdam, Germany
[4] GeoZS, Geological Survey of Slovenia, Ljubljana, Slovenia
[5] GEUS, Geological Survey of Denmark and Greenland, Copenhagen, Denmark
[6] BGS, British Geological Survey, The Lyell Centre, Edinburgh, United Kingdom
[7] GSI, Geological Survey Ireland, Booterstown Hall, Ireland
[8] Marsh Technology, Ireland
[9] ISPRA, Italian Institute for Environmental Protection and Research, Department for The Geological Survey of Italy, Roma, Italy

Acronyms

AH: Anthropogenic Hazards

CCUS: CO2 Capture, Use, Transport and Storage

ECCSEL: European Carbon Dioxide Capture and Storage Laboratory Infrastructure

EGDI: European Geological Data Infrastructure

EGS: EuroGeoSurveys – Association of the Geological Surveys of Europe

EPOS-IP: EPOS Implementation Phase

FAIR: Findable, Accessible, Interoperable, Reusable

GNSS: Global Navigation Satellite System

GIM: Geological Information and Modelling

HTTP: HyperText Transfer Protocol

ICDP: International Continental Scientific Drilling Program

ICS-C: EPOS Integrated Core Services-Central Hub

ICS-D: EPOS Integrated Core Services-Distributed

IGSN: International Geo Sample Number

INSPIRE: Infrastructure for spatial information in Europe

IODP: International Ocean Discovery Program

ISO: International Standard Organisation

IUGS/CGI: Commission for the Management and Application of Geoscience Information of the International Union of Geological Sciences

URI: Uniform Resource Identifier

OGC: Open Geospatial Consortium

RDA: Research Data Alliance

TCS: EPOS Thematic Core Services

WFS: Web Feature Service

WMS: Web Map Service

W3C: World Wide Web Consortium