GEO CONNECT³d

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Deliverable 3.3

Ways to disclose essential subsurface data and information to different stakeholders

Authors and affiliation:
Johanna Van Daele – VPO
Katrijn Dirix – VITO
Helga Ferket – VPO

E-mail of contact person:
johanna.vandaele@vlaanderen.be

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GENERAL INTRODUCTION

This deliverable presents how the annotated Roer-to-Rhine-model (R2R) can be disclosed to civil servants and policy makers for in-depth discussions on subsurface management in the R2R area. This entails different geo-resources, subsurface applications (e.g., ground water production, geothermal energy, CO_2-storage, etc.) and hazards. On a methodological level, several ways to disclose essential data on the subsurface were explored. Additionally, it was attempted to reach out to stakeholders from different organizational (e.g., public, private, civil society) and political levels (i.e., federal, inter-regional, regional, local) during several workshops and conferences. Their opinion about planning and organizing the exploitation of the subsurface, as well as their feedback on the Structural Framework (SF) and Geomanifestations (GM) approach are incorporated in this report as well.

This report furthermore builds on results from four (sub-)tasks of GeoConnect³d:

- Development of an IT-tool to disclose the augmented SF+GM info to stakeholders in an easily accessible and transparent way (T3.1 & T3.2);
- Identification of new insights regarding potential subsurface use by integrating the SF and GM databases of the R2R study area (D5.2c);
- Exchange with stakeholders at the level of the R2R area about the potential applications and valorization of the deep subsurface, the possible footprint with respect to current and future activities, and the associated challenges and research needs (D5.1 & M8a);
- Interaction with stakeholders at the pan-European level to inform them how annotated models such as the R2R-model can provide useful data to gain knowledge on the possible deep subsurface applications (M9 & D3.2).

Firstly, this report describes the methodological aspects of the SF and GM database (chapter 1). This is followed by a short summary of the feedback received from the stakeholder public, both on the content of the databases and the visualization and usability (chapter 2). Lastly, a short analysis is made in which way the SF+GM approach of GeoConnect³d meets the needs of policy makers, and recommendations for future research activities are given (chapter 3).

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1 CHAPTER 1: METHODOLOGICAL CHALLENGES AND DECISIONS

1.1 Input selection

The construction of every new database inevitably starts with the question what will be included and, consequently, what will be left out. Straightforward criteria have to be defined for this, both for the developers (to build an "as-complete-as-possible" and correct database) and for future users (to know for what the database can and cannot be used, or for later database expansion). Generally, these decisions concern which kind of entries will be included, the information sources considered as sufficiently reliable and the level of detail that is both desirable and workable. For the Structural Framework (SF) and Geomanifestations (GM) databases, a few additional, very specific questions needed to be carefully considered:

- What minimum size of units and limits are included in the Structural Framework? Are we going to gather 2D or 3D information? For which reference surfaces will we gather information?
- What different types of Geomanifestations are included? When is an entry defined as anomalous? Are 'normal' values completely excluded or kept as separate records in the database?

For the Structural Framework, it was concluded to include both detailed and more large-scale data, as the zooming-feature allows distinguishing between both (see section 1.2.2). To cover for the different attributes that are associated with the data, depending on whether they originated from 3D fault planes or rather 2D maps, most of the database attributes were made optional. Furthermore, each project partner was asked to start the process by constructing a shortlist of the most important structures in his area. These structures then provided the backbone for grouping all the data in the study area into a logical hierarchy.

The GM database of the R2R study area comprises the following types of Geomanifestations: thermal anomalies, CO_2-seeps, He-anomalies, polymetallic veins, seismicity data, illite crystallinity, volcanic phenomena, seismic amplitude anomalies, collapse structures and surface movement. Clear definitions were agreed upon for each Geomanifestation type, and are summarized below in

TABLE 1. Evidently, it is easier to establish distinct criteria for Geomanifestations if they can be represented in a quantitative way compared to more qualitatively characterized Geomanifestations. To check if a specific entry qualified as ‘anomalous’, data from published articles and (technical) reports, webpages and tourism leaflets was used (e.g., thermal anomalies, volcanic phenomena), as well as results from own research and interpretations (e.g., seismic amplitude anomalies and collapse structures).

TABLE 1: DEFINITIONS OF THE DIFFERENT GEOMANIFESTATION TYPES INCLUDED IN THE GM DATABASE FOR THE R2R AREA.

Geomanifestation type	**Definition (“or”)**
Thermal anomalies	- shallow (< 500 m) T > 12 °C - deep (> 500 m) T > 10 °C + 30 °C/km - springs/ponds that do/did never freeze over severe winters
CO_2-seeps	- CO_2-rich water; > 250 mg CO_2/l - ‘dry’ CO_2-mofettes - cold water geysers - travertine precipitation - visual observations of bubbles (Sauerbrunnen, Sauerlinge, Drees, …)
He-anomalies	- gas with > 5.22 ppmv He - $^3He/^4He > 1.4 * 10^{-6}$ (R/RA > 1)
Polymetallic veins	Locations of metal-rich veins, including polymetallic and 5-element veins (Bi, Co, Ni, Ag, U)
Seismicity data	An earthquake (either induced or naturally occurring)
Illite crystallinity	Illite crystallinity data that are anomalous with respect to the expected maximum burial depth according to its stratigraphic position
Volcanic phenomena	Volcanoes, maars and calderas in the Eifel area
Seismic amplitude anomalies	Distinct expressions on a seismic image, detected or confirmed using AVO analysis
Collapse structures	Local depressions on seismic data
Surface movement	More than 2 mm movement of the earth surface in the satellite line-of-sight (INSAR-data)

It was decided to only include anomalous values, i.e., actual Geomanifestations. This has the implication that anomalies with a quantitative character (e.g., temperature or concentration values) cannot, at least within the GM database, be compared to surrounding non-anomalous values (e.g., a neighboring spring with less CO_2 or a colder temperature), but only to other anomalies. Despite losing the functionality of comparing Geomanifestations with the local background signature, this approach was found most consistent across the diverse Geomanifestation types (not all are quantitatively defined), and most efficient (focus on the real target, anomalies, while not having to inventory tons of ‘normal’ data).

1.2 Structure of the database

Once it had been decided which type of entries would be included in the database, its structure had to be designed to bring order in the huge amount of data points, lines and polygons.

The applied database structure actually is one of the most important strengths of the GeoConnect³d databases, especially for the Structural Framework. Both the Structural Framework and Geomanifestations databases consist of three interconnected components:

1. Semantic data (vocabulary structure)
2. Spatial data (including geometry data and shapefile attributes)
3. Database attributes

1.2.1 Semantic data

In order to organize, contextualize and visualize the elements in the different zoom levels, all entries are included in a hierarchical structure based on the Simple Knowledge Organization System (SKOS) (see Deliverable 2.4 (Barros & Piessens, 2020) for full details). SKOS allows for concepts to be identified using URIs. Each concept can be labelled with lexical strings, documented with various types of notes, linked to other concepts and organized into informal hierarchies and association networks. These networks are aggregated into concept schemes, and mapped to concepts in other schemes (Miles et al., 2009). The vocabulary hence serves as a dictionary explaining all the elements present in the Structural Framework and Geomanifestations databases.

SKOS uses two categories of semantic relations: hierarchical and associative, both of which contain three types of concepts to express relationships between elements: broader, narrower and related (FIGURE 1).

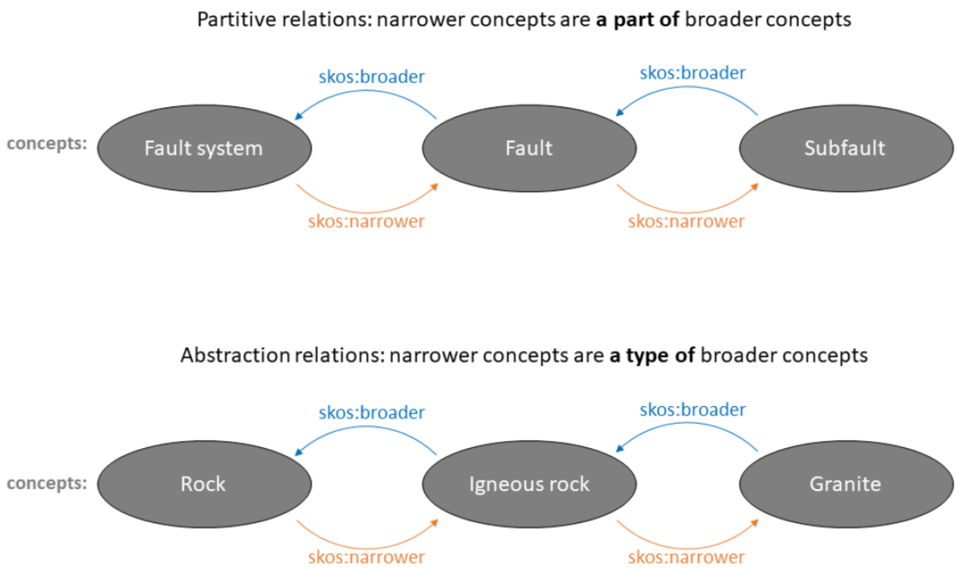


FIGURE 1: DIFFERENT TYPES OF RELATIONSHIPS ADOPTED IN THE GEOCONNECT³D STRUCTURAL FRAMEWORK AND GEOMANIFESTATIONS DATABASES

The vocabulary structure is created by means of a spreadsheet. In this spreadsheet the hierarchical structure is visualized by a set of 'concept-columns'. Narrower information is always stored in a column right to the broader concepts. Each concept is linked to a unique conceptID and contains a definition and at least one bibliographic citation. In addition, information is stored regarding the type of limit, unit or Geomanifestation. Finally, in the case of the SF, columns are foreseen that provide the link between the limits and the units.

conce	conce	conce	concept	concept	concept	notation	gc3d:limitType	gc3d:limitType	dcterms:type	limitTo	definition
	Pripyat-Dnieper Donets fault system					GSB_c1071	LT_0401|Normal fault		L_0002|Fault system	GSB_c3066|Pripyat-Dnieper Donets rift	Fault system bounding the Pripyat-Dnieper-
	Eger fault system					GSB_c2020	LT_0401|Normal fault		L_0002|Fault system	GSB_c3061|Eger graben	Fault system bounding the Eger Graben (Jäh
	NW European Rift System					TNO_001001	LT_0401|Normal fault		L_0001|Large-scale fault system		Northern segment of the European rift syst
		West-Netherlands large scale fault system				TNO_001002	LT_0401|Normal fault		L_0001|Large-scale fault system	TNO_99001|West Netherlands Basin	Westernmost part of the European rift syst
		Roer Valley Graben large-scale fault system				VITO_c01000	LT_0401|Normal fault	LT_0402|Reverse fault	L_0001|Large-scale fault system	VITO_99001|Roer Valley graben	Faults part of the Roer Valley Graben which
			Cenozoic faults in the RVG large-scale fault syst			VITO_c01005	LT_0401|Normal fault		L_0002|Fault system		Group of faults situated within the RVG larg
			Reactivated Mesozoic faults in the RVG large-sc			VITO_c01006	LT_0402|Reverse fault	LT_0402|Reverse fault	L_0002|Fault system		Group of faults situated within the RVG larg
			Non-reactivated Subhercynic faults in the RVG l			VITO_c01007	LT_0401|Normal fault	LT_0404|Thrust fault	L_0002|Fault system		Group of reverse- and thrust faults faults si
			Feldbiss fault system			VITO_c01100	LT_0401|Normal fault	LT_0402|Reverse fault	L_0002|Fault system		Group of normal faults in the western bord
				Neeroeteren-Grote_Brogel_O-(		VITO_c01101	LT_0401|Normal fault	LT_0402|Reverse fault	L_0003|Fault		Normal fault in the RVG large-scale fault sy
				Grote_Brogel_W		VITO_c01102	LT_0401|Normal fault	LT_0402|Reverse fault	L_0003|Fault		Normal fault in the RVG large-scale fault sy
				Bocholt		VITO_c01103	LT_0401|Normal fault		L_0003|Fault		Normal fault in the RVG large-scale fault sy
				Hamont-Valkenwaard fault		VITO_c01104	LT_0401|Normal fault		L_0003|Fault		Normal fault in the RVG large-scale fault sy
				Reppel		VITO_c01105	LT_0401|Normal fault		L_0003|Fault		Normal fault in the RVG large-scale fault sy
				Rotem-Heerleide fault		VITO_c01106	LT_0401|Normal fault	LT_0402|Reverse fault	L_0003|Fault		Normal fault in the RVG large-scale fault sy
				Elen		VITO_c01107	LT_0401|Normal fault		L_0003|Fault		Easternmost limit of the Feldbiss fault syste
				Süsterseeler Fault		GD NRW_c0018	LT_0401|Normal fault		L_0003|Fault		The Süsterseeler Fault is a branch of the Fel
				Rauw-Hoge Mierde fault		VITO_c01108	LT_0401|Normal fault		L_0003|Fault		Westernmost limit of the Feldbiss fault syst
				Rauw_2		VITO_c01109	LT_0401|Normal fault		L_0004|Subfault		Subfault of the Rauw fault.
				Cenozoic faults in the Feldbiss f		VITO_c01110	LT_0401|Normal fault		L_0002|Fault system		Group of faults situated within the Feldbiss
				Mesosoic faults in the Feldbiss f		VITO_c01111	LT_0401|Normal fault	LT_0402|Reverse fault	L_0002|Fault system		Group of faults situated within the Feldbiss
				Reusel fault		TNO_001003	LT_0401|Normal fault		L_0003|Fault		Fault parallel to- and east of the Rauw - Hc

FIGURE 2: EXAMPLE OF THE SEMANTIC DATA STRUCTURE INPUT FOR THE STRUCTURAL FRAMEWORK IN SPREADSHEET FORMAT.

This information is subsequently transformed into an online-information system that allows stakeholders to explore the vocabularies of the databases in a user-friendly way (https://data.geoscience.earth/ncl/geoera/geoconnect3d).

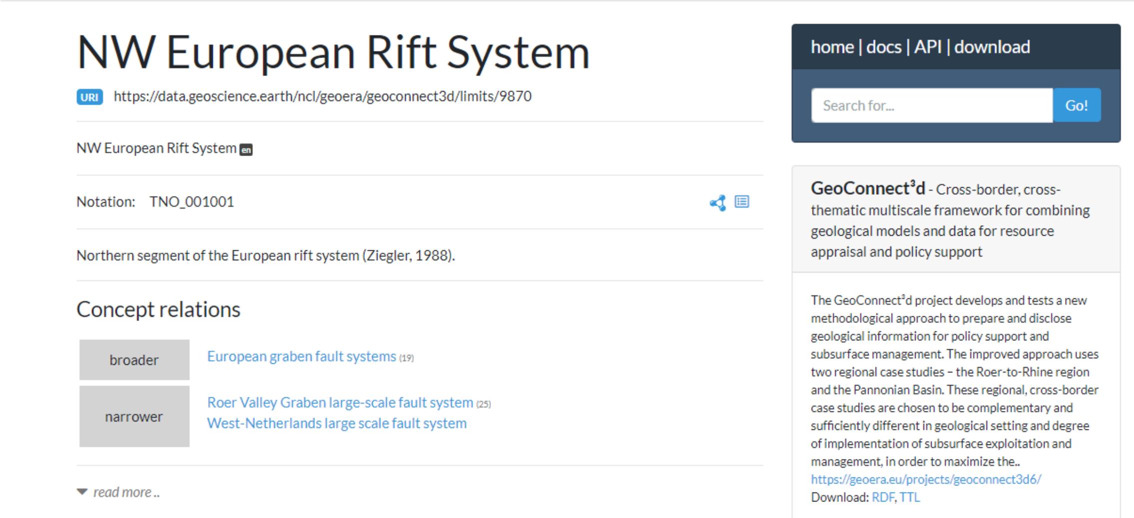
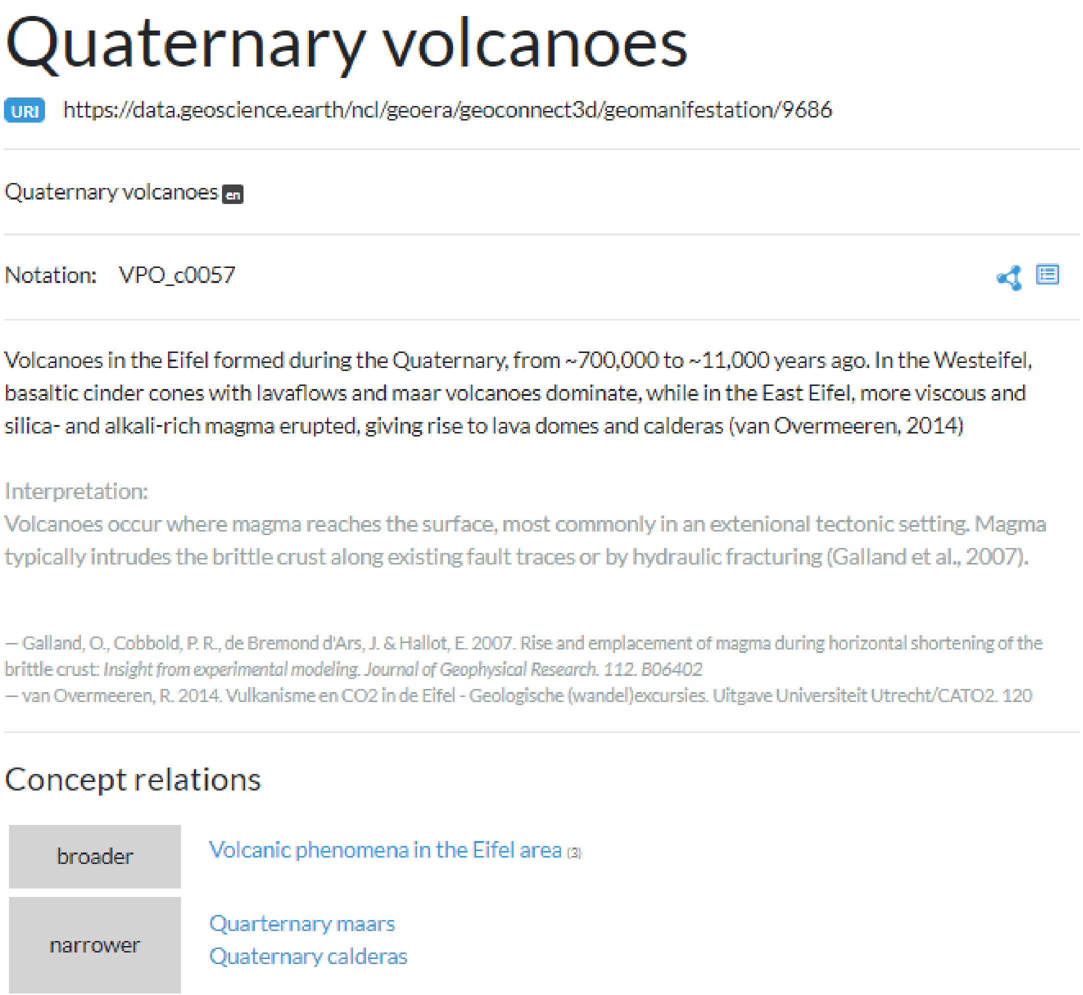


FIGURE 3: EQUIVALENT OF THE EXAMPLE IN FIGURE 2 IN THE INFORMATION SYSTEM THAT VISUALIZES THE SEMANTIC INFORMATION OF THE STRUCTURAL FRAMEWORK AND GEOMANIFESTATIONS DATABASES.

This approach was chosen as it allows to embed relationships between different entries in a very clear and understandable way, which proves to be a great help and added value for constructing and querying the database. At the same time, this methodology allows maintaining the flexibility that geological data needs. The biggest advantage of this methodology lies in the possibility to specify the differentiating characteristic of each concept level for every individual group or type of data. This is particularly helpful for the GM database, where different concept levels can represent, for example, a distinct location, mineralization type, lithological formation, age or volcanic phenomena type (FIGURE 4 & FIGURE 5).

concept	concept	concept	notation	definition	scopeNote	bibliographicCitation
Volcanic phenomena in the Eifel area			VPO_c0052	Geomorphological features that are associated to the magmatic activity in two Tertiary (Hocheifel and Siebengebirge) and two Quaternary (West and Easteifel) volcanic fields in the Eifel, such as volcanoes, maars and calderas (van Overmeeren, 2014).	Volcanic phenomena occur where magma reaches the surface or undeep subsurface, most commonly in an extenional tectonic setting. Magma typically intrudes the brittle crust along existing fault traces or by hydraulic fracturing (Galland et al., 2007).	Galland, O., Cobbold, P. R., de Br & Hallot, E. 2007. Rise and empl magma during horizontal shorte brittle crust: Insight from experi modeling. Journal of Geophysica B06402
	Tertiary volcanoes		VPO_c0054	Volcanoes formed in the Eifel during two periods in the Tertiary: ~42-34 Ma in the Hocheifel, and at 26-18 Ma more eastwards, in the Siebengebirge. The magmatic rock composition varies from basalt to trachyte. In contrast to the Quaternary volcanism, lava flows are rare (van Overmeeren, 2014).	Volcanoes occur where magma reaches the surface, most commonly in an extenional tectonic setting. Magma typically intrudes the brittle crust along existing fault traces or by hydraulic fracturing (Galland et al., 2007).	Galland, O., Cobbold, P. R., de Br & Hallot, E. 2007. Rise and empl magma during horizontal shorte brittle crust: Insight from experi modeling. Journal of Geophysica B06402
		Tertiary maars	VPO_c0053	Maars associated to the Tertiary volcanoes in the Hocheifel and Siebengebirge.	Maars are generated during explosive eruptions when rising magma (mostly along fault traces) encounters groundwater (van Overmeeren, 2014).	van Overmeeren, R. 2014. Vulka de Eifel - Geologische (wandel)e Universiteit Utrecht/CATO2. 120
	Quaternary volcanoes		VPO_c0057	Volcanoes in the Eifel formed during the Quaternary, from ~700,000 to ~11,000 years ago. In the Westeifel, basaltic cinder cones with lavaflows and maar volcanoes dominate, while in the East Eifel, more viscous and silica- and alkali-rich magma erupted, giving rise to lava domes and calderas (van Overmeeren, 2014)	Volcanoes occur where magma reaches the surface, most commonly in an extenional tectonic setting. Magma typically intrudes the brittle crust along existing fault traces or by hydraulic fracturing (Galland et al., 2007).	Galland, O., Cobbold, P. R., de Br & Hallot, E. 2007. Rise and empl magma during horizontal shorte brittle crust: Insight from experi modeling. Journal of Geophysica B06402
		Quarternary maars	VPO_c0055	Maars associated to Quaternary volcanoes in the West- and Easteifel.	Maars are generated during explosive eruptions when rising magma (mostly along fault traces) encounters groundwater (van Overmeeren, 2014).	van Overmeeren, R. 2014. Vulka de Eifel - Geologische (wandel)e Universiteit Utrecht/CATO2. 120
		Quaternary calderas	VPO_c0056	Calderas associated to Quaternary volcanoes in the West- and Easteifel.	Calderas result from the collapse of a large, undeep magma chamber, after it erupted explosively and rapidly discharged its magma (van Overmeeren, 2014).	van Overmeeren, R. 2014. Vulka de Eifel - Geologische (wandel)e Universiteit Utrecht/CATO2. 120

FIGURE 4: EXAMPLE OF THE HIERARCHICAL STRUCTURE IN THE GEOMANIFESTATION DATABASE IN SPREADSHEET FORMAT. FOR THE 'VOLCANIC PHENOMENA IN THE EIFEL AREA', FURTHER DISTINCTION INTO SEPARATE CONCEPTS IS BASED ON AGE AND MORPHOLOGY.



Quaternary volcanoes

URI https://data.geoscience.earth/ncl/geoera/geoconnect3d/geomanifestation/9686

Quaternary volcanoes en

Notation: VPO_c0057

Volcanoes in the Eifel formed during the Quaternary, from ~700,000 to ~11,000 years ago. In the Westeifel, basaltic cinder cones with lavaflows and maar volcanoes dominate, while in the East Eifel, more viscous and silica- and alkali-rich magma erupted, giving rise to lava domes and calderas (van Overmeeren, 2014)

Interpretation:
Volcanoes occur where magma reaches the surface, most commonly in an extenional tectonic setting. Magma typically intrudes the brittle crust along existing fault traces or by hydraulic fracturing (Galland et al., 2007).

— Galland, O., Cobbold, P. R., de Bremond d'Ars, J. & Hallot, E. 2007. Rise and emplacement of magma during horizontal shortening of the brittle crust: *Insight from experimental modeling. Journal of Geophysical Research. 112. B06402*
— van Overmeeren, R. 2014. Vulkanisme en CO2 in de Eifel - Geologische (wandel)excursies. Uitgave Universiteit Utrecht/CATO2. 120

Concept relations

broader	Volcanic phenomena in the Eifel area (3)
narrower	Quarternary maars Quaternary calderas

FIGURE 5: EQUIVALENT OF THE EXAMPLE IN FIGURE 4 IN THE ONLINE SYSTEM THAT VISUALIZES THE SEMANTIC INFORMATION OF THE STRUCTURAL FRAMEWORK AND GEOMANIFESTATIONS DATABASES.

1.2.2 Spatial data

Associated with the semantic structure are spatial data. These data consist of geometry shapefiles and shapefile attributes. Geometry data can be of point, line or polygon-format. In the geometry shapefiles the link is made between the conceptID of the vocabulary files. This allows to enrich the spatial data with the hierarchical information present in the vocabulary file, hence providing structure to the spatial information (FIGURE 6).

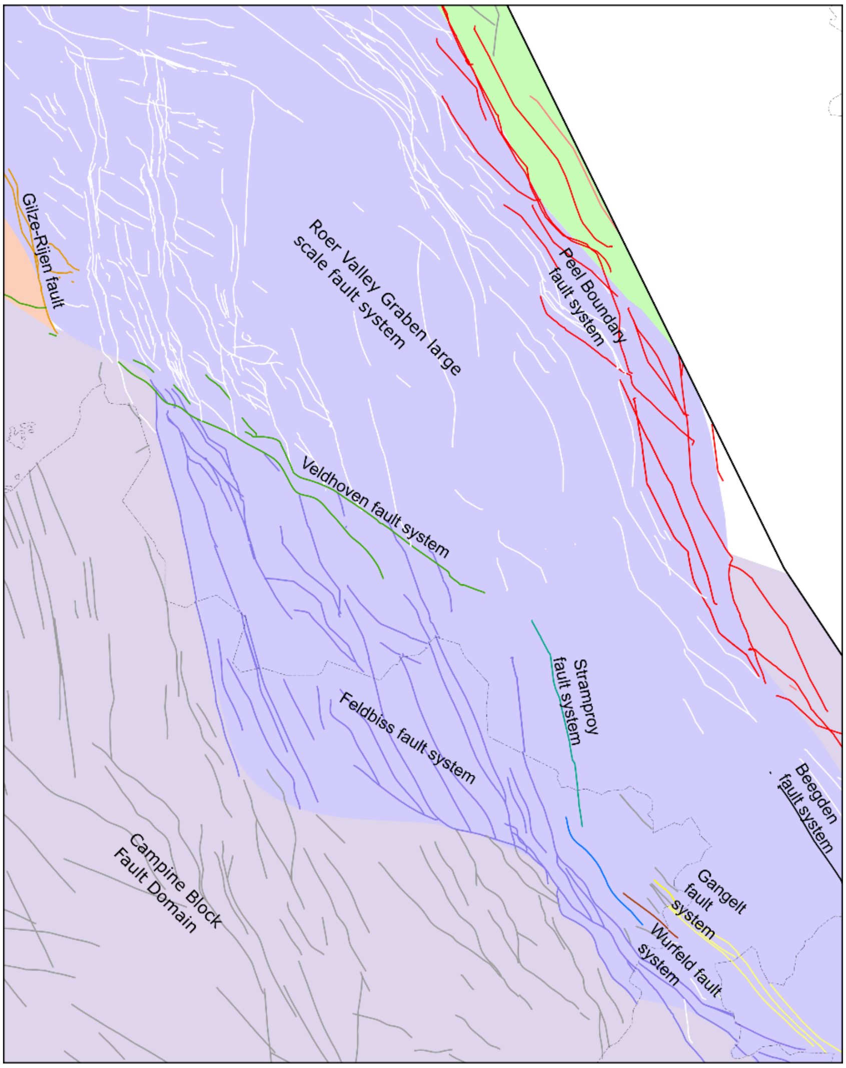


Figure 6: Structural Framework limits colored according to the vocabulary structure: all traces within the purple area are hierarchically part of the Roer Valley Graben large scale fault system. Some of them have been described in more detail (e.g., 'Stramproy fault system'), while others are assigned directly to the large-scale concept (e.g., the limits colored in white). Figure from Deliverable 5.2c (Van Daele et al., 2021b).

It was decided to only include 2D spatial data in this project. However, the three-dimensional aspect of the data is partly covered by providing an attribute 'reference surface' in the geometry files. This attribute gives information on the stratigraphical level on which a specific element is valid, so linking these data with (local) layer models will provide an indication of depth to the data.

Another attribute of the spatial data in the Structural Framework is the 'buffer'. This attribute reflects the uncertainty of limit traces, or, in the case of the pan-European limits, the complete extent of the system that is visualized (Figure 7).

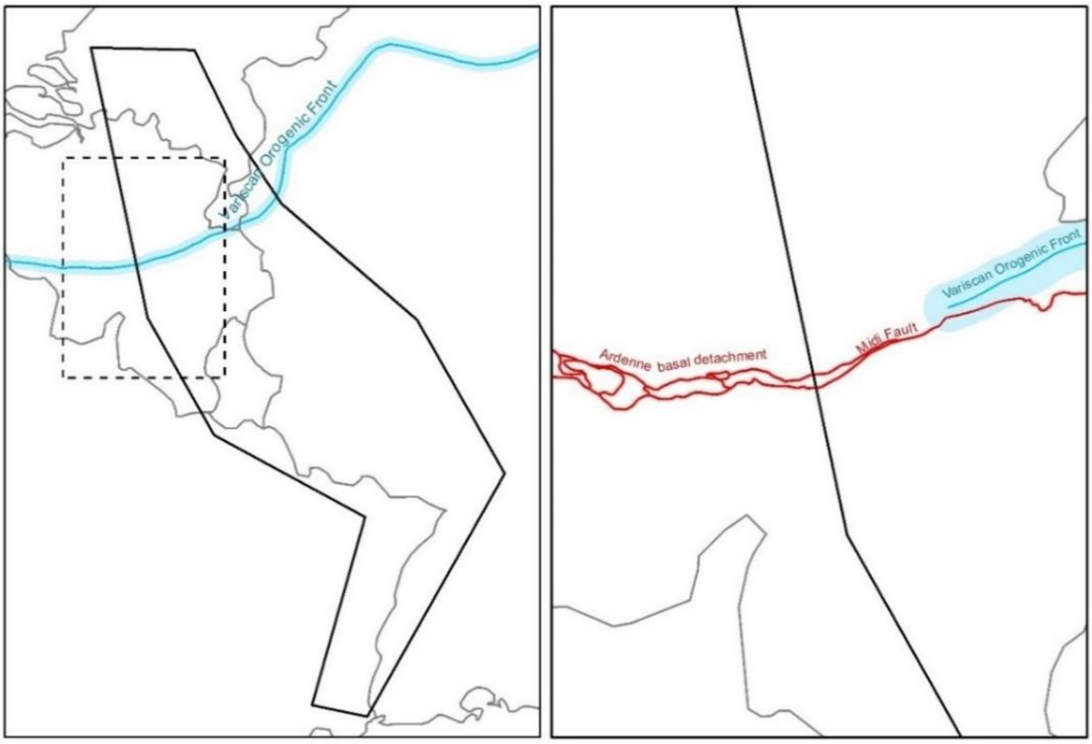


FIGURE 7: BUFFER AROUND THE PAN-EUROPEAN VIEW OF THE VARISCAN OROGENIC FRONT. RIGHT: ZOOMING IN TO THE AREA COVERED BY DASHED RECTANGLE ON THE LEFT.

1.2.3 Database attributes

Another important step in data collection is to decide which attribute information, in addition to the GIS spatial data, will be attached to every entry, and in what way. A balance has to be found between showing the essential characteristics of every feature in a structured and accessible way, while also safeguarding a manageable and straightforward functionality for the users, and not overloading them with too much information.

For constructing the SF, one of the major challenges regarding the database attributes was the fact that the input originates from very different sources across the various project partners. When limits and units are derived from geological maps, much less attributes can be extracted as compared to when they are derived from 3D geological unit- and fault planes. As a result, many of the database attributes (e.g., timing, dip direction, etc.) are left optional in this project. The only mandatory fields for each element are the reference surface and a bibliographic reference.

For quantitatively defined Geomanifestations, often multiple literature sources with quantitative data for a single Geomanifestation exist. This information might not always be relevant, or can be conflicting as the parameter analyzed (e.g., temperature) might vary over time. When all those values would directly be attached to the GIS features without extra context, this would lead to confusion. Therefore, only the most essential info, i.e., the parameter that demonstrates its anomalous nature, is made available in the Attribute Table, and can be visualized and queried for. In case of variation through time, the most anomalous value is taken. A more elaborate overview, with data from different references (if applicable) and including valuable additional data like geochemistry and year of analysis, is provided in the factsheets (see TABLE 2). All factsheets can be accessed through the repository https://search.europe-geology.eu.

TABLE 2: OVERVIEW OF THE INFORMATION INCLUDED FOR EVERY GEOMANIFESTATION TYPE IN BOTH THE ATTRIBUTE TABLE AND FACTSHEETS

Geomanifestation type	**Data included in Attribute Table** *if available*	**Data included in Factsheet** *if available*
Thermal anomalies	Maximum temperature (°C) Depth (m) *if not at surface*	Temperature (°C) Depth (m) Total Dissolved Solids (g/l) Cl, Na, SO_4, free CO_2 (mg/l) He (ppmv), $^3He/^4He$ (R/Ra) Year of analysis
CO_2-seeps	Maximum CO_2-concentration (mg/l)	
He-anomalies	Maximum He-concentration (ppmv) Maximum $^3He/^4He$ (R/Ra)	
Polymetallic veins	Primary metal Secondary metals	-
Seismicity data	Depth (m) Magnitude Date & time	-
Illite crystallinity	Kübler index (Δ°2θ) b-unit (Å)	Kübler index (Δ°2θ) b-unit (Å)
Volcanic phenomena	*Type of volcanic phenomenon (volcano, maar or caldera) and age (if known) is implemented in the conceptID (Vocabulary Table)*	
Seismic amplitude anomalies	Depth (m)	Seismic anomaly description AVO anomaly (class) Depth (m)
Collapse structures	Displ. Top Dinantian (TWT) Displ. Base Westfalian (TWT) Displ. Base Cretaceous (TWT) Displ. Base Cenozoic (TWT) Link to faults (name faults) *if known* Visible on gravimetry (y/n) Active during Cretaceous (y/n) Uncertain (y/n)	Displ. Top Dinantian (TWT) Displ. Base Westfalian (TWT) Displ. Base Cretaceous (TWT) Displ. Base Cenozoic (TWT) Link to faults (name faults) *if known* Visible on gravimetry (y/n) Active during Cretaceous (y/n) Uncertain (y/n) Discussion + interpretation
Surface movement	-	-

1.3 Data availability and coverage

For the SF database, large differences exist between the different project partners with regard to the structural data that is available. Flanders and The Netherlands are the only two areas for which a regional 3D structural model is readily available. For the other regions, information was compiled from a combination of geological maps, literature, and local 3D models. This difference is particularly visible in the spatial representation of the database when zooming to the most detailed scales. For the more regional scales, the availability of generalized limits, combined with the semantic system ensures an instructive model.

Another important aspect of the data coverage of the SF is the link with the third dimension. Although this dimension makes up an inherent part of the structure of an area, data regarding this aspect is often lacking and visualization is complicated. For a further elaboration on this point see Deliverable 5.2c (Van Daele et al., 2021). This is also the case for the SF dataset. Especially when derived from maps, faults are generally only mapped when they are expressed at the surface. Structural information regarding the subsurface of an area is mainly derived from seismic data, which are not often available on a regional scale.

A final challenge for the SF was the link between the conceptual semantic structure and the more tangible spatial data. Not only was it difficult to create a solid definition for each of the introduced concepts, it was often challenging to provide a spatial attribute for the concepts. One of the main assumptions of the SF is that units are defined by limits. However, in many cases no limits are available for units that are well-known in literature, or limits are only valid for a specific tectonic period. As an example, the way the Caledonian deformation front has up until now been defined in literature, is vague compared to the kind of definitions expected by the SF. This requires a significant additional effort to adust these definitions, but the resulting SF is clearer and devoid of conflicts when compared to what has previously been published.
At a fundamental level, any deformation front is defined as a separation between deformed rocks that are part of an orogen, and non-deformed rocks. The published Caledonian deformation front on Baltica is one continuous line that limits the deformed rocks both along the Thor and Iapetus sutures. This simplification can not be copied into a SF, because the each of these Caledonian sutures coincides with a different orogen, the one along the Thor suture earlier than the one along the Iapetus. Therefore, this deformation front is split into two deformation fronts, with the younger one overprinting the older one (FIGURE 8). This provides more information and is conceptually more correct (even if reconstructing the fronts in the overprinted area may be close to impossible).
Because of how a deformation front is defined, it is clear that one will exist on each side of an orogen. However, in literature only the northern deformation front is indicated or indeed mentioned along the Thor suture. This is in agreement with the traditional approach to only show information that is observable. However, in order to make a SF complete, also the inferred but not observed limits are shown. For these instances, dashed lines are used to indicate that a line is placed on theoretical grounds as has been done in FIGURE 8 (it must exist, but observations lack to correctly place it).

These examples indicate how, by breaking away from a more traditional geological approach, the SF may require additional reflection, literature verification and even redefining or introducing limits, but at the same time providing more and clearer information.

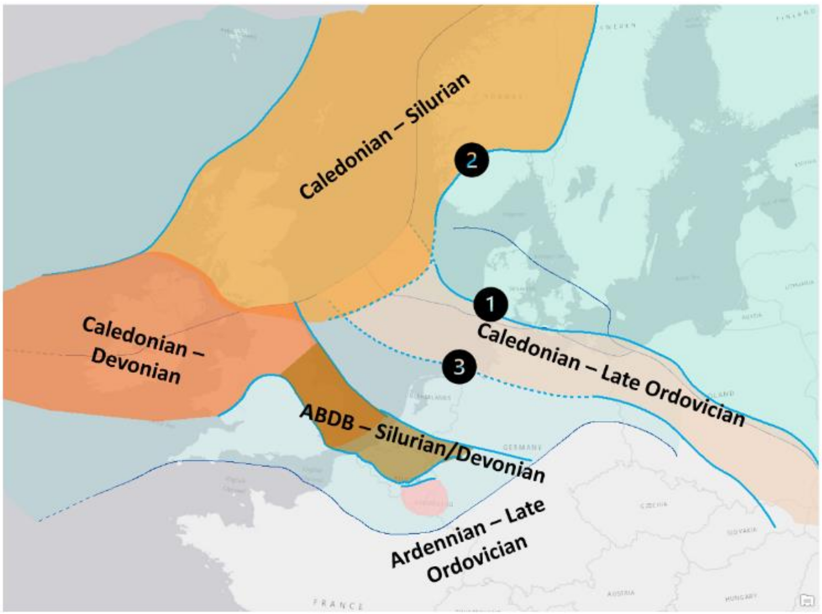


FIGURE 8: SIMPLIFIED STRUCTURAL FRAMEWORK OF THE CALEDONIAN AND TIME-EQUIVALENT DEFORMATION BELTS. THE LIMITS DISCUSSED IN TEXT ARE THE DEFORMATION FRONTS (1) AND (2) WHICH ARE GROUPED IN LITERATURE AS ONE CALEDONIAN DEFORMATION FRONT IN BALTICA, BUT SEPARATED IN A SF, AND (3) WHICH IS A LARGE AND NON-OBSERVED PART OF A DEFORMATION FRONT, NOT EARLIER RECOGNIZED OR DISCUSSED, BUT ESSENTIAL TO PRESENT A COMPLETE AND INCLUSIVE SF.

For the GM database, a large part of the data is derived from earlier studies that have been published in peer-reviewed articles. This is a very time- and cost-efficient way of collecting a big amount of data, covering a large area and variability of datatypes. However, it also implies a dependency on the (primary) interests of these research projects, the researchers involved and the data quality standards applied, which do not necessarily correspond to those of GeoConnect³d. Therefore, areas devoid of data do not automatically imply no Geomanifestations occur in that area. Other reasons can explain a local lack of anomalous values in the database. Maybe, for a particular historical or geographical reason, the area was never subject of intensive subsurface research in which data of interest for GeoConnect³d was collected. Or the studies conducted in this region had a different goal. Consequently, (part of the) data required to assess if a Geomanifestation qualifies as such may be missing. Therefore, the entry cannot be included in the database, which unavoidably leads to some data loss. Another issue of data bias may arise if certain Geomanifestations are just more difficult to detect (e.g., dry CO_2-seepage) and hence less consistently documented. Even though the GM database aims to be as complete as possible, these are important sidenotes that should be taken in mind while using the database and drawing interpretations from it.

1.4 Visualization options

1.4.1 Structural Framework

To inform policy makers and get them involved in constructive discussions about any given topic, it is of utmost importance to provide the necessary information in a clear and correct way. Visualization is vital for this, especially in case of GeoConnect³d, as the subsurface is a complex and relatively unknown topic for most non-geologists. As communicators, we have to guide stakeholders in viewing and understanding the data in the right context, so they can apply the acquired insights as support to solve pending policy questions. The way of visualization needs to be reflected upon on two levels: the representation of (1) individual datapoints and -lines, and (2) the relation between the data elements.

As for the Structural Framework, the zooming feature that was built in the Structural Framework is of particular importance. A total of ten different scales of visualization were defined, ranging from the pan-European zoom level of 1: 15,000,000 up to a scale of 1: 25,000, matching the scale of the local geological models that are zoomed into. When zooming to larger scales, generalized structures will appear and detail will increase when zooming in (FIGURE 9). This feature improves the readability of the maps, allowing the end-user to first understand the large-scale geological picture of an area, and acquire more insights on the details when zooming in. While the most detailed information generally originates from the local geological models of the project partners, the generalized structures were often created within the GeoConnect³d project.

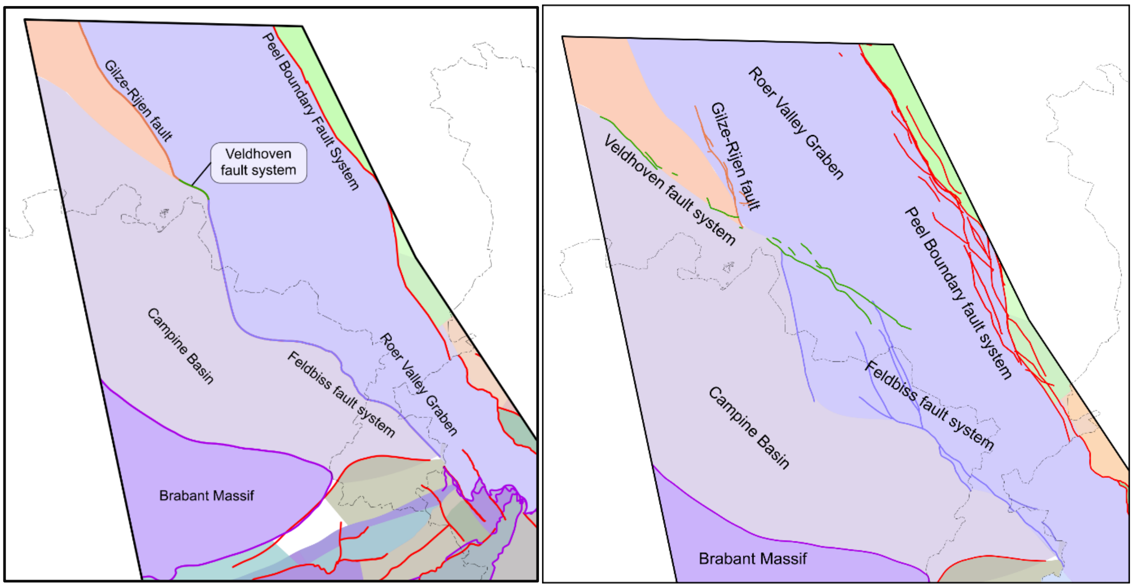


FIGURE 9: EXAMPLE OF ZOOMING IN THE GEOCONNECT³D DATABASE. LEFT: ZOOM TO 1: 1,000,000; RIGHT: ZOOM TO 1: 500,000. FIGURE FORM DELIVERABLE 5.2C (VAN DAELE ET AL., 2021B).

As explained in section 1.2.2, data can only be visualized in 2D in this project. Nonetheless, reference surfaces for the Structural Framework and optional attributes related to depth or timing for the Geomanifestations provide a link with the third dimension. It must be accepted, however, that a full 3D environment would further enhance the power of the Structural Framework as a communication tool.

One of the lessons learned from constructing the SF was that data that is hierarchically structured using a vocabulary does not automatically provide spatial structure. This is because:

1. Different 'themes' are present in the vocabulary structure (plate boundaries, deformation fronts, etc.) and those themes may spatially overlap. This is particularly relevant when working with (polygon) units.
2. The 3rd dimension is lost in the 2D map view of the Structural Framework, while this dimension is often essential to visualize the fact that structures can be superimposed in time and depth.
3. The inclusion of line traces at many reference surfaces for a specific fault will generate a lot of extra data that hamper the readability of the Structural Framework maps. Visualisations should hence be filtered to show only one reference surface for each limit.

It can hence be concluded that, when using the SF-methodology as developed within GeoConnect³d to disclose subsurface data, it is of vital importance that the information platform visualizing the Structural Framework:

- is constructed as a dynamic tool offering query options to filter the data;
- has advanced visualization options (trancparency, fill, strike patterns, layer order, etc.), which can help overcome the fact that 3D information of different themes is compiled on a 2D map.

1.4.2 Geomanifestations

Quantitative Geomanifestations (e.g., temperature or geochemistry related) generally allow for straightforward visualization of the anomaly. In this project, up to four classes were used to illustrate the extent of anomaly with proportional symbol size. Qualitative Geomanifestations (e.g., a volcano or polymetallic vein) mostly would be represented on a map with a categorical symbol. However, it often is possible to include some secondary, still valuable information (e.g., age or metal content). As it does not concern a continuous parameter, different categories can be indicated by the same symbol in different colors. In

TABLE 3, an overview is given of which parameter is suggested to visualize a given Geomanifestation type, and in what way.

In any case, the public should not be overloaded with details. Therefore, it is important to only include additional features when they contribute to the message that is meant to be brought forward by that specific figure. For the general R2R-scale view, a simplified legend is proposed without Attribute visualization. FIGURE 10 shows proposed detailed and simplified legenda of the R2R Geomanifestations (constructed using ArcGIS Desktop).

TABLE 3: OVERVIEW OF RECOMMENDED VISUALIZATION WAY OF THE R2R GEOMANIFESTATIONS

Geomanifestation	Preferred visualization way
Thermal anomaly	Graduated classes according to the extent of thermal anomaly (taking into account maximum T and depth attributes)
CO_2-seep	Graduated classes according to the maximum CO_2-concentration
He-anomaly	Graduated classes according to the maximum He-concentration or maximum $^3He/^4He$
Polymetallic veins	Symbol for occurrence, color = major metal
Seismicity data	Graduated classes according to magnitude
Illite crystallinity	Graduated classes according to Kübler Index
Volcanic phenomenon	Symbol for occurrence, color = age
Seismic amplitude anomalies	Polygons for occurrence
Collapse structures	Polygons for occurrence, line thickness = throw at a certain level
Surface movement	Polygon for occurrence
Georeferenced maps represent the same information as individual datapoints of the same Geomanifestation type, but less detailed in spatial extent, hence they are represented by the same symbols but in paler color	

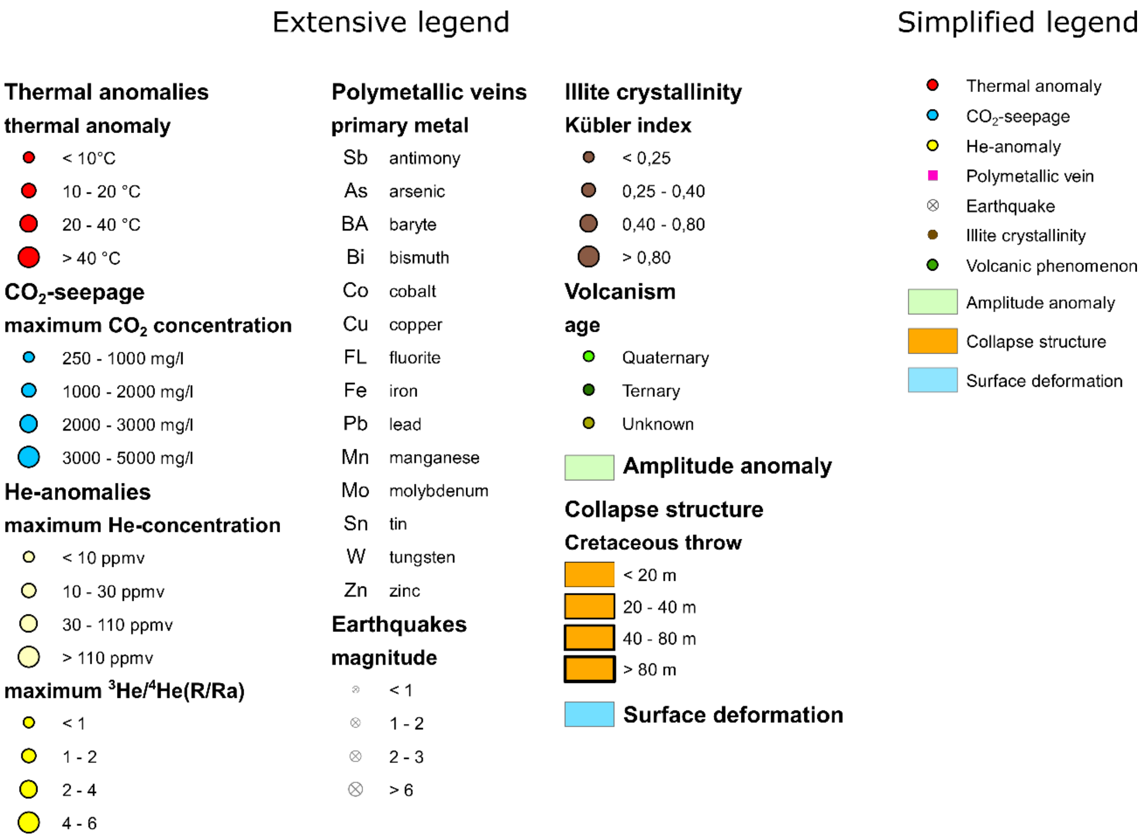


FIGURE 10: EXAMPLE OF THE DETAILED AND SIMPLIFIED LEGEND OF THE R2R GEOMANIFESTATION DATABASE IN ARCGIS DESKTOP.

A particular visualization of individual SF and GM entries has an important highlighting function for bringing across the message. Nevertheless, individual datapoints are not enough to be of support for policy-makers. Often their relative distribution is at least equally important, both spatially and genetically. For this aspect, the combination of Structural Framework and Geomanifestations is particularly valuable, as in this way, the connection between individual anomalies and the geology can be drawn and illustrated to outsiders in a relatively straightforward way. Again, a reflection has to be made which info will be included in the picture (i.e., is necessary for the main message), and how. It is difficult to phrase strict rules for this, as this depends from example to example.

1.5 Visualization in the online webviewer

Both the spatial and semantic data are published in an online information system hosted on the EGDI servers (https://data.geus.dk/egdi/?mapname=egdi_geoera_geoconnect3d). This online map viewer serves as the entry point for the end-users to the project results for both the Structural Framework and Geomanifestations data. This platform should allow to visualize the data in a similar way as was illustrated in sections 1.4.1 and 1.4.2, and in addition provide links to the semantic data structure, Factsheets and Attribute information.

Unfortunately, at the time of writing, the platform is not yet fully operational. This delay is caused by the fact that for clear visualization of the SF, relatively advanced functionalities are required, e.g., symbolization based on multiple categories, and queries to display the different scale-levels correctly. Implementing this on the available platform has proven challenging, even if bilateral meetings with GIP were carried out in 2020 and 2021 to discuss our needs in advance. This is one of the threats we mention in the SWOT analysis: an advanced information platform is required to properly visualize the project results.

For future projects, we recommend that there should be closer collaboration between GIP-P and the project itself, and tests with dummy data earlier on in the project.

1.6 Communication and outreach

Lastly, when all the database work has been done (decision making, data selection and inventorying), and both the Structural Framework and Geomanifestation databases are published on an information platform, it remains to bringing the message to potential end-users of the database, in this case policy makers concerned with the subsurface management. As mentioned above, a good visualization already can be of great help for this, but also the way the story is brought by the communicators can influence the ultimate success of the Structural Framework and Geomanifestations databases.

In the GeoConnect³d workshop of the GPS event, on the 10th of July 2021, a first step in this process was achieved. The purpose of this event was twofold: (1) to communicate the results of the project to policymakers and all other interested stakeholders and (2) to get stakeholder feedback on how the SF + GM tool can be improved. The next chapter goes more in detail into this latter aspect. The GeoConnect³d results were furthermore presented during the Geologica Belgica meeting in Tervuren (September 15th – 17th, 2021). Received feedback, although not collected in a systematic way as during the GeoConnect³d workshop, is also incorporated in the next chapter.

In addition to scientific conferences and workshops, there are various other outreach means to give publicity to the GeoConnect³d online platform to the stakeholders. First of all, the weekly GeoConnect³d blog provides an excellent way to announce the publication of the online web viewer as soon as possible. As it concerns the final result of the project, a dedicated email to all stakeholders that were involved or showed interest at one point during the project, might be considered as well.

Additionally, the scientific papers that came forth from research carried out in the framework of GeoConnect³d (e.g., Barros et al., 2021; VITO, in prep) offer a relevant bridge towards the academic community. Through engaging their interest for the project in this way, these people may become ambassadors of the project results (https://geoera.eu/projects/geoconnect3d6/), which in turn may lead to dissemination to and use by, for example, students (a.k.a. future geologists). We also believe the Geomanifestation Factsheet format, linked to the spatial data in EGDI, has large potential to reach a broader public by captivating their interest in and enthusiasm for the geosciences through associations with geoheritage or geotourism.

1.7 SWOT analysis

In the discussion above, a lot of aspects of the SF + GM databases, both positive and negative, have been touched upon already. In this section, these are concisely summarized (see also

TABLE 4).

The ultimate strength of the Structural Framework and Geomanifestation approach lies in its novel and unique data structure. The combination between the vocabulary structure and spatial data allows the discovery of new insights in subsurface properties and geological processes controlling the presence of georesources and geohazards. Another strength of the specific GeoConnect³d approach is the integration of multi-disciplinary, cross-border data, which offers a much larger data set and leads to cross-over insights and therefore better constrained policy support. Spatial and genetic patterns appear due to the large amount of data included in the databases and a database structure that permits flexible but easy and powerful visualization. Especially the zoom-feature is a great asset in presenting the subsurface and its characteristics to non-geologists. And, even though this report is written from the view and experiences encountered in the R2R study area, the GeoConnect³d project has demonstrated its transferability to other areas.

A weakness of the Geomanifestation database is its limitation to include only anomalous values. Although the method followed to inventories these anomalies is the most time-efficient and targeted approach, it renders a comparison to surrounding background values impossible. As for the Structural Framework, an important asset of the methodology is that it should allow to disclose geology in an accessible way by means of a spatial information system. However, in its current form, partially related to the broad group of stakeholders the developed tool is designed to address, only an advanced spatial platform is able to provide for the functionalities and filter-options that are required to visualize the dataset. To overcome this, a number of pre-processed figures where constructed (see Deliverable 5.2c; Van Daele et al., 2021b). These figures visualise many of the project results:

- The Structural Framework at various zoom levels
- The Structural Framework enriched with vocabulary information
- Overviews of all the mapped Geomanifestations
- Detailed views of specific Geomanifestations in relation to the Structural Framework

These figures are readily available for policy makers and other stakeholders and are in their own right valuable products to communicate geology and help solve management issues.

When using the database to infer new conclusions, it is important to take into account that the project results are currently largely dependent on literature data and interests of other research projects, imposing some data loss and bias. The latter aspect needs to be highlighted well in order to avoid misunderstandings and misinterpretations. Another threat for making the SF + GM tool successful for data-supported decision making in subsurface management matters, is that communication and outreach might fail to bring it to the wide public in such a way that stakeholders (mostly policy-makers) effectively start using it. Follow-up after the end of the project is absolutely essential for this, as an outdated database, both concerning the data included as well as the technical aspects of the web viewer, easily gets abandoned.

If well-advertised, the Structural Framework and Geomanifestation database can become a widely-known and –used tool, and probably will call for improvement at some point or on some aspects. Adding newly acquired data or other Geomanifestation types and expanding the database to additional countries or regions (e.g., in post-GeoERA research) undoubtedly would increase its general applicability. When new data are added, it would also be useful to update the lessons learnt (Deliverable 5.2c; Van Daele et al., 2021) to reflect additional lessons for policy challenges. Another opportunity for improving the project results would be the development of a European thesaurus system to hierarchically organize structural geological data. This project has shown that concepts are often not clearly defined, and the relation between geological concepts described in literature and elements modelled and mapped in geological projects is sometimes ambiguous. Also, the inclusion of the aspects of timing and third dimension will increase the power of the database as a scientific and communication tool.

TABLE 4: OVERVIEW OF THE STRENGTHS, WEAKNESSES, OPPORTUNITIES AND THREATS OF THE STRUCTURAL FRAMEWORK AND GEOMANIFESTATION DATABASE

Strengths	**Weaknesses**
• Vocabulary provides a solid data structure • Unique combination of multi-disciplinary data • Cross-border approach • Extended database • Large visualization power • Methodology transferable to other study areas • Zooming feature enhances communication • Lessons learnt for policy challenges	• Only anomalies included (background comparison not possible) • Dependence on literature data • Incomplete spatial coverage • Thorough understanding of regional and local geology needed to draw new conclusions from the GM datasets
Opportunities	**Threats**
• Improving the Structural Framework vocabulary on a European level • Expand with new studies, additional Geomanifestation types and structures of other countries • Inclusion of 3D and aspect of timing • Can become widely used tool • Identification of data gaps (underexplored areas) • Testing hypotheses of geological processes • Locating georesources sweet spots	• Mis-interpretations when used uncarefully • No follow-up (i.e., including new observations and interpretations, implementing continuous refinement, …) can lead to outdated web viewer • Complex: advanced information platform required to make it user-friendly

2 CHAPTER 2: FEEDBACK FROM STAKEHOLDERS

2.1 Feedback occasions

During the GeoConnect³d workshop of the GPS event (10th of July 2021), feedback from the audience was asked via multiple interactive poll questions. As mentioned in the minutes of that workshop, Deliverable 3.2 (Van Daele et al., 2021a), the background/interest of this audience (n = 54) was very diverse, going from private partners (6%) over policy makers (11%) to geological surveys (56%). Universities (20%) and research institutions (7%) were represented as well.

On the conference Geologica Belgica (15th – 17th of September, 2021), the (almost) final results of the GeoConnect³d project were highlighted in several oral and poster presentations as well. No detailed information is available on the audience that attended this event, but it can be assumed to represent the community of geologists working in Belgium, with a focus on the academic sector, research institutions and policy advisors. During this conference, the opinion of the audience was not collected in a structured way like at the GeoConnect³d workshop. Nevertheless, during the ad hoc questions to the presenters and following discussions, interesting points were raised.

2.2 Added value for subsurface resources, applications and hazards

The Structural Framework was received very positively during the GeoConnect³d workshop, with the majority of the respondents (strongly) agreeing with its usefulness in constraining the subsurface geology (FIGURE 11) and almost all of them saw potential in the Structural Framework to solve subsurface management issues (FIGURE 12). This was also generally recognized during the Geologica Belgica conference.

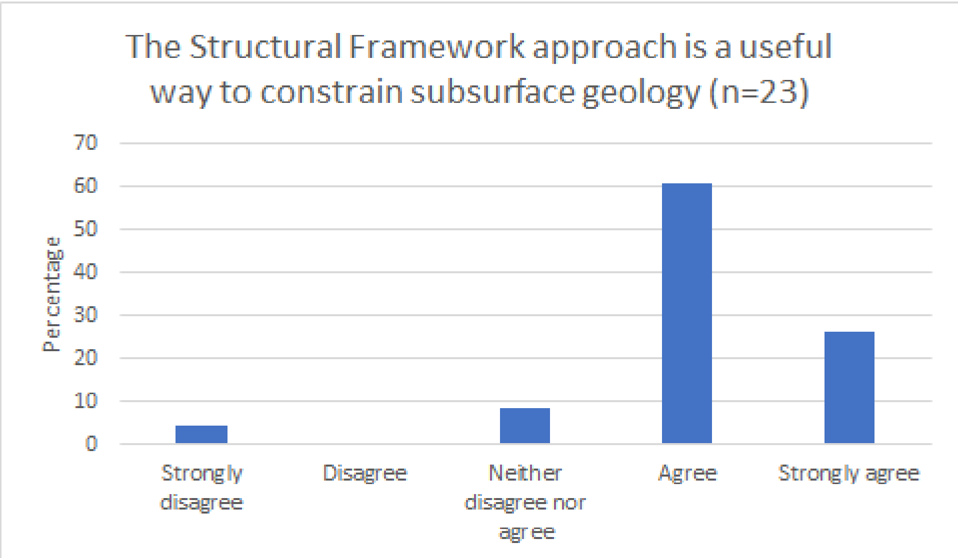


FIGURE 11: OPINION ON THE USEFULNESS OF THE STRUCTURAL FRAMEWORK TO CONSTRAIN THE SUBSURFACE GEOLOGY DURING THE GEOCONNECT³D WORKSHOP (23 RESPONDENTS).

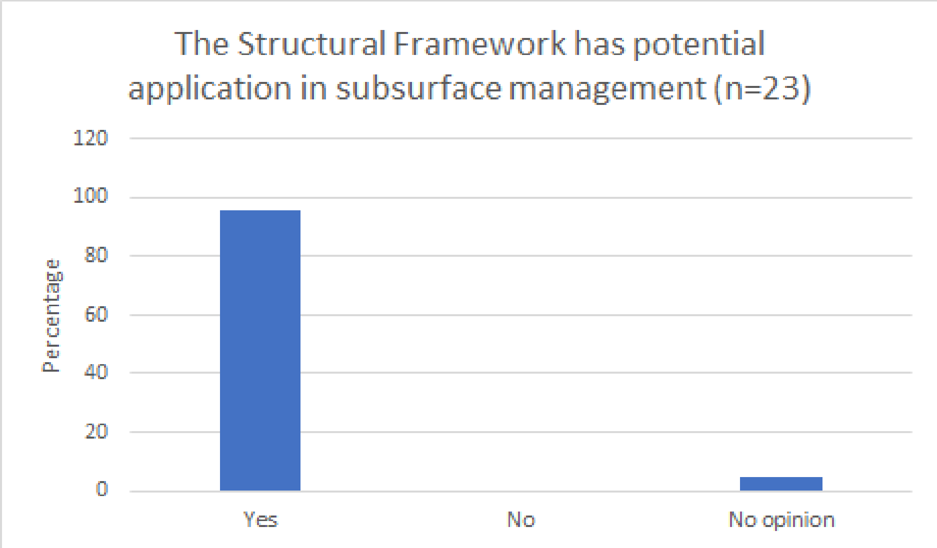


FIGURE 12: OPINION ON THE POTENTIAL APPLICATION OF THE STRUCTURAL FRAMEWORK IN SUBSURFACE MANAGEMENT DURING THE GEOCONNECT³D WORKSHOP (23 RESPONDENTS).

Concerning the Geomanifestations, their overall applicability for a wide range of subsurface applications was confirmed by the audience of the GeoConnect³d workshop (see Figure 4). Additionally, 80% of the respondents (n=5) declared afterwards to be interested in feeding data to the Geomanifestations database in the future to help its expansion towards an even more broad applicability. Regarding the seismicity dataset, the suggestion was given to make it a dynamic (instead of a static) database, e.g., with automatic updates to include new seismic events. Now, updates have be done manually. Lastly, it was highlighted that attention should be payed to nomenclature consistency in all parts of the viewer (entries, Factsheets, publications, …).

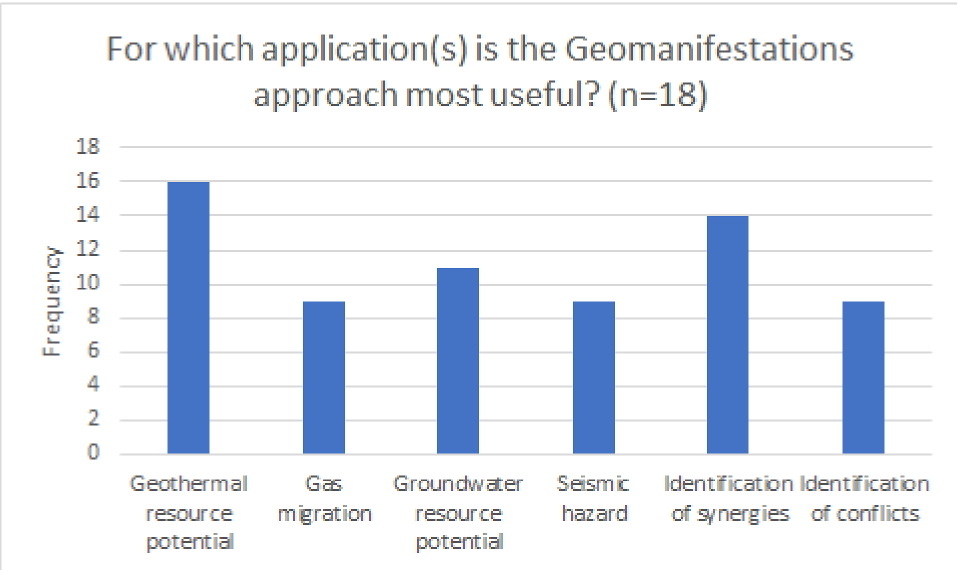


FIGURE 13: OPINION ON THE USEFULNESS OF THE GEOMANIFESTATIONS FOR SPECIFIC SUBSURFACE APPLICATIONS DURING THE GEOCONNECT³D WORKSHOP (68 ANSWERS BY 18 UNIQUE RESPONDENTS).

2.3 Utility in subsurface management discussions

The Structural Framework and Geomanifestations database were received as a good support tool for discussions about subsurface management (issues). Its disclosure in the (upcoming) web-based viewer is considered as a great, useful way to make the GeoConnect³d results widely accessible, under the condition that enough background information and guidance to make the link between a certain Geomanifestation type and its applicability for subsurface management (issues) is provided for the stakeholders. The audience of the GeoConnect³d workshop indicated following specific advantages, often additionally upvoted by other members of the public:

	Upvotes
“Generally good”	2
“It opens the view and facilitates discussions”	2
“Easier to harmonize geology across borders”	2
“Easy to communicate to non-specialists”	2
“Good for people with some background”	1
“General view of layers, tectonic elements and zones with good permeability”	0
“It provides a framework for the synthesis of subsurface and surface data”	0

The lack of chronological units was stated as a disadvantage of the Structural Framework in such discussions.

The questions “What aspect(s) of the Structural Framework visualization would you like to see improved to make it straightforward to use?” and “What changes could improve the utility of the Structural Framework in the subsurface management perspective” were answered in a very similar way by the audience. The extension towards 3D, and even 4D, was mentioned most often. Other aspects that came up concerned the integration of surface information (such as water, land use, urban infrastructure development) and of environmental impacts. The inclusion of cross-border solutions, development of sub-themes by launching further projects, and synthesis of datasets were highlighted as work that would further increase the applicability of the GeoConnect³d results. An interesting question was raised whether an explicit connection would be made between the GM and SF, or whether this was left for the user to figure out himself based on the GIS-data. This option is certainly worth considering for follow-up research.

One of the participants eloquently phrased the opportunities embedded in the Structural Framework and Geomanifestations approach in view of a European-wide policy on subsurface management as follow: “A great opportunity is there for progressing towards "consilience", i.e., a synthesis of different information sets to provide totally innovative solutions to unsurmountable problems in the sustainable use of the subsurface.”

It was positive to learn that the research carried out in the framework of GeoConnect³d was perceived by a diverse audience of stakeholders as useful for discussions concerning the subsurface management. The suggestions for improvement are ideas that indeed will increase its value and applicability even more. However, they also were a bit unexpected, as incorporating these aspects would increase the complexity of the Structural Framework considerably, while the primary goal was to make subsurface data more accessible (i.e., with only the key information), especially towards non-geologists. We advise a careful consideration of what is included in the datasets, and in what way, as to not overcomplicate its overall use.

2.4 Visualization of the Structural Framework and Geomanifestation database

Unfortunately, the online web-viewer for the Structural Framework and Geomanifestations was not finalized in time to organize a final survey to inquire specifically about the visualization of all data that was collected in the GeoConnect³d project. This implies no detailed feedback from interested stakeholders is available on this topic.

3 CHAPTER 3: CONCLUSIONS AND RECOMMENDATIONS

3.1 Lessons learnt on disclosing subsurface data

- The combination of a vocabulary structure and spatial data offers great potential in disclosing subsurface data in an accessible way.
- Lots of decisions need to be made in order to construct the databases. Precise documentation and a consequent data treatment approach are hereby essential.
- Incomplete spatial coverage of Structural Framework elements or Geomanifestation data due to the lack of data availability hampers the regional applicability of the databases.
- Including the third dimension would offer significant added value for disclosing the subsurface data.
- The GeoConnect³d database allows extensive visualization possibilities. However, it is important not to overload the user with (unnecessary) details of entries' Attributes if these don't contribute to the main message. As this may differ from user to user, flexibility in the visualization possibilities on the future web viewer is crucial.

3.2 New insights from stakeholder feedback

- In general, the results from the GeoConnect³d project are regarded as valuable and useful for subsurface management (issues) and discussions on this topic.
- A lot of data can still be added. A relatively simple database does not meet the standards or expectations of stakeholders. However, a simple visualization, including all information of interest, remains key to disclose it to them.
- Uniform data synthesis is much appreciated as step-up to solve subsurface management

3.3 Recommendations for post-GeoERA research

- A regional thesaurus providing a hierarchical structure and definitions for large-scale geological structures on a European scale would be of added value for the geological community. It would provide a good starting point for many geological cross-border harmonization projects and would provide an excellent reference for non-experts trying to understand regional geology.
- When building spatial information systems, focus should shift from 2D-map viewers to applications embracing the third dimension. This does not necessarily mean that the models need to be rendered in a full 3D environment: tools that allow to draw geological profiles based on a 2D map would already cover for many of the demands regarding this aspect.
- Expansion of the database with new or additional data sources to cover more subsurface applications and issues. However, it remains advisable to guard the 'boundary' of mainly incorporating (new) observational data in the database, while it is left to the users to make integrated interpretations themselves.

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