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Lessons learnt from the R2R case

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GENERAL INTRODUCTION

This report summarizes the methodological aspects of constructing the Structural Framework and Geomanifestations database for the Roer-to-Rhine are (Geoconnect^{3}d WP3), and discusses the new insights learned by integrating the Structural Framework with the Geomanifestations database, especially regarding policy support.

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1 PILOT AREA DESCRIPTION

1.1 Traditional geological description

The Roer-to-Rhine (R2R) area focusses on the border regions between Belgium, The Netherlands, Germany, Luxembourg and France. Geologically, this area incorporates from North to South: the onshore southern North-Sea Basin, the Roermond Graben, the Variscan front zone with its Ardennian inliers, the western Eifel area, and the Upper Rhine Graben in the Alpine foreland. These geological domains can be largely divided into: lower Paleozoic basement, Devonian-Carboniferous sedimentary-tectonic cycle, post-orogenic continental sedimentation, Triassic-Cretaceous marine sedimentation, and Cenozoic sedimentation.

In Flanders, in northern Belgium, the western and central parts of the project area are located on top of the Brabant Massif, which is a relatively stable WNW-ESE trending continental block consisting of Cambrian to Silurian strata that were strongly deformed during the Caledonian phase. North-east of the Brabant Massif, the lower Paleozoic strata are covered by Devonian and Carboniferous strata which define the so-called Campine Basin. During the Carboniferous, the Campine Basin was part of a major foreland basin just north of the Variscan Orogen.

In the eastern part of the Campine Basin, the upper Paleozoic strata are covered by a wedge of late Permian to early Jurassic layers that show a stepwise, fault-controlled northeastward thickening towards the Roer Valley Graben (RVG). Fault-controlled subsidence of the Roer Valley Graben probably started in the Jurassic, during the Kimmerian tectonic phase(s), differentiating this fault-bound structure from the more western, less subsiding parts of the Campine Basin which are often referred to as Campine Block. The Campine Block can therefore be considered as the western shoulder of the Roer Valley Graben. Upper Jurassic and Lower Cretaceous sedimentary units are absent in Flanders, probably as the result of strong erosion during the latest Jurassic (Vercoutere & Van den Haute, 1993). During the Late Cretaceous, the Sub-Hercynian inversion phase inverted the RVG into a structural high. Simultaneously, the Campine Block experienced subsidence and was filled by the Upper Cretaceous sediments of the Chalk Group. Inversion of the Roer Valley Graben ended in the latest Cretaceous and was succeeded by a tectonically relatively quiet period up to the late Oligocene. From the late Oligocene onwards, the Roer Valley Graben experienced differential subsidence again, and hence became part of the so-called Roer Valley Rift System, an area of about 20 km wide and 130 km long characterized by differential subsidence along a number of major, mainly NW-SE oriented, normal faults. This area is currently still tectonically active.

In the Walloon Region, in southern Belgium, there are predominantly consolidated Paleozoic rocks of the Rhenish Massif, composed of Cambrian to Silurian rocks deformed by the Caledonian phase and a Devonian to Lower Carboniferous cover that was strongly deformed at the end of the Carboniferous during the Variscan Orogeny. The complex Variscan front zone is located between the Walloon and Flemish regions. After the Variscan Orogen, the area also experienced local faulting during the Jurassic and Cenozoic extensional phases, but was situated outside the Roer Valley Graben or Roer Valley Rift System.

In the French area of R2R, the deformed Paleozoic strata are covered by Triassic-Paleogene strata, defining the Paris Basin. Further towards the east, at the border with Germany, the latter strata are covered by a thick succession of Cenozoic siliciclastics in the Upper Rhine Graben that developed as a rift basin from the Eocene onwards.

1.2 Geological challenges

Although the R2R study area is not very extensive, it is situated at the border zones of 5 countries and it was affected by **almost the entire geologic deformation history of Europe**. It comprises strata deformed by the Caledonian orogeny, the Variscan orogeny and younger rifting that occurred in response to the Alpine deformation phase. Hence, the construction of one model for this area is a huge geological challenge but, in the end, the Structural Framework created for GeoConnect³d can be considered as a micromodel for the Pan-European exercise.

Adding to this challenge is the **limited 3D knowledge** of the subsurface of many parts of the region. Regional 3D models exist for the Upper Paleozoic to recent strata for Flanders and the Netherlands, but for the area south of the Brabant Massif and the Eifel Area, containing mainly strongly deformed Paleozoic rocks, generally only 2D geological maps exist. By illustrating the changes in depth and thickness of sedimentary units across faults, the 3D models allow better insights into timing and vertical extent of faulting. For areas only covered by 2D models, the timing and continuation in depth of many structures remains **hypothetical**. Specifically in these areas, the current state of geological knowledge leaves open multiple theories, and when placing elements in a broader, Pan-European context, the **cross-border continuation of the structures** is often unclear and **geological conflicts frequently arise.**

In the areas that are covered by 3D models, it is challenging to **link concepts often used in geological literature to actual, mapped structures**. As an example, the 'Beringen fault' is traditionally displayed as one large, continuous fault line. However, when interpreting this fault using 2D seismics it becomes clear that it represents a fault zone consisting of many different faults. Upscaling this detailed information provided by the 3D geological models to a level that can be linked with the large-scale geological concepts used in literature can be challenging. In addition, when crossing borders, **concepts can change name or meaning**, which again complicates the harmonization of the geology.

A specific example of a set of geological challenges are presented by **Geomanifestations** such as thermal anomalies, seismicity, seismic anomalies or surface movements in the area. They can be an indication for several geological (i.e. natural) and induced (i.e. anthropogenic) processes acting in the subsurface, such as fluid flow, volcanism, peat oxidation, gas extraction, subsurface injection, heat storage and sinkholes, either due to collapse of abandoned mines or dissolution (karst). The Structural Framework has the possibility to indicate which Geomanifestations are related to faults and which not.

The **identification of active faults,** or their potential to become active, is of crucial importance for subsurface management as it can indicate areas with the largest seismic hazard risk or rule out areas for subsurface exploitation. Although there is good documentation of both instrumental and historic earthquakes in the area, it is hard to link their location and magnitude to actual faults.

More in general, it is important to understand the **tectonic history** of an area, as it provides insights into the timing of formation and reactivation of geological structures. However, studying tectonic history is challenging, because younger tectonic phases may reactivate or overprint structures originating from older phases. Other structures may have disappeared from the geological record due to erosion or dissolution. Even with detailed geological information in depth available (such as 2D or 3D seismics) interpretations on this aspect often remain tentative.

1.3 Subsurface management challenges

The R2R study area comprises five countries and many borders. All these countries encounter the challenge of dealing with **reservoirs** (geothermal, hydrocarbon, groundwater, ...) **that continue cross-border**. This factor is especially relevant for countries with a small territory, e.g., Luxembourg, or countries having their best subsurface potential in border regions, e.g., the Campine Basin in Belgium. European legislations do not allow to extract natural resources on a foreign territory. The ESPOO Convention sets out obligations to assess the environmental impact of certain activities at an early stage of planning via (S)EIA, whereby member states have to notify and consult each other on all major projects under consideration that are likely to have a significant adverse environmental impact across boundaries. In the R2R study area, a complex geology is present on a limited distance and several geological layers and faults cross national borders. The challenge is two-fold; policymakers need: 1) a good understanding of the geology and of the reservoirs crossing the borders to adequately predict **spatial impact and potential interferences** around subsurface projects and 2) an unambiguous fault model with **faults crossing the border** in a logic continuation instead of stopping at the border or shifting in locality or interpretation. The correct positioning of fault zones is crucial for almost all subsurface applications, especially for evaluating seismic hazards. Therefore, cross-border harmonization and data exchange are absolutely essential.

A second general subsurface management challenge relates to the fact that **geological data and insights are often fragmented over different geodisciplines and sectoral domains**. In the field of raw materials, there is a lot of data on lithological composition, metallic occurrences, specific geofluids, mineralized veins, etc. In the field of groundwater there are ample data on aquifers, aquitards, barriers or conducting faults, geochemical anomalies, etc. In the geo-energy domain, there is mainly interest in trap structures, the distribution of reservoir characteristics, the presence of gases, anomalous temperatures, etc. Although each discipline collects and samples from its own perspective, a lot of geological information is of interest and value for other subsurface applications as well. Even if there is not an obvious link between applications, nearly all projects benefit from each piece of information that contributes to the understanding of the role of faults and the assessment of connectivity for fluid flow. That is a common concern for geothermal projects, gas storage, hydrocarbon extraction, thermal storage, etc. Opportunities are missed when existing data and insights are not valorized, while exploration investments are substantial. Furthermore, this knowledge should be **communicated to policymakers** in a straightforward and understandable way.

Specific subsurface challenges that are relevant for all countries in the R2R area are:

- Recognizing (deep-seated) faults and understanding the role they may play in all kind of geofluid-related processes
- Unraveling the key factors controlling geothermal potential
- Understanding migration pathways and processes for gases in general, and more specifically their implications on the long-term effectiveness of CO_2-storage

A third challenge concerns the fact that the available subsurface space available is limited. In order to meet sustainable climate and energy goals, various applications such as geothermal energy, energy storage, CO_2-sequestration and the storage of nuclear waste can be employed. However, the spatial limitation implies that **careful management** is absolutely essential to avoid both fragmented suboptimal use and overexploitation of the subsurface. Moreover, a critical ex ante evaluation, taking into account all potential georesources and subsurface functions, as well as future policy needs (e.g., climate targets, strategic energy supply, strategic raw materials, …), is required before making permanent choices for subsurface destinations that would exclude future uses. Again, this is especially relevant for relatively small areas such as the Flemish territory. There, only the Campine Basin has a suitable geology for deep subsurface applications that depend on good reservoir conditions (sufficient volume with fair porosity-permeability).

Additionally, the deep subsurface often has been explored only partly and therefore has highly variable data densities. In countries with an extensive hydrocarbon-exploration history (e.g., the Netherlands), deep subsurface data is quite readily available. However, this is not the case everywhere. For example, the general geological structure of the deep subsurface of Flanders is synthetized in a 3D model based on very limited seismic and borehole data, thus mainly relying on geological concepts. Therefore, the effective potential for several subsurface applications remains largely **uncertain**. Especially quantifications for parameters like transmissivity, porosity, permeability, stress distribution, etc. are lacking. For those areas lacking obvious indications for its deep subsurface potential, an alternative strategy to recognize favourable zones to explore and exploit would be welcome. One possible strategy is that observations, predictions or **lessons learnt** from well-explored and well-documented areas are, insofar possible, **transferred to less explored regions**, where there are no direct clues for prospectivity.

1.4 Starting material

In the tables below, the sources used for construction of both the Structural Framework (TABLE 1) and the Geomanifestations database (TABLE 2) are presented.

TABLE 1: DATA SOURCES THAT WERE USED FOR CONSTRUCTING THE STRUCTURAL FRAMEWORK FOR EACH PART OF THE R2R STUDY AREA.

Partner	Data source
Flanders	- 3D geological model of Flanders (G3Dv3) by the Flemish Government - Mapped and modelled faults by the Flemish Government - Regional cross-border mapping projects (the so-called H3O models) - Scientific literature on the geology of Flanders - Historical geological maps - Subcrop maps of the Brabant Massif by the GSB - Outcrop maps of the Brabant Massif by Herbosch & Debacker, 2018
Wallonia	- Recent geological and structural maps of Walloon Region (incomplete coverage) - Historical geological maps - Subcrop maps of the Brabant Massif by the GSB - Outcrop maps of the Brabant Massif by Herbosch & Debacker, 2018 - Maps from different publications, usually on general geological setting
The Netherlands	- 3D geological models of the Netherlands (DGMv2.2, DGM-deep, v5) by TNO - Mapped and modelled faults by TNO - Historical (previous) geological mapping (mainly the 1:250.000 map sheets) - Scientific literature on the geology of the Netherlands - Regional cross-border mapping projects (the so-called H3O models)
Germany	- Geological maps of Germany - 3D geological model of Rur-Scholle - Information System Geologische Übersichtskarte von Nordrhein-Westfalen 1:500.000
Luxembourg	- Published and unpublished maps of different scale and quality - Scientific literature on the Luxembourgian geology
France	- Geological map of France (scale 1:1.000.000) - Scientific literature on the French geology

TABLE 2: DATA SOURCES THAT WERE USED FOR EACH GEOMANIFESTATION TYPE AND PER COUNTRY TO BUILD THE GEOMANIFESTATIONS DATABASE (BE = BELGIUM, NL = THE NETHERLANDS, GER = GERMANY, LU = LUXEMBOURG, FR = FRANCE).

Geomanifestation type	Data source	BE	NL	GER	LU	FR
Seismic amplitude anomalies	2D seismic sections	VITO				
Collapse structures	2D seismic sections, gravimetry data	VITO				
Thermal anomalies	published scientific literature or publicly available popular websites/leaflets	VPO	VPO	VPO		VPO
CO_2-seeps	published scientific literature (VPO) or own fieldwork (GSB)	VPO, GSB		VPO	SGL	
He-anomalies	published scientific literature	VPO	VPO	VPO	SGL	
Volcanic phenomena	published scientific literature or publicly available popular websites/leaflets			VPO		
Seismicity data	KNMI-hosted earthquake dataset (www.knmi.nl)	TNO	TNO	TNO	TNO	
Polymetallic veins	Minerals4EU database (restricted access to project partners)	GSB			(SGL)	GSB
Illite crystallinity	Data from the unpublished PhD thesis of Larangé (2002)	GSB				
Surface movement	INSAR-data processed over 5 years (2015-2020) (www.bodemdalingskaart.nl)		TNO			

Note: this table does not indicate that the Geomanifestation database covers all observations of a given Geomanifestation type in that country, but that (at least some) Geomanifestations occurring in that country have been included.

2 IMPLEMENTING THE STRUCTURAL FRAMEWORK AND GEOMANIFESTATIONS

To implement the Structural Framework (SF) and the Geomanifestations, the two-step Structural Framework-Geomanifestations methodology was followed (Barros et. al., 2020). This means that both the Structural Framework and the Geomanifestations have the following structure in common:

- Spatial data
- Database attributes
- Semantic data

The semantic data covers all the elements of the Structural Framework and their conceptual relationships, following the Simple Knowledge Organization System (SKOS, 2009) data model. The semantic data are linked with the spatial data, in which the data structure foresees zoom levels that allow for visual representation of larger- or smaller-scale structures, depending on the zoom level. In addition, a number of none-spatial attributes are stored in a spreadsheet-format.

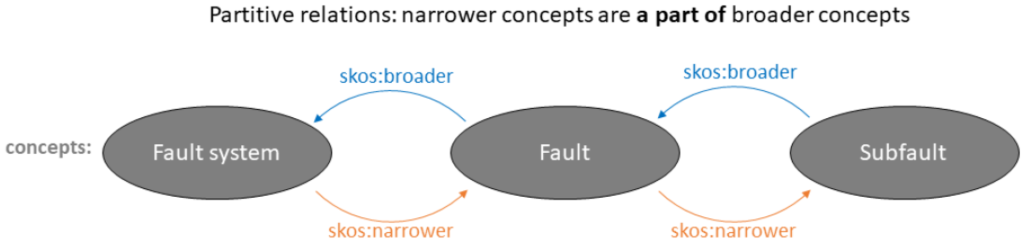
2.1 Implementing the Structural Framework

The R2R area was the pilot area that was used to actually employ the two-step Structural Framework-Geomanifestations methodology (Barros et. al., 2020) that was then applied to the other project areas of GeoConnect³d. Therefore, the implementation of the SF in this area was an incremental process comprising of 4 main stages:

1) Conceptual development of the SF methodology
2) Development of a Pan-European SF
3) Creation of the SF by each of the project partners individually
4) Merging of the individual SF into one overall structure

2.1.1 Conceptual development of the SF methodology

During this first stage, the main focus was put on how the SKOS data model could be applied to create a meaningful Structural Framework. It was concluded that the semantic data of the Structural Framework need to comprise limits and units, and that both hierarchical-partitive and associative-abstraction relations were to be used to be able to describe the geological structure.



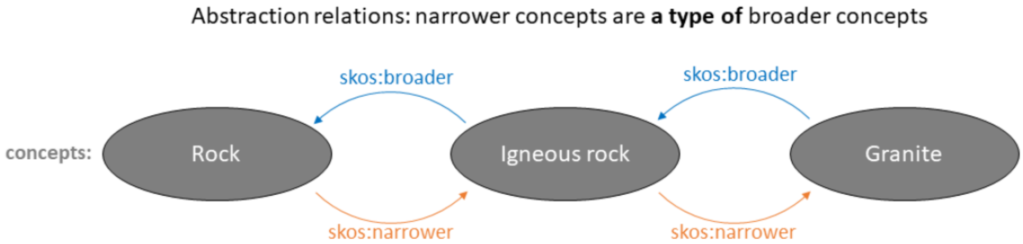


FIGURE 1: THE DIFFERENT TYPES OF HIERARCHICAL RELATIONSHIPS ADOPTED IN THE SEMANTIC DATA STRUCTURE OF THE R2R SF (BARROS ET. AL., 2020)

In addition, as different partners are contributing to the R2R SF, it was decided to use mapping properties (exact match, close match, …) on the level of the semantic data to link data from different sources and to harmonize the semantic concept schemes.

2.1.2 Development of a Pan-European SF

To be able to link the SF of the different project partners, and to provide a hierarchical backbone of the SF, it was decided to develop a Pan-European SF. This task, although not foreseen in the project proposal, was considered valuable to improve the understanding of the SF in a more regional view and was developed within WP3 as an additional test of the methodology.

An interesting aspect of this Pan-European SF is that the highest level of the vocabulary is structured based on partitive modelling, resulting in a thematic subdivision of limits and units (FIGURE 2). On a second level, abstraction relations are used to populate the vocabulary with instances (e.g., the Paris Basin and the North-West European Coal Basin are both **types of** basins). Then, partitive relations are used to further detail the structure and model the data (e.g., the Mons Basin and the Campine Basin are both **part of** the North-West European Coal Basin). This way of structuring is less intuitive compared to using large-scale geological areas as a backbone (e.g., using ‘the Eifel area’ or ‘the Campine Basin’ as broadest concepts in the Pan-European SF). However, using the thematic implementation allows the SF to provide a flexible and workable structure for many different types of limits and units (see FIGURE 5).

Limits
European plate boundaries
European crustal boundaries
European deformation fronts
European faults
European orogenic unconformities
European basal unconformities
Stratigraphic contacts
European lineaments

Units
Plate tectonic units
European orogens
European massifs and inliers
European basins
European volcanic deposits
European (other) lithostratigraphic units
European (other) lithotectonic units

FIGURE 2: BROADEST CONCEPTS IN THE PAN-EUROPEAN SF, SUBDIVIDING GEOLOGY INTO DEFINED THEMATICS.

2.1.3 Adoption of the SF by each of the project partners individually

In a second phase, each of the partners worked individually on inventorying and structuring the data within its area of legislation. The approach that was followed differed significantly because of large differences in available information and geological complexity of different areas within the project.

For Flanders and the Netherlands 3D geological models are available, comprising both layers and faults. Hence, these models were used as the primary source of information. These datasets have in common that they are comprised of many (3D) faults which, when plotted together on a surface map, do not readily provide insight into the main geological structure of the area. Therefore, in both areas, intersections of the 3D fault planes with a number of reference geological layers were made, and a number of fault attributes (e.g., strike, dip, throw, etc.) were calculated. These results were then used to classify the input dataset and detect structure.

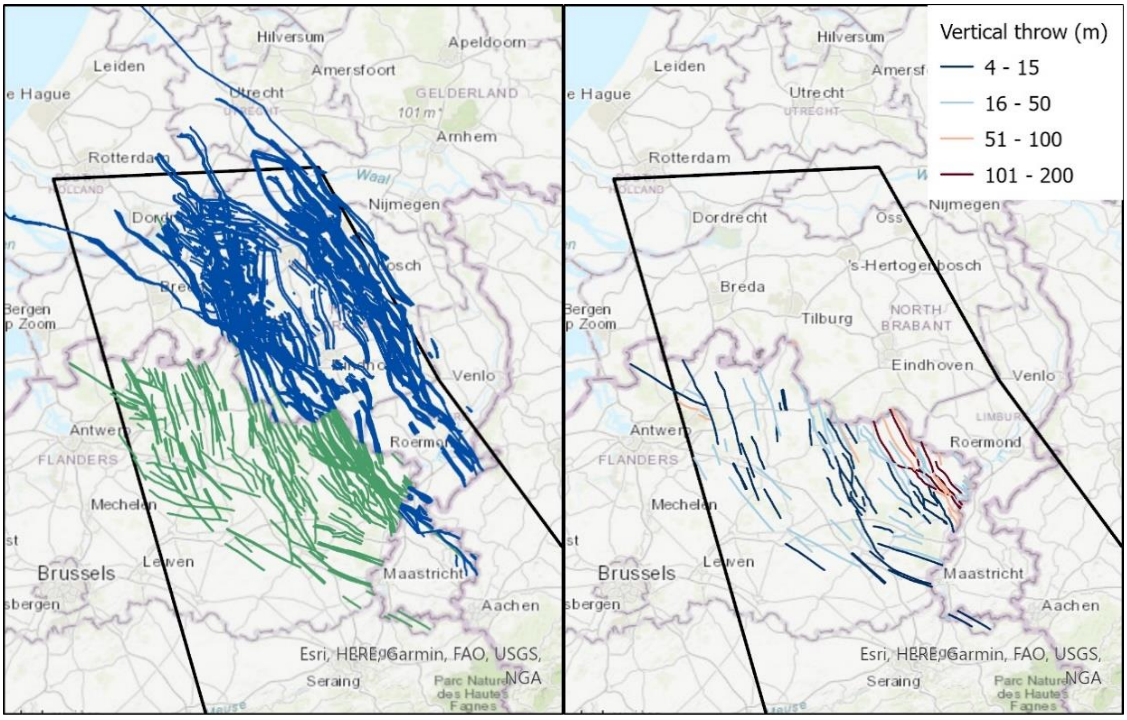


FIGURE 3: LEFT: VIEW ON INPUT DATA FOR THE SF IN THE NETHERLANDS AND FLANDERS. THE GREAT ABUNDANCE OF FAULT STRUCTURES HAMPERS THE INTERPRETATION OF THE MAP IN TERMS OF GEOLOGICAL STRUCTURE. RIGHT: FLEMISH FAULTS FILTERED TO DISPLAY ONLY THE REFERENCE SURFACE OF THE CRETACEOUS AND DISPLAYING THE VERTICAL THROW. THIS REPRESENTATION HELPS TO DETECT THE MORE IMPORTANT LIMITS WITHIN THIS AREA.

The figure above demonstrates how filtering the input data and displaying fault attributes can help to distinguish larger- and smaller-scale structures. Insights from these classification exercises were subsequently used to group faults and enter them in semantic concept schemes. The units were entered in the SF in a second stage, and were created based on the limits.

For Wallonia, the available information is more disperse, and the geological complexity of the area is significantly larger. Therefore, for this area the semantic concept scheme was much more used as a starting point of the analysis, allowing to structure the data that is often conceptually described in geological literature, but for which spatial representations are more difficult to obtain. Mainly maps at different geological scales were used to create units and limits to populate the SF in this area, and limits are almost uniquely mapped as surface expressions. As the Walloon area is a geologically complex region and forms the central link between most of the project partners, a comprehensive approach was used for populating the Structural Framework, as is displayed below (FIGURE 4).

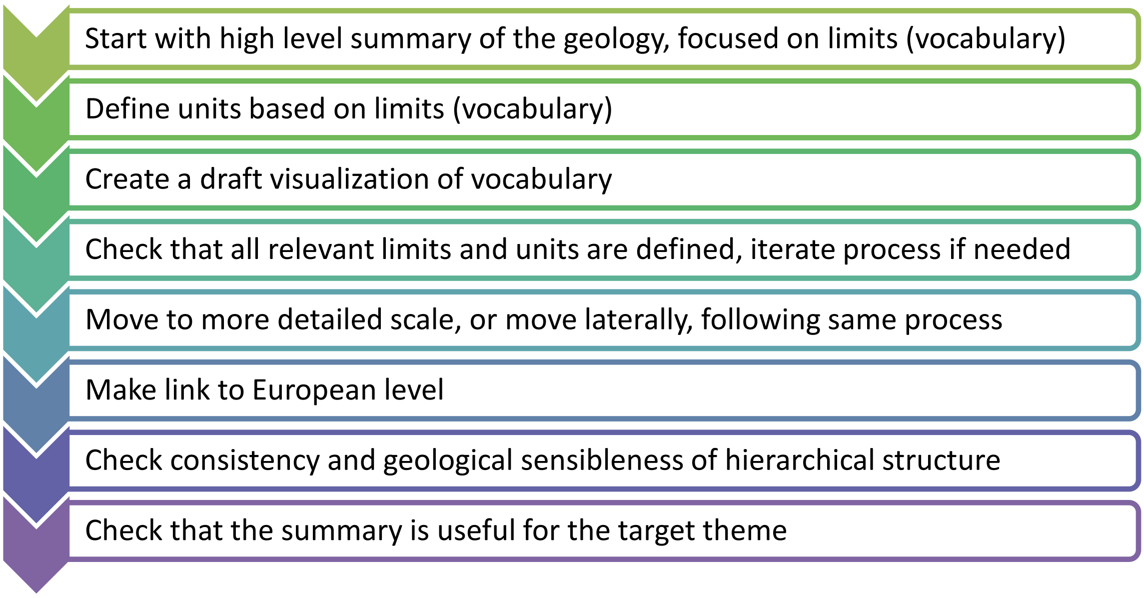


FIGURE 4: APPROACH TO CONSTRUCT THE STRUCTURAL FRAMEWORK OF THE WALLOON AREA.

Also in Nordrhein-Westfalen and Luxembourg, the geology is complex and 3D information is scarce. In Nordrhein-Westfalen, first a set of geometries and attributes of limits were compiled using maps and a geoinformation system (see TABLE 1). Subsequently, units were defined using these limits, after which both structure types were integrated in a vocabulary structure. For Luxembourg, first a tectonic map of the area was produced, including all the major faults. Subsequently, faults with similar tectonic attributes were grouped to feed into the vocabulary structure.

In the third phase, the SFs of the different partner areas were merged, both semantically and spatially. This was an iterative process during which the data was harmonized at (1) the conceptual level, (2) the spatial level and (3) in terms of scale.

2.2 Implementing the Geomanifestations database

Ten Geomanifestation types were inventoried and included in the GeoConnect³d Geomanifestations database for the R2R study area (see TABLE 3). Most of them potentially relate to the presence of deep-seated faults which, in combination with the Structural Framework, gives a powerful opportunity to identify active faults and investigate their role in the distribution of fluids, gases and heat in the subsurface.

TABLE 3: GEOMANIFESTATIONS INVENTORIED FOR THE R2R STUDY AREA, THEIR DEFINITION AND THE RATIONALE FOR SELECTING THEM.

Geomanifestation type	Definition (“or”)	Rationale for selection
Thermal anomalies	- shallow (< 500 m) T > 12 °C - deep (> 500 m) T > 10 °C + 30 °C/km - springs/ponds that do/did not freeze over winter	Can indicate either a rapid ascent of heated fluids along deep-seated faults or strongly fractured rocks, either an elevated heat flux of the Earth crust
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, …)*	Can indicate proximal volcanic phenomena (on-going or in the past) or migration through carbonate rocks, and the presence of fractured rocks or deep-seated faults
He-anomalies	- gas with > 5.22 ppmv He - $^3He/^4He > 1.4 * 10^{-6}$ (R/RA > 1)	Typically indicate mantle-contribution to the gas-budget, which reached the surface along deep-seated faults
Polymetallic veins	Locations of metal-rich veins, including polymetallic and 5-element veins (Bi, Co, Ni, Ag, U)	Indicate past hydrothermal activity, can help to identify crustal discontinuities such as faults and unconformities
Seismicity data	An earthquake (either induced or naturally occurring)	Can indicate movement/activity of faults
Illite crystallinity	Illite crystallinity data that are anomalous with respect to the expected maximum burial depth according to its stratigraphic position	Can indicate anomalous burial histories or depths
Volcanic phenomena	Volcanoes, maars and calderas in the Eifel area	Indicates where magma migrated towards the surface, most often along existing fault traces or by hydraulic fracturing
Seismic amplitude anomalies	Distinct expressions on a seismic image, detected or confirmed using AVO analysis	Can indicate the presence of fluid-bearing layers or gas accumulations
Collapse structures	Local depressions on seismic data	Can be related to evaporite or limestone dissolution by fluid migration along faults.
Surface movement	More than 2 mm movement of the earth surface in the satellite line-of-sight (INSAR-data)	Can indicate aseismic slip of faults, but also peat oxidation, gas extraction, subsurface injection, collapse or rebound of abandoned mines, or dissolution (karst)

Data on these Geomanifestations were mostly collected from literature or existing databases (see TABLE 2). Little new field work, analyses or investigations were performed. This was only the case for the seismic anomalies (seismic amplitude anomalies and collapse structures) and CO_2-springs in the region of Spa (Belgium). While a dominantly literature-based approach allows to build an extensive dataset covering most of the R2R area in a cost- and time-efficient way, this has the disadvantage that not all desired information can for all cases be retrieved. If one (crucial) part of info is missing, a specific entry cannot be taken up in the database which automatically results in some kind of data-availability bias. Below, a summary on the data collection procedure for each Geomanifestation type is given.

Temperature data are readily available in the whole R2R area. However, information on the depth of the temperature measurement is much less consistently recorded. In these cases, it is difficult to assess if it concerns an anomalous temperature (e.g., a temperature of 40 °C is definitely anomalous at the surface, while, according to a general geothermal gradient of 10 + 30 °C/km, this temperature is to be expected when observed at depths of about 1 km). Therefore, both the temperature and depth values of thermal anomalies were included as Attributes in the database.

As indicated in TABLE 3, anomalous **CO_2-concentrations** can manifest in multiple ways, mostly depending on the local water household. New quantitative data was gathered in the framework of the GeoConnect³d project only for the CO_2-springs in the area of Spa, Belgium (Barros et al., 2021). Literature was used for inventorying the CO_2-seeps observed in the rest of Belgium, the Netherlands, Luxembourg and Germany. Quantitative data on CO_2-concentrations are less often available compared to temperature data. Nonetheless, visual observation of gas bubbles (assumed to be predominantly CO_2) is often reported, especially in the Eifel area. This consequently is reflected in the name of springs by terms like 'Saüerlinge', 'Sauerbrunnen' or 'Sprudel'. These records have also been included in the Geomanifestations database, to enlarge the dataset and limit the bias based on quantitative data availability. However, the CO_2-anomaly dataset inherently contains more data on springs, streams and ponds than on dry gas seeps, as the former always has been the focus in the traditional way of surveying. This constraint counts for the **He-gas observations** as well, with the additional note that it is a less standard practice to analyze He-content or He-isotope composition, leading to a less extensive dataset compared to that of the CO_2-seeps. For both the CO_2-seeps and He-anomalies, also overview maps from literature were georeferenced and included as 'multipoints' in the database, in addition to the dataset built up from individual observation points. For these Geomanifestation types, if available, the maximum CO_2-concentration as well as the maximum He-concentration and $^3He/^4He$-value were added as Attributes, respectively.

The occurrence of and information on the **polymetallic veins** was transferred from the Minerals4EU database towards the GeoConnect³d database structure. This was a straightforward exercise that did not pose significant problems.

In the same way, the seismicity anomalies (**earthquakes**) in the Netherlands, Belgium, Germany and Luxembourg were directly obtained from the Royal Netherlands Meteorological Institute (KNMI). One of the tasks of KNMI is to monitor seismic activity and they also host an online earthquake dataset (https://www.knmi.nl/kennis-en-datacentrum/dataset/aardbevingscatalogus).

Deriving **illite crystallinity** values for the Brabant Massif and upper Paleozoic cover was quite straightforward as well, given the constrained study area and the single data source that was used as reference source (Lagrangé, 2002).

Inventorying **volcanic phenomena** (volcanoes, maars and calderas) in the Eifel area was done either by collecting individual data points or through multipoints derived from georeferenced maps. A lot of literature exists on the Eifel volcanism, and there is a general consensus on the location of these volcanic phenomena, as well as of their age in most cases. Only for a few entries, the age of activity could not be determined from literature. The fact that no quantitative data other than the volcanism age was included in the database, made data collection significantly easier.

The two types of seismic anomalies, seismic amplitude anomalies and collapse structures, have been investigated and interpreted on existing 2D seismic lines in Flanders in the framework of the GeoConnect³d project. As **seismic amplitude anomalies** are difficult to interpret, specific pre-stack processing of the seismic lines was carried out. Subsequently, an Amplitude Variation with Offset (AVO) analysis was performed on the detected anomalies. This sort of analysis is ideal to analyze observed seismic anomalies, but also to detect additional seismic anomalies which do not show up or remained unnoticed on the seismic image. In total, four of these anomalies were detected and interpreted. For the **collapse structures,** seismic lines in the Flemish part of the Campine Basin were evaluated. Collapse structures can be recognized on the seismic data as often symmetric, sag structures with related sharply downwards dipping reflections towards their centre. Their mean vertical throw at four stratigraphic surfaces was estimated (top Dinantian, base Westphalian, base Upper Cretaceous and base Paleogene), and the relationship of the collapse structures to one or more faults from the Structural Framework was added, as well as the visibility of the structures on the bouguer gravity anomaly map (Debacker et al., 2018).

For the **surface movement** Geomanifestation, own research, analyses and interpretation was performed as well. From 16.821.270 INSAR data points, a selection was made where surface movements ranged from -2 to +2 mm over the 5-year period 2015-2020. For these, a polygon was constructed by grouping smaller areas of uplift using a concave-hull operation. The results are the rates of deformation following a linear regression model (velocity in mm/year). In this way, the outlines of INSAR-derived surface deformation in the coal mine area (Limburg, the Netherlands) were obtained.

After literature review, data collection, and selection according to the Geomanifestation definitions (see TABLE 3), more than 2300 Geomanifestation entries were retained and included in the Geomanifestations database (TABLE 4). Sometimes a certain location displays anomalous values for multiple parameters (e.g., a thermal, CO_2-rich spring), in which case it was stored multiple times in the database. All information associated with these Geomanifestation records (GIS, Attribute information, Vocabulary-concept, Factsheet) could be readily incorporated in the database structure. The Vocabulary structure, as well as the factsheets, mainly reflect a Geomanifestation-type and geographical subdivision. Locations with multiple references containing quantitative data were encountered regularly, in which case only the most anomalous value was kept in the Attribute Table. A more complete overview of the literature data available and (published) interpretations of the Geomanifestations origin are given in the factsheets. In total, more than 65 factsheets have been written for Geomanifestations in the R2R area (TABLE 4), including anomaly- or region-specific factsheets as well as more general, overarching factsheets (e.g., for the AVO-analyses or illite-crystallinity in Flanders).

TABLE 4: NUMBER OF GEOMANIFESTATION ENTRIES INVENTORIED FOR THE R2R STUDY AREA, AS WELL AS THE NUMBER OF FACTSHEETS GIVING A MORE IN-DEPTH DISCUSSION.

Geomanifestation type	Number of database entries	Number of factsheets
Thermal anomalies	233 (VPO)	20 (VPO)
CO_2-seeps	243 (VPO) + 50 (GSB)	19 (VPO) + 1 (GSB)
He-anomalies	39 (VPO)	1 (VPO)
Polymetallic veins	187 (GSB) + 4 (SGL)	1 (GSB)
Seismicity data	1264 (TNO)	1 (TNO)
Illite crystallinity	236 (GSB)	15 (GSB)
Volcanic phenomena	37 (VPO)	1 (VPO)
Seismic amplitude anomalies	4 (VITO)	5 (VITO)
Collapse structures	45 (VITO)	1 (VITO)
Surface movement	1 (TNO)	1 (TNO)

2.3 Results of the Structural Framework and Geomanifestations

2.3.1 Structural Framework

2.3.1.1 Pan-European level

As the SF at the pan-European level was structured conceptually in a thematic way (see section 2.1), this is also the clearest way to visualize the result. The figure below visualizes four of the main themes present in the pan-European SF: plate tectonics, orogens, (Paleozoic) massifs, inliers and deformation belts, and (Mesozoic and Cenozoic) basins, including graben structures. Each thematic view presents different aspects of the regional geology of the R2R area (FIGURE 5). On a pan-European scale, large and complex structures such as suture zones and orogenic fronts are the limits to the plate tectonic units that include paleoplates, terranes, and orogens and their deformation belts. Large-scale unconformities and faults are also important limits that define large massifs and basins.

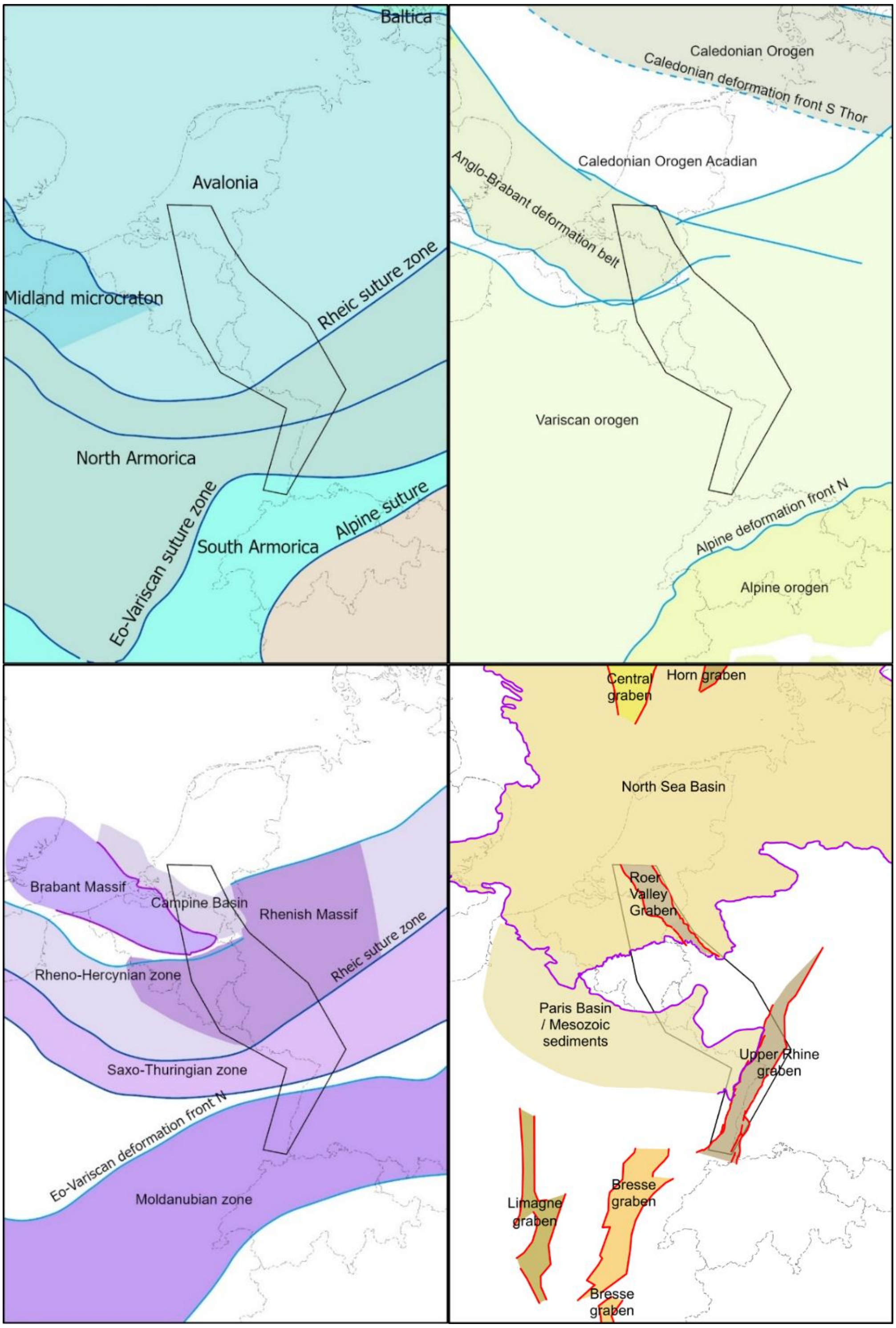


FIGURE 5: DIFFERENT THEMES OF THE PAN - EUROPEAN SF. UPPER LEFT: PLATE TECTONICS, WITH MAIN LIMITS BEING (PAST) PLATE BOUNDARIES IN DARK BLUE. UPPER RIGHT: OROGENS, WITH MAIN LIMITS BEING OROGENIC FRONTS IN LIGHT BLUE. LOWER LEFT: PALEOZOIC MASSIFS AND DEFORMATION BELTS, AS A DETAILING OF LARGE-SCALE OROGENS, WITH LIMITS INCLUDING PLATE BOUNDARIES, DEFORMATION FRONTS AND OROGENIC UNCONFORMITIES (IN PURPLE). LOWER RIGHT: MESOZOIC AND CENOZOIC BASINS AND GRABENS, WITH MAIN LIMITS BEING BASAL UNCONFORMITIES AND FAULTS (IN RED).

2.3.1.2 R2R-area

When zooming in from the Pan European level to the area covered by R2R, a large number of units and limits appear, at times replacing large-scale features, gradually revealing the more local geology and its increasing complexity. As an example, the Variscan Orogenic Front in Belgium, represented as a single line in pan-European view, is then represented as the Ardennes basal detachment thrust system on more detailed scale (FIGURE 6). This is a usual case in geology: depending on the scale you are investigating an area, different types of limits (and therefore units) are more relevant. An orogenic front is a wide, complexly deformed zone that can only be defined as a limit when looked at within pan-European context; zooming into country scale adds the possibility of "breaking down" this concept into a thrust system representing the outermost extent of orogenic effects. In this case, to represent the full width of the thrust system, a halo (or buffer) is used around the limit at pan-European view. The buffer is the tool being used to represent the uncertainty of all limit traces (FIGURE 6).

FIGURE 6: ZOOMING IN FROM PAN-EUROPEAN TO R2R SCALE - THE EXAMPLE OF THE VARISCAN OROGENIC FRONT. LEFT: PAN-EUROPEAN VIEW. RIGHT: COUNTRY-SCALE VIEW (ZOOMING IN THE AREA INSIDE THE DASHED RECTANGLE ON THE LEFT). NOTE HALO (OR BUFFER) REPRESENTING THE UNCERTAINTY OF TRACES AT DIFFERENT SCALES.

The starting point of the resulting SF for R2R is focused on country-scale geological features. In FIGURE 7 below, faults are indicated in red, unconformities in purple and lithostratigraphic contacts in black. It displays that units are generally bounded by limits, although not all units are clearly delimited in space, such as the Brabant Parautochton. It is important to note that this 2D visualization aims to display the most important structures in the area, but that the structures shown are not representing a specific stratigraphic level or tectonic phase. For example, it shows both the Paleozoic Brabant massif as well as the Cenozoic Roer Valley Graben.

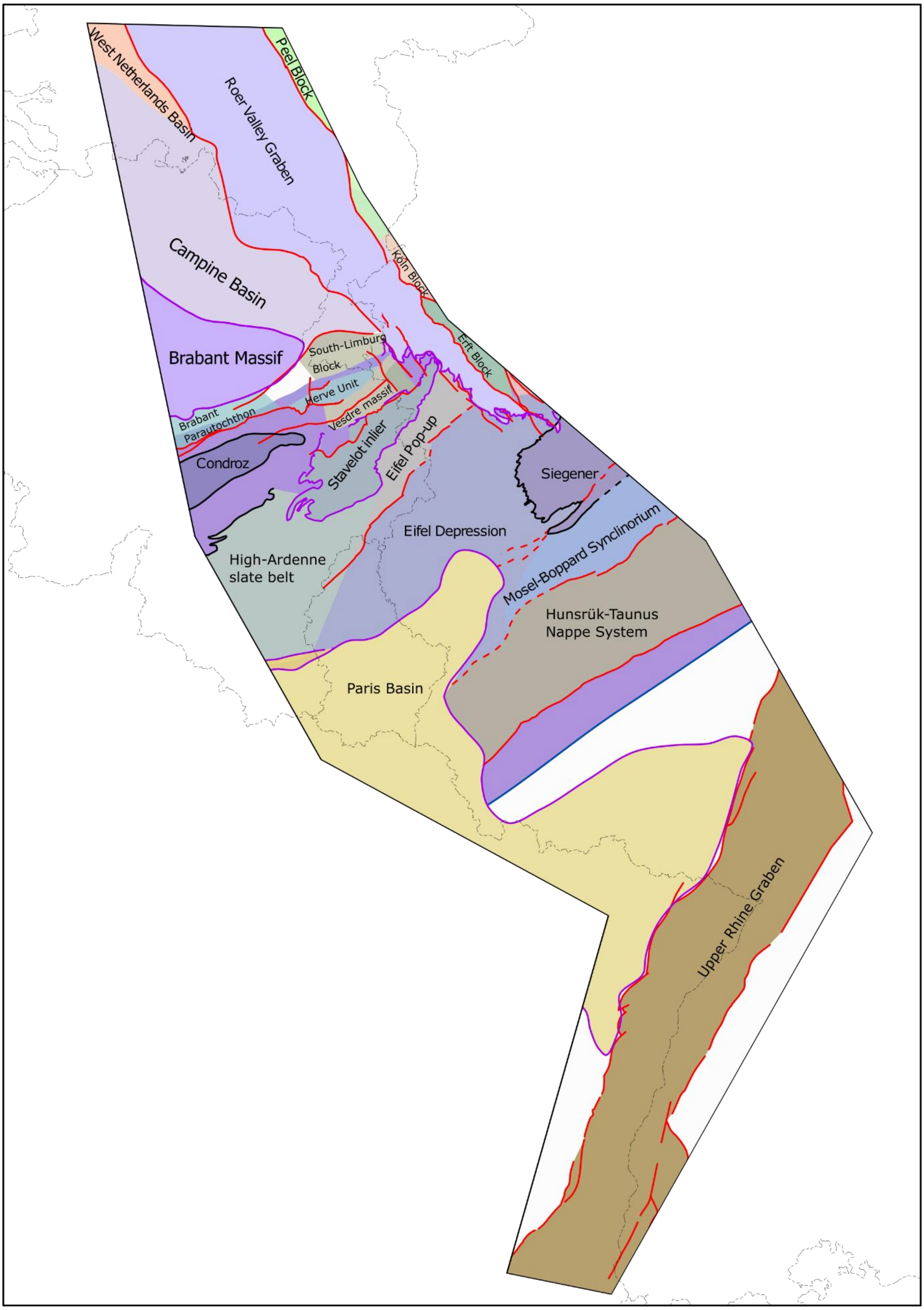


FIGURE 7: OVERVIEW OF THE SF IN THE R2R AREA, ZOOMED OUT TO THE SCALE OF 1: 2 000 000.

2.3.1.3 Roer Valley Graben area

One of the advantages of the Structural Framework is that it allows to display more detailed information when zooming in to smaller scales. As an example, the figure below shows that while the western and eastern borders of the Roer Valley Graben are displayed as a single line on the zoom level of 1: 2 000 000, zooming to 1: 1 000 000 allows to display more detail. Starting from this zoom level, traces of the actual, 3D modelled faults are shown. At the scale of 1: 1 000 000 only the most important faults (generally those with the largest throw) are displayed, while on the scale of 1: 500 000 traces of all the modeled faults in the area are included.

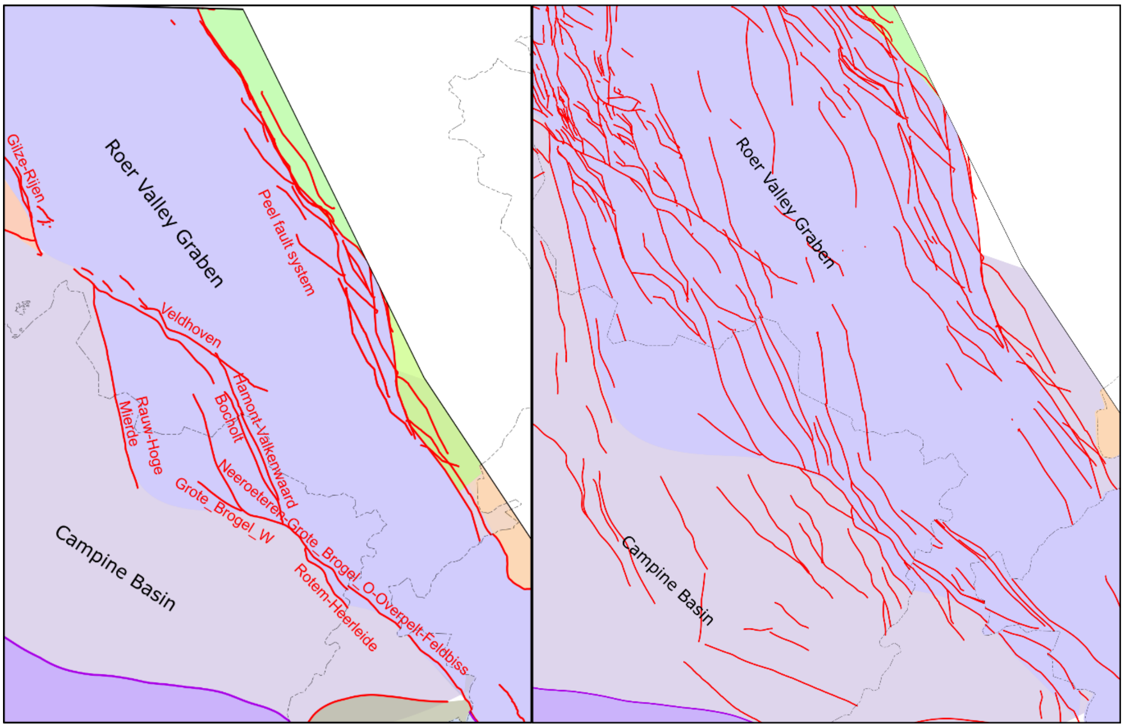


FIGURE 8: SNAPSHOTS FROM THE ROER VALLEY GRABEN AREA AT ZOOM LEVELS OF 1: 1 000 000 (LEFT) AND 1 : 500 000 (RIGHT)

2.3.1.4 Ardennes-Eifel area

Also in the geologically more complex area of the Ardennes and the Eifel, more detail appears at smaller zoom levels. Contrasting to the Roer Valley area, focus at the 1: 1 000 000 level is more on the units, while more limits start appearing from the most detailed zoom level included in the Structural Framework (1: 1 250 000).

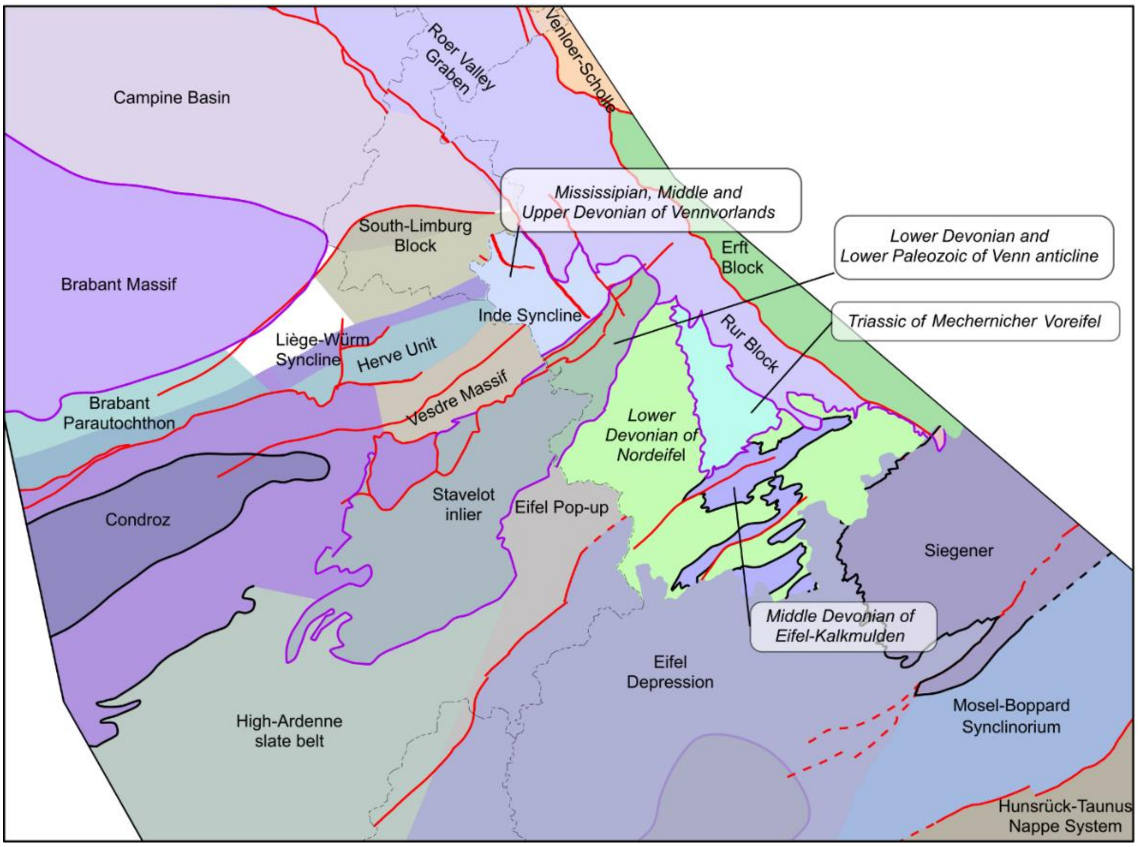


FIGURE 9: SNAPSHOT FROM THE ARDENNES- EIFEL AREA AT A ZOOM LEVEL OF 1: 1 000 000

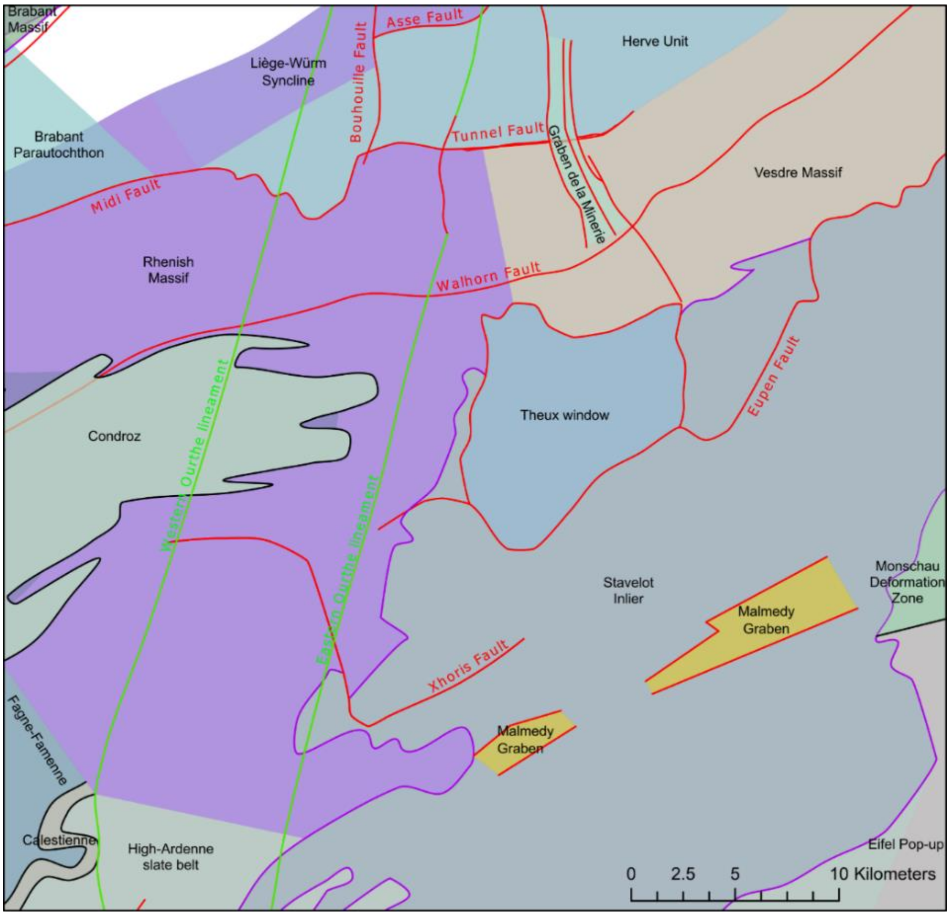


FIGURE 10: SNAPSHOT FROM THE ARDENNES- EIFEL AREA A ZOOM LEVEL OF 1 : 250 000

2.3.2 *Geomanifestations*

As discussed in section 2.2, a wide variety of Geomanifestations were inventoried within this project. In FIGURE 11, all of them are displayed spatially, in relation to the Structural Framework on the scale of the R2R area.

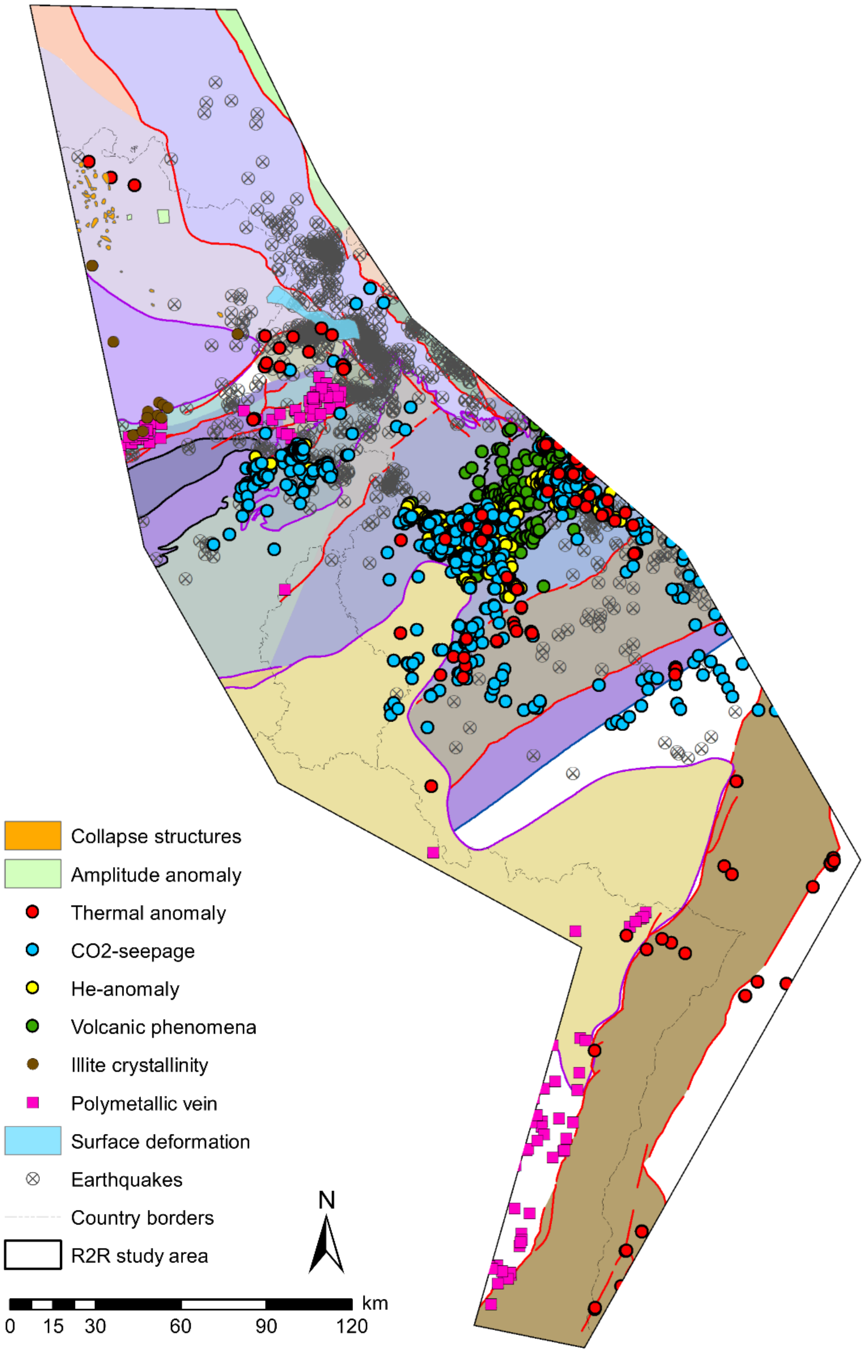


FIGURE 11: OVERVIEW OF THE DISTRIBUTION OF ALL GEOMANIFESTATION TYPES COLLECTED FOR THE R2R STUDY AREA.

3 EVALUATING THE STRUCTURAL FRAMEWORK AND GEOMANIFESTATIONS

3.1 Structural Framework

3.1.1 Different approaches to populate the Structural Framework

In the course of the project, it became clear that different approaches can be followed to organize the data into a Structural Framework. Depending on the type of input data available and the geological structure of the area, different emphasis tends to be put. For example, Flanders and the Netherlands are characterized by a generally simple shallow geology, while in Wallonia the strata are very strongly deformed and faulted, resulting in a complex structure of distinctive basins and inliers. Moreover, both the geological layers and the faults of Flanders and the Netherlands have been mapped in 3D, bringing forth a vast amount of data readily available for input in the SF. In Wallonia on the other hand, because of the complex geology, 3D models are only available on a local scale (basin of Liège, basin of Mons), and in large parts of the region one has to rely on information derived from 2D geological maps of different scale and quality. This difference led to the situation where the basis of the SF constructed for Wallonia was strongly focused on units, while the SF constructed for The Netherlands and Flanders was in a first phase almost exclusively linked to limits. While this is conceptually not a problem for the SF-structure, it is very apparent when putting the data together spatially, and initially hampered the applicability of the SF for providing large-scale insight in structure of the area. A final harmonization step using all available data was able to better integrate both datasets (see FIGURE 5).

Another example of differences in approach towards the SF can be found in the comparison between the SF developed by Nordrhein-Westfalen and the one developed by the Geological Survey of Belgium. In the area around the NE tip of the Stavelot-Venn Inlier, the geology can be defined with a focus on lithotectonic units (as done by the GSB) or lithostratigraphic units (as done by GD NRW). Interestingly, overall limits of both approaches largely coincide and are therefore compatible at a general level, although further subdivisions of the geology are present within the lithotectonic thematic at a more detailed level (FIGURE 9).

3.1.2 Relating limits and units conceptually

The SF structures the geological information. Because that structure is based on relations, it becomes easier to explain and remember that information.

An important advantage of the SF is that it provides a great tool to facilitate the link between modeled or mapped (spatial) data and information described on a more conceptual level in geological literature. For example, the Feldbiss Fault zone is in literature quite clearly defined as one of the western fault zones bordering the Roer Valley Graben. However, when mapping this area using 2D seismics, it becomes clear that this area is comprised of many faults, spanning an area of over 20 km and differing significantly in terms of vertical throw. Here, the SF provides an elegant solution to structure the data: using the hierarchical relationships and concept-level structure, it is possible to assign individually named faults or groups of unnamed faults all to a higher-scale concept using a 'broader'-relationship (TABLE 5). For example, in FIGURE 12, all faults colored in blue are conceptually linked to the Feldbiss fault system, and on a larger scale also to the Roer Valley Graben large scale fault system. As not all faults that are part of the Feldbiss fault system are of equal size (in terms of throw), the SF was organized in such a way that when zooming out, only the more important faults of this fault system remain visible. Finally, on the largest zoom levels, more conceptual fault traces were constructed in order to provide for a simplified western border of the Roer Valley Graben (FIGURE 13).

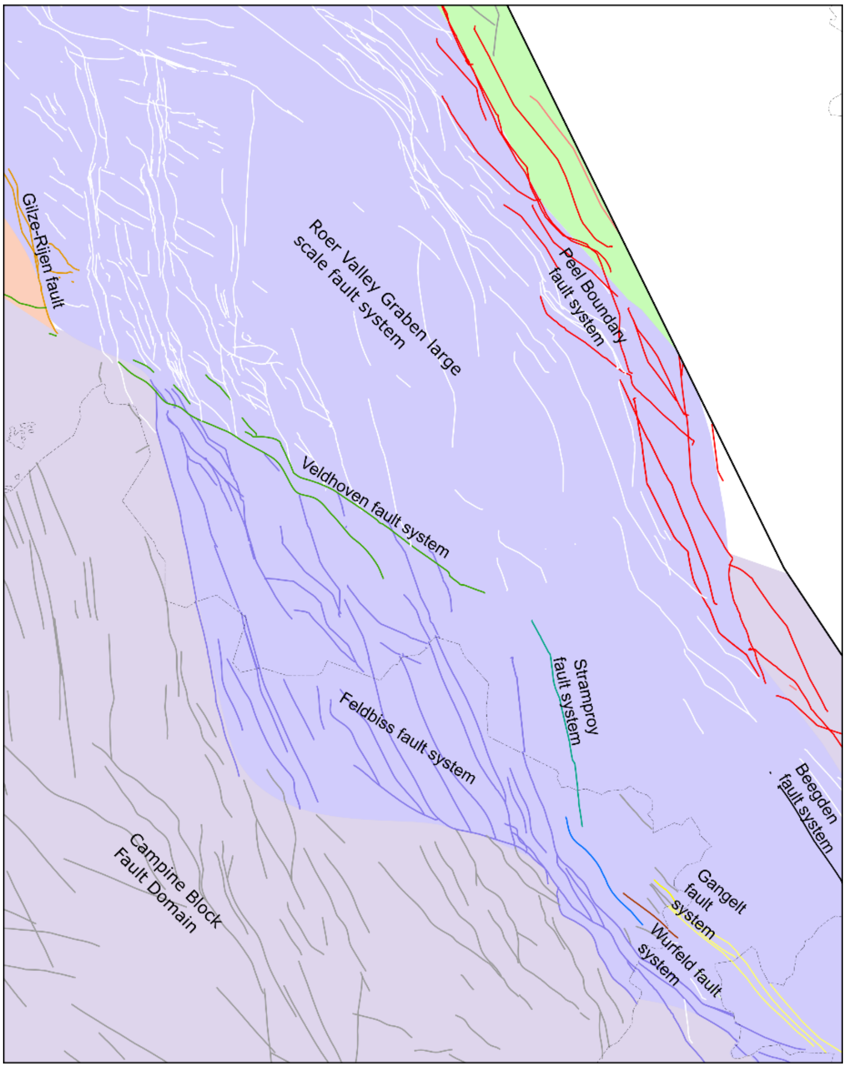


FIGURE 12: DETAILED VIEW OF THE SF IN THE RVG AREA (ZOOM LEVEL: 1: 500 000). THE FAULT TRACES ARE COLORED ACCORDING TO THE VOCABULARY STRUCTURE: ALL TRACES WITHIN THE PURPLE AREA ARE HIERARCHICALLY PART OF THE ROER VALLEY GRABEN LARGE SCALE FAULT SYSTEM, BUT SOME OF THOSE HAVE BEEN DESCRIBED IN MORE DETAIL (E.G., 'STRAMPROY FAULT SYSTEM') WHILE OTHERS ARE ASSIGNED DIRECTLY TO THE LARGER SCALE CONCEPT (E.G., THE WHITE FAULTS).

This facilitating role in linking data with concepts is particularly useful in a context where information originating from separate models (for example different countries) needs to be integrated. In the RVG-area, this becomes clear in its western border zone. In Belgium, the Feldbiss fault zone is generally used as a concept to define the structure representing the western border of the Roer Valley Graben. This structure hence comprises many faults in this area. On the contrary, in The Netherlands and in Germany, the Feldbiss fault is generally described as a single, individual fault. When combining the three datasets into one concept scheme, this conceptual distinction becomes immediately apparent and can hence be harmonized.

TABLE 5: EXTRACT FROM THE VOCABULARY STRUCTURE OF THE ROER VALLEY GRABEN LARGE-SCALE FAULT SYSTEM

Level 1	Level 2	Level 3
Roer Valley Graben large-scale fault system		
	Feldbiss fault system	
		Neeroeteren-Grote_Brogel_O-Overpelt-Feldbiss
		Hamont-Valkenwaard fault
		Rauw-Hoge Mierde fault
		…
	Campine block fault Domain	
		Hoogstraten fault
		Eckelrade fault
		Elsloo fault
		…
	Gilze-Rijen fault	
	Veldhoven fault system	
	…	

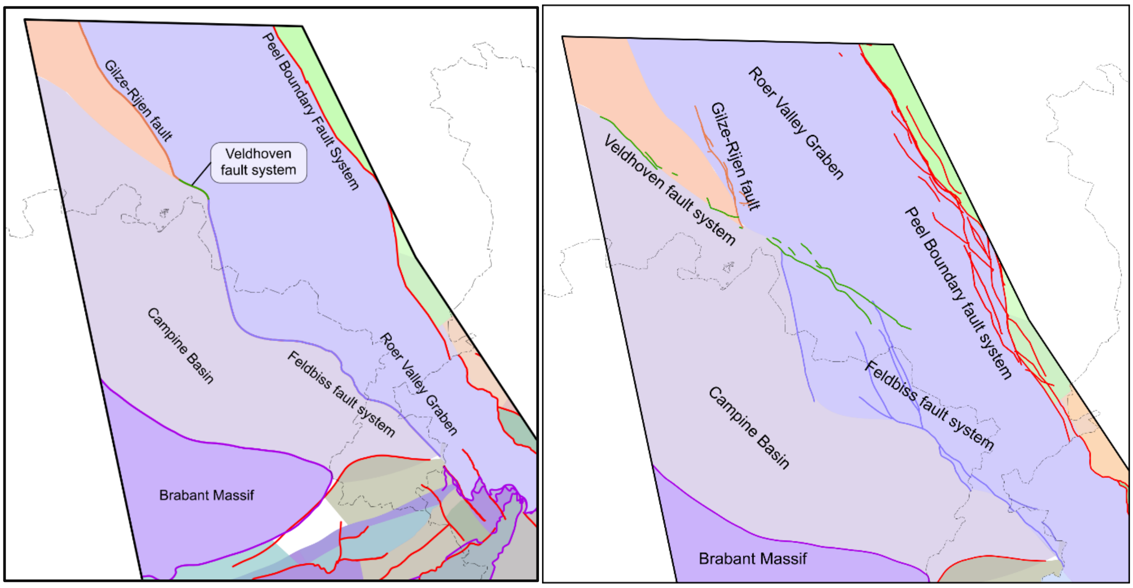


FIGURE 13: THE SF IN THE RVG AREA, WITH THE LIMITS COLORED ACCORDING TO THE VOCABULARY STRUCTURE. LEFT: ZOOM TO 1: 1 000 000, RIGHT: ZOOM TO 1: 500 000. MANY OF THE FAULTS NOW GROUPED ACCORDING TO A HIGHER-LEVEL CONCEPT IN THE VOCABULARY (E.G., FELDBISS FAULT SYSTEM), ARE ALSO INVENTORIED AT A MORE DETAILED LEVEL, AS CAN BE SEEN BY THE INDIVIDUALLY NAMED FAULTS IN FIGURE 8 (LEFT).

Likewise, the SF structure provides an elegant framework for harmonizing and structuring border-crossing units and limits. For example, the Roer Valley Graben is limited to the west by respectively the Gilze-Rijen fault, the Veldhoven fault system and the Feldbiss fault system, the latter of which crosses three countries. Traces of the three faults (fault systems) are present in the SF as separate geometrical objects within each country. However, as there is a joined vocabulary structure available, each of the project partners can assign the geometries of the limits and units they inventoried to the same geological concept in the vocabulary. This approach allows to bring a lot of structure into the data, both on a conceptual and on a visual level.

Nevertheless, the SF is based on vocabulary, which follows definitions based on relations between limits and units and hence requires the information to be scientifically consistent. While constructing the SF, weaknesses, gaps, uncertainties and conflicts in our current understanding of the geology of the area became very apparent. As an example, in the Belgian Ardennes, it was not easy to delineate the ductile deformation zones by orogenic fronts, since when information on more detailed scales is available it is possible to see deformation beyond generally accepted limits of orogenic fronts (e.g., beyond the northernmost limiting thrust faults in the Variscan front, see discussion in Belanger et al., 2012). It is also not trivial to link orogenic fronts to sutures in such areas with multiple deformation episodes, such as the Ardennian "Caledonian" deformation. Of debated origin, this deformation episode is contemporaneous to the initial deformation phase of the Caledonian Orogen (North-German Polish Caledonides) caused by the closure of the Thornquist Sea, but was possibly a result of rotation of cratonic cores within Avalonia, or a subduction-caused deformation linked to the early phases of the Rheic closure (for more details, refer to discussions in Verniers et al., 2002 and Sintubin et al., 2009). This results in an "isolated" orogenic front, which brings challenges to a visual representation (FIGURE 14). Also, the allocation of specific geological structures to one of the more general themes present in the Pan-European framework proved to be complicated, as was specifically apparent for the thematic concept 'basin'. In local literature, the term 'basin' is often used to describe certain areas that underwent extensive orogenic reworking, even though the units seen today are a deformed and reworked version of the original basins. In the SF approach, these units are more adequately defined as lithotectonic units instead (e.g. the Namur basin / Namur synclinorium / Brabant Parautochton – for more details, refer to discussion in Belanger et al., 2012).

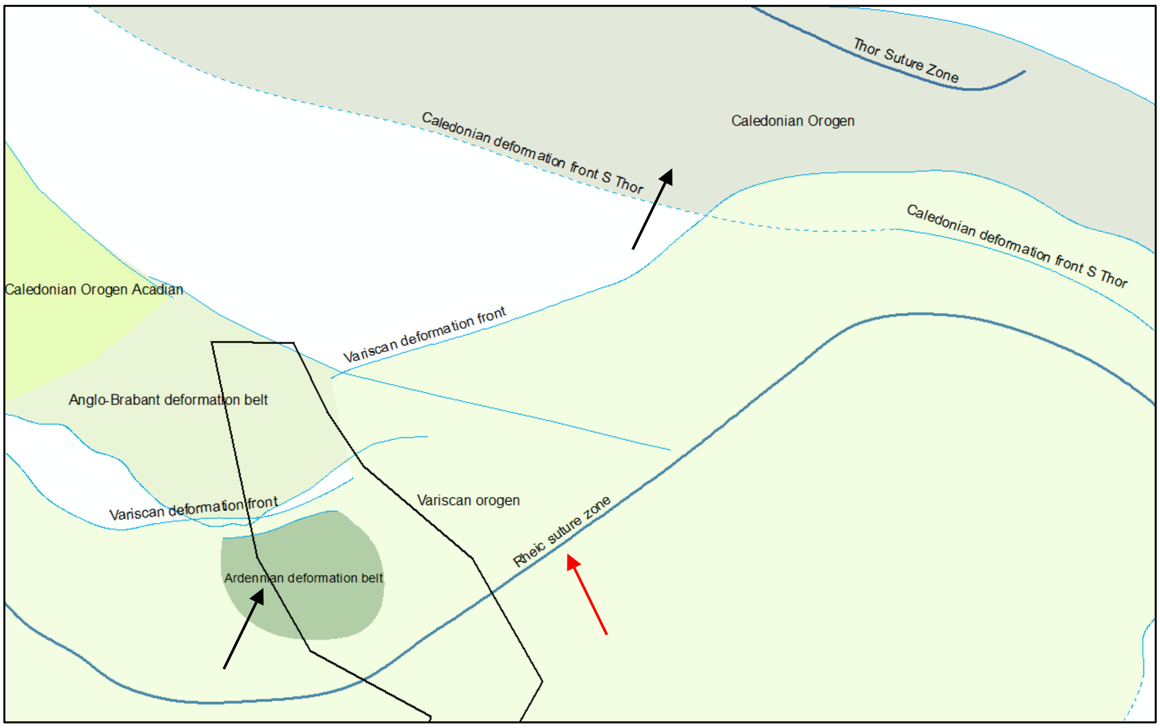


FIGURE 14: ILLUSTRATION OF ONE OF THE CHALLENGES FACED WHEN CONSTRUCTING THE SF. THE ARDENNIAN DEFORMATION BELT IN BELGIUM, WITH DEFORMATION CONTEMPORANEOUS TO THE INITIAL PHASE OF THE CALEDONIAN OROGEN (BOTH INDICATED WITH BLACK ARROWS). HOWEVER, THE CAUSE OF THE ARDENNIAN DEFORMATION IS LESS LIKELY TO BE THE THOR OCEANS' CLOSURE AS FOR THE CALEDONIAN OROGEN, BUT RATHER SUBDUCTION-RELATED DEFORMATION IN THE EARLY PHASES OF THE RHEIC OCEANS' CLOSURE (LOCATION OF SUTURE INDICATED BY RED ARROW. ALTHOUGH DIFFICULT TO REPRESENT VISUALLY, THIS DISCUSSION IS PRESENTED IN THE PROJECT VOCABULARY.

3.1.3 Relating limits and units spatially

The general idea for the use of the SF is that the entry level for a user is visual information, and that the underlying structure becomes evident through zooming or querying the system. However, while the vocabulary created within the project offers a solid hierarchical structure into which all units and limits can fit, it was learned that conceptual structure does not (and does not need to) automatically generate spatial, visual structure. This is mainly because units and limits residing in separate concepts may overlap spatially, because they are part of a different type of concept (e.g. massif, deformation front, lithotectonic unit, etc.) or because they are linked to a specific period of time, with different structures becoming relevant in different tectonic phases (see FIGURE 15 and section 3.1.5).

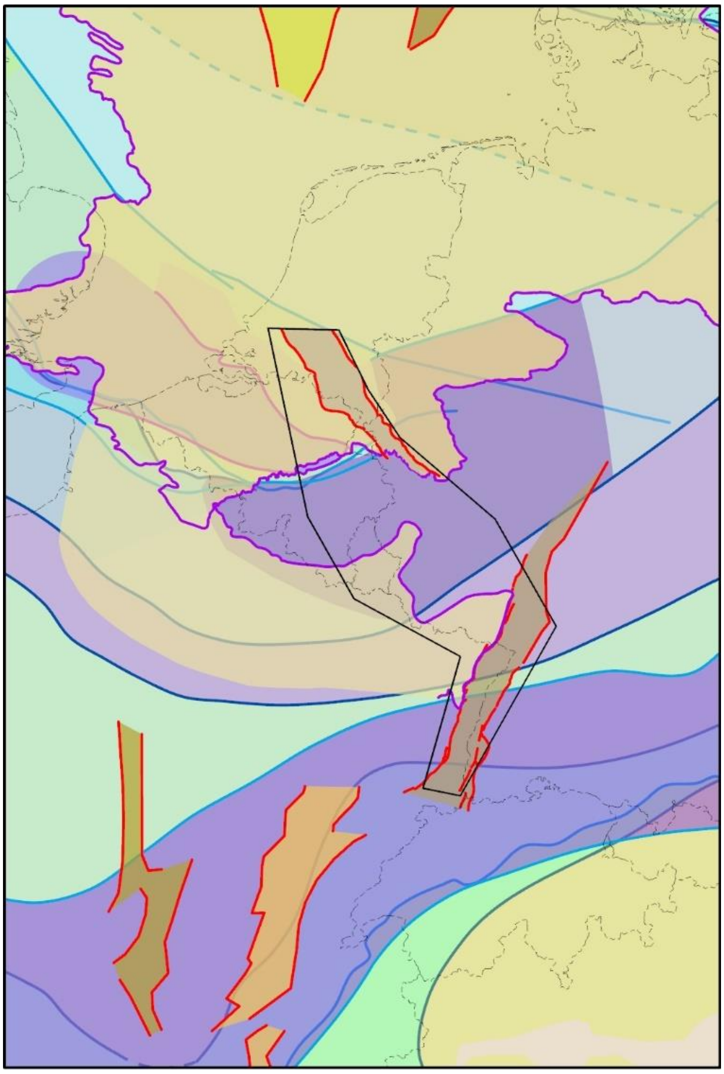


FIGURE 15: PAN-EUROPEAN SF WITH ALL THE LAYERS TOGGLED ON. ALTHOUGH CONCEPTUALLY STRUCTURED, VISUALIZING ALL ENTRIES TOGETHER CREATES AN UNCLEAR MAP. THIS IS BECAUSE (1) DIFFERENT STRUCTURES ARE RELEVANT FOR DIFFERENT DEPTHS/STRATIGRAPHIC LEVELS AND (2) BECAUSE THE PAN-EUROPEAN VOCABULARY STRUCTURE OF THE UNITS WAS ORGANIZED IN A THEMATIC WAY (PLATE TECTONIC UNITS, MASSIFS, BASINS, OROGENS,…).

Also for structures crossing borders, it is of major importance that, in addition to the conceptual harmonization discussed in the previous paragraph, the structures are spatially harmonized. For example, the spatial representation of a first version of the integrated SF resulted in a visual break in the structure on the Belgian-Netherlands border, although the geology in the area had already been harmonized in a cross border project. The deviations were the result of a different approach that was followed in the allocation of the faults to specific concepts. The SF framework principles helped in this case to single out and explain these differences, after which they could be resolved in an efficient way.

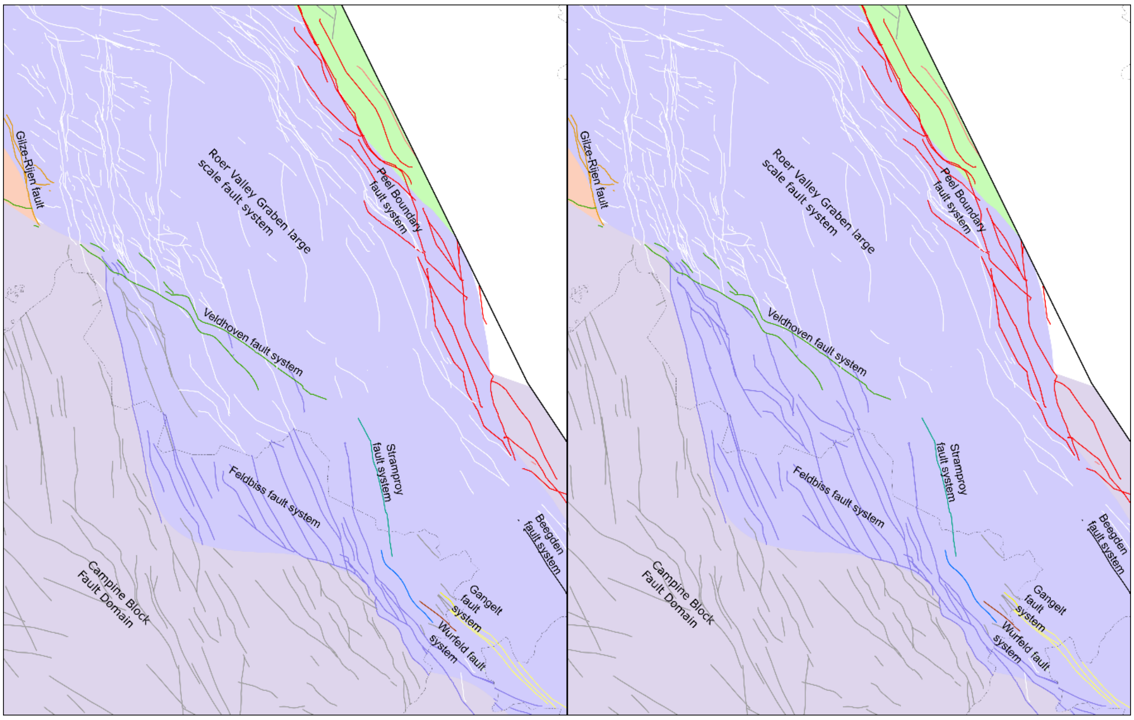


FIGURE 16: FORMER VERSION OF THE SF (LEFT) IN COMPARISON WITH THE CORRECTED ONE (RIGHT). NOTE THAT IN THE LEFT FIGURE, ON THE BORDER OF BELGIUM AND THE NETHERLANDS (GREY DASHED LINE), THE SAME FAULTS CHANGE FROM COLOR FROM WHITE (ROER VALLEY GRABEN LARGE SCALE FAULT SYSTEM) TO BLUE (FELDBISS FAULT SYSTEM), DUE THE FACT THAT IN THE NETHERLANDS, THESE FAULTS WERE ASSIGNED TO A HIGHER-LEVEL CONCEPT WHEN COMPARED TO THE FLEMISH INPUT. ALSO, IN THE LEFT FIGURE, SOME FAULTS THAT ARE SITUATED WITHIN THE AREA COVERED BY THE ROER VALLEY GRABEN UNIT (BLUE) WERE ASSOCIATED WITH THE CAMPINE BLOCK FAULT DOMAIN (GREY). IN THE RIGHT FIGURE, BOTH CASES WERE CORRECTED, CREATING A HARMONIZED MAP.

Finally, we learned that while the data structure of the SF is solid, it was not a trivial exercise for project partners to work with the SF in the course of the project The SF consists in its core of different files, which can be linked based on ID’s. During the GeoConnect³d project, this step of joining the spatial data with the vocabulary structure was to be performed by GIP-P at the end of the project. However, this integration should be readily available for project partners during the project, as the examples in this paragraph have shown that the link between concept and geometry can provide many new insights for data harmonization.

3.1.4 The importance of zoom levels to create spatial structure

The vocabulary structure is generally considered as the most important asset of the SF in structuring the data. However, we have learned that to visualize this conceptual structure, zoom levels are also of crucial importance. The left figure below illustrates that when insufficient attention is given to this aspect, the map representation of the SF will result in a blurred image of closely spaced limits

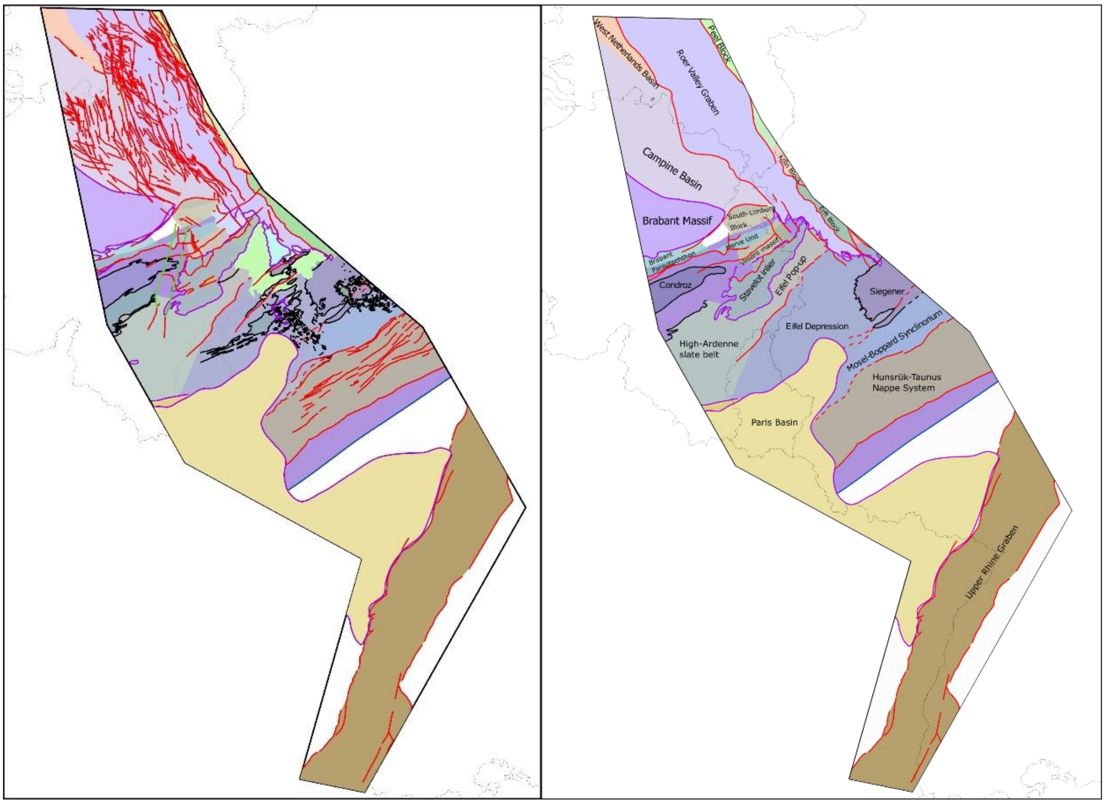


FIGURE 17: THE R2R SF WITHOUT ZOOM LEVELS, HENCE SHOWING ALL STRUCTURES THAT ARE PRESENT UP TO THE SMALLEST SCALE (LEFT), AND THE SF INCLUDING THE ZOOM-LEVEL FEATURE, HENCE SHOWING ONLY LARGER-SCALE STRUCTURES WHEN ZOOMING OUT (RIGHT).

Two approaches can be followed to differentiate in these zoom levels. The first is to start from a set of existing geometries, select the most important structures (for example based on fault throw), and assign larger-scale zoom levels to them when compared to other structures. However, experience has shown that in some cases, specifically for strongly zoomed-out visualizations, it may be better to provide simplified, boundary crossing geometries (FIGURE 17). Creating such geometries has proven not a trivial task. They represent a simplification of often highly complex areas and the discussion of how much generalization is allowed, and where to exactly place the zoomed-out traces in relation to structures mapped or modeled at smaller-scale levels in different models can spur up geological discussions. As an example, the western border of the RVG comprises a wide area of faulted structures. Before being able to define a generalized trace for this border, all the limits in this area had to be harmonized, both spatially and conceptually. The final generalized structure defining the western border of the RVG is comprised of 3 separate geometries attached to different conceptID's, but harmonized spatially to provide a single trace for this limit.

3.1.5 The aspect of timing and 3D

Including the third dimension is often a complicating factor in geology. This is often due to the simple fact that it is difficult to visualize this dimension on the 2D maps that are classically used to explain geology. In addition, 3D information is often lacking, or only available at the basis of individual points. Nonetheless, geology always represents the combined result of multiple tectonic phases of different geographic influence areas, geometries and kinematics, and only by including the third dimension true insight can be gained in the geological structure of an area. For example, studying the third dimension gives insights into the vertical and horizontal extents of the faults and allows to differentiate the amount of vertical throw at different levels. The amounts of vertical throw provide insights in the timing of fault activity, which is of crucial importance when interpreting Geomanifestations, such as thermal anomalies, CO2-seeps or seismicity data. Although the SF methodology foresees including 3D geometries, software limitations currently limit visualization to 2D. A work-around in R2R for limits is to introduce different geometries for different reference surfaces. Hence, a single fault object is composed of multiple 2D fault lines, each representing the intersection of a 3D fault plane with a specific reference layer. It has to be noted that the traces of these reference surfaces should not be visualized all together on a map, because they will create a blur of closely spaced, quasi parallel fault traces.

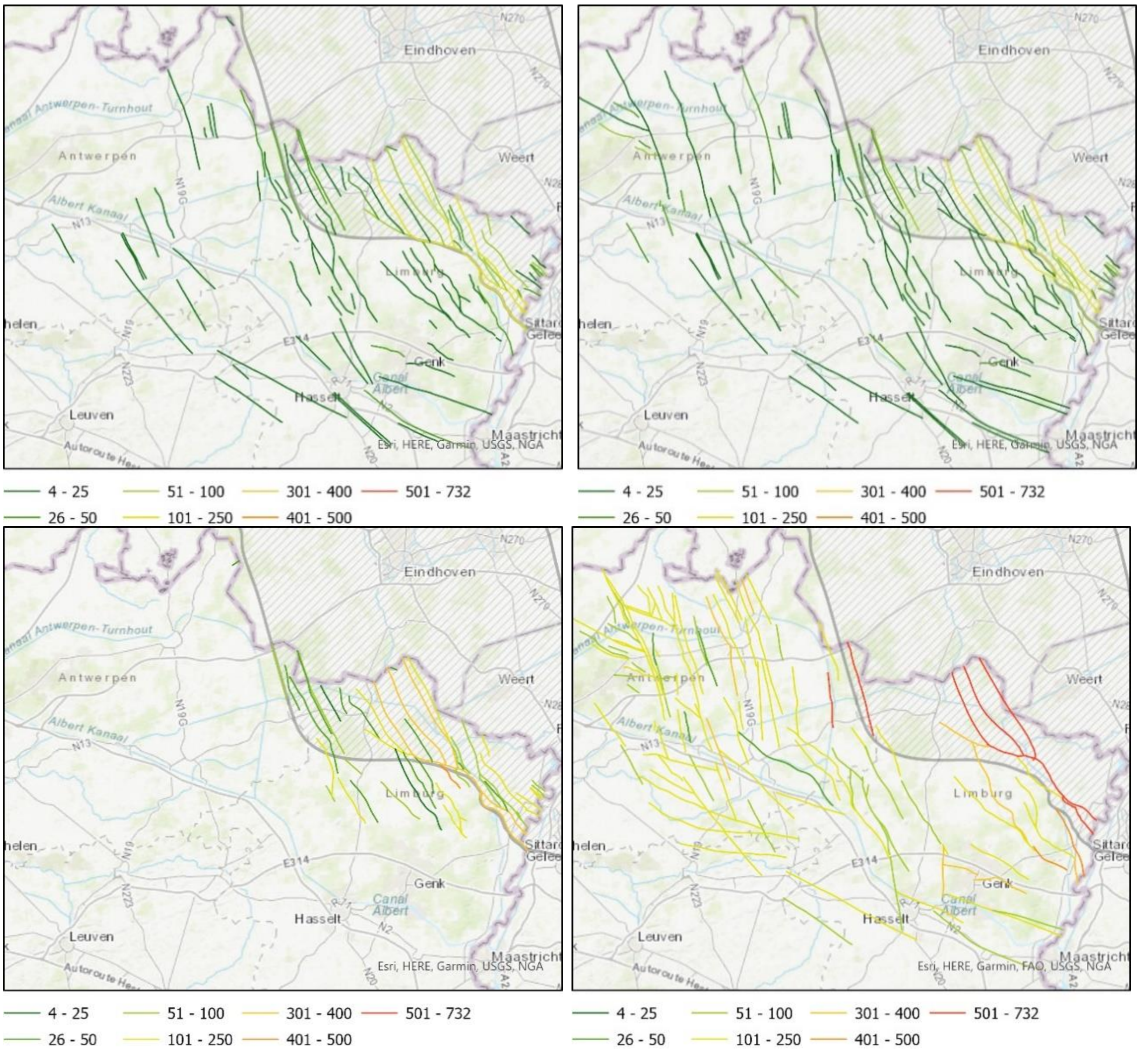


FIGURE 18: FAULT GEOMETRY AND VERTICAL THROW (M) CHANGE WITH DEPTH IN FLEMISH FAULTS. FAULT LINES REPRESENT 2D INTERSECTIONS BETWEEN 3D FAULT PLANES AND GEOLOGICAL LAYERS. HENCE, FAULT TRACES FOR SPECIFIC SURFACES ARE ONLY DISPLAYED WHEN THAT SPECIFIC REFERENCE SURFACE IS PRESENT. UPPER LEFT: BASE CENOZOIC. UPPER RIGHT: BASE CRETACEOUS. LOWER LEFT: BASE PERMIAN. LOWER RIGHT: TOP DINANTIAN. DASHED AREA: ROER VALLEY GRABEN. THIS FIGURE ILLUSTRATES, FOR EXAMPLE, THAT THE NUMBER OF FAULTS AND THEIR THROWS ARE MUCH LARGER IN THE DEEPEST LAYERS IN FLANDERS, WHEN COMPARED TO THE CENOZOIC.

For the units, only 2D polygons can practically be inserted in the current version of the SF. This complicates the visualization of the relation between certain structures, such as the relationship between the units of the RVG, the Campine Block and the Campine Basin. While the Campine Basin is defined as the northeastern flank of the Brabant Massif that is covered by Upper Paleozoic strata, the Campine block is explained as a relatively high area in the western flank of the Roer Valley Graben. Hence, the term 'Campine Basin' is mainly relevant when discussing Paleozoic structures and processes, while the concept of the Campine Block is used when discussing Mesozoic and Cenozoic tectonic phases (FIGURE 19).

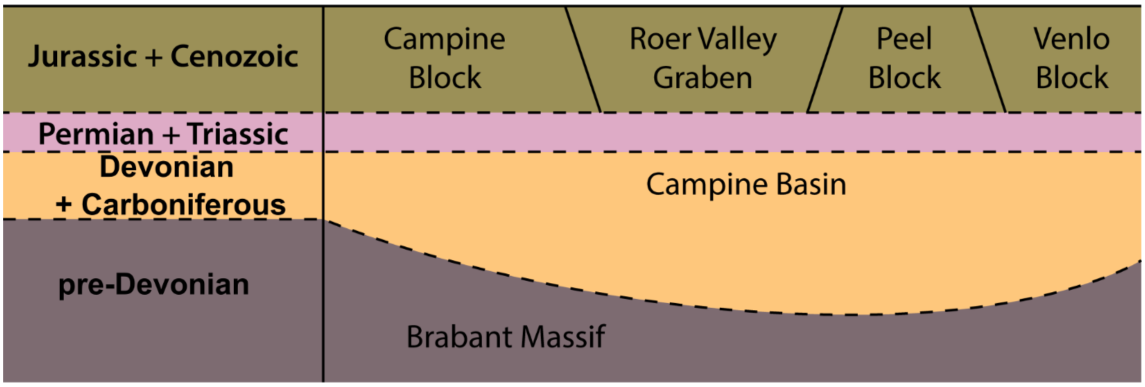


FIGURE 19: SCHEMATICAL SECTION DISPLAYING THE RELATIONSHIP BETWEEN A NUMBER OF KEY UNITS IN THE R2R AREA.

While the aspect of the third dimension focuses mainly on the visualization of the geological structure with depth, also the aspect of timing is important. This is a more conceptual attribute of the SF, and should not be confused with the reference surfaces now already present in the SF. The latter ones simply indicate that a fault is present at a certain stratigraphical level, but that does not mean the fault was active during this time, as faults generally also affect stratigraphic units older than the fault activity itself. In addition, faults that became active during one tectonic phase can be reactivated by a later one, and kinematics of the same faults can vary between the tectonic phases. For example, faults in the boundary zone of the RVG were active as normal faults during the Jurassic, were reversely reactivated during the Late Cretaceous and were active again as normal faults during the Cenozoic (FIGURE 20). Hence, a database including this aspect should foresee that a single fault can be linked with multiple tectonic phases.

Understanding fault activity during different tectonic phases is not a trivial task as data that allow to clearly deduce this information are often scarce. In addition, the timing of tectonic phases is not always easy to constrain to specific litho- or chronostratigraphic intervals. For example, in Flanders, a major episode of normal faulting (during one of the middle Mesozoic Kimmerian phases) took place sometime prior to the Late Cretaceous and after the Triassic. However, no syn-tectonic sediments are preserved in Flanders from this episode, probably as the result of strong post depositional erosion, so it remains difficult to put constraints on the exact timing of the fault activity.

While the inclusion of the aspect of timing is a complex task, taking up this attribute in the Structural Framework adds a very useful dimension to it. As the history of the units and limits is visualized, classifying the SF using their timing of activity immediately provides a level of large-scale structure in the data.

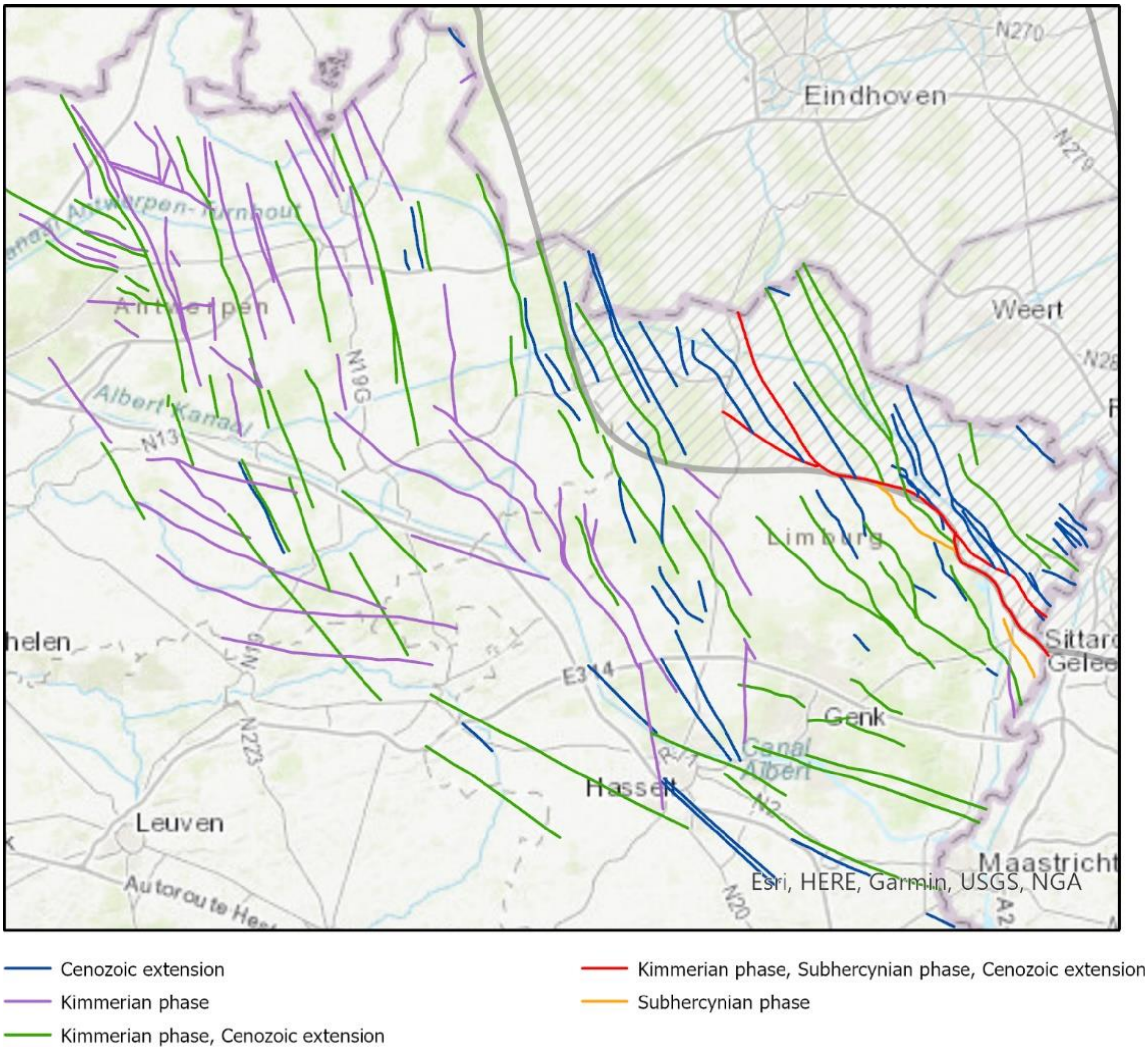


FIGURE 20: CLASSIFICATION OF FLEMISH FAULTS ACCORDING TO THEIR ASSUMED TIMING OF ACTIVITY. IN GENERAL, THE CENOZOIC AND KIMMERIAN PHASE WERE PERIODS OF TECTONIC EXTENSION, GENERATING NORMAL FAULTS, WHILE THE SUB-HERCYNIAN PHASE WAS ONE OF TECTONIC INVERSION, CREATING REVERSE FAULTS.

3.1.6 Comparison with traditional representations of geology

The SF presents clear differences when compared to traditional representations of geology, such as geological maps (e.g., FIGURE 21), 3D models etc.

As an expansion to traditional Structural Frameworks, not only structural geology elements are added, but also other important surfaces such as contacts and unconformities. The SF focuses on these surfaces (SF limits) as a starting point of the model. Because the location of limits is less prone to interpretation mistakes than that of geological units, this results in a more robust model that can provide a stable backbone for external data. By focusing on limits, the SF also results in a more explicit representation of the state-of-the-art geological knowledge, including unknowns - represented as open ends in units. These can efficiently highlight areas in which investigations in more detail are needed (refer to the example of the Ardennian “Caledonian” deformation, FIGURE 14).

The zooming and interactive capabilities of the SF help in the representation of geology in different contexts and scales. Another strong added value is the embedded semantic data through the vocabulary, which organizes by thematic, defines, contextualizes, and relates every element inside the SF. The combination of these features makes geological knowledge more accessible and easier to understand. Finally, being an online tool fed by a simplified GIS-spreadsheets system, the SF can as well more easily accommodate for future interpretation changes and findings and the evolution of geological knowledge of a region, when compared to traditional maps and models.

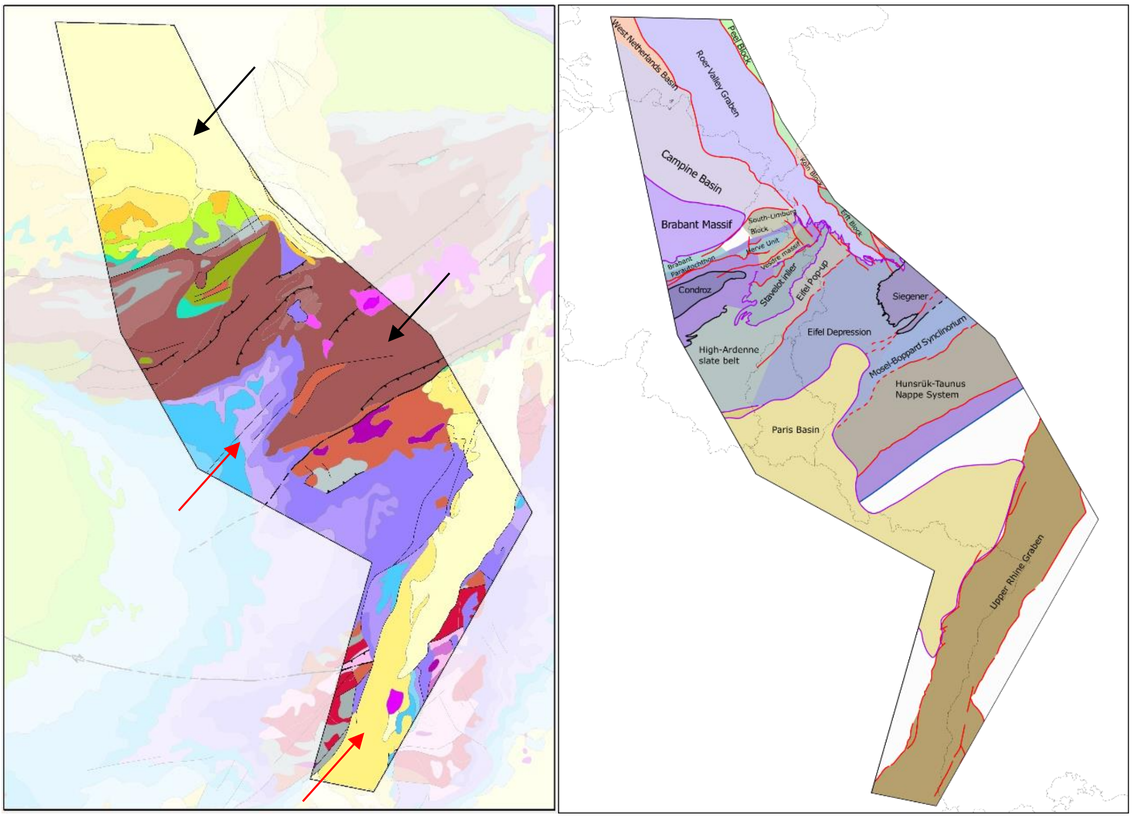


FIGURE 21: COMPARISON BETWEEN THE IGME GEOLOGICAL MAP (ASCH, 2005) ON THE LEFT AND THE R2R SF ON THE RIGHT. NOTE A FEW EXAMPLES OF HOW GEOLOGICAL UNITS OF THE SAME AGE (SAME COLOR) IN THE IGME MAP, INDICATED BY THE BLACK ARROWS, ARE SUBDIVIDED IN DIFFERENT SF UNITS, AND HOW UNITS OF DIFFERENT AGES (DIFFERENT COLORS) IN THE IGME MAP, INDICATED BY THE RED ARROWS, ARE A SINGLE UNIT IN THE SF.

3.1.7 Conclusions and recommendations

- The SF methodology is a very powerful tool to structure data: modeled data can be linked with literature concepts, cross boundary structures can be integrated and larger-scale structures can be distinguished from smaller-scale structures.
- When making a SF with different parties covering areas with strongly different geological structure and/or strongly different sources of data, first a general vocabulary structure should be created, to which the project partners then can add more detailed information. It is important to take into account that the most zoomed-out levels of the SF should also provide visual structure, as the visual representation of the SF forms the entry point for the end users.

- Future versions of a SF should include the link with timing on a conceptual level, for example by distinguishing different tectonic phases. The geological structure of an area is always and inherently the result of multiple phases of differing geological activity, and gaining true insights can only be done when this aspect is fully included. The visual representation of the SF should also allow displaying the structures related to specific tectonic phases.
- It would be useful to better integrate the third dimension into the visualization of the Structural Framework. This may provide significant added value when using the SF to communicate about geological structure to end users.

3.2 Geomanifestations

3.2.1 Added value of the different Geomanifestation types

On the **scale of the R2R area**, broad spatial correlation between different types of Geomanifestations (or the lack thereof) and their relation to large-scale structures can be identified.

For the inter-comparison between Geomanifestation-types, FIGURE 22 illustrates the co-occurrence of Quaternary volcanic phenomena in the Eifel area with the highest $^3He/^4He$-values. While CO_2-seeps are observed in the whole R2R area, the most significant CO_2-anomalies occur in spatial association to the Quaternary volcanism as well. This is especially the case for the Western Eifel. In contrast, it is remarkable that the locations with the highest $^3He/^4He$ do not correspond to those with the highest He-concentrations, which mostly occur outside the volcanic Eifel region, or in its eastern part. Limited data are available for the latter parameter, but the relative amount of He in gas seeps in the R2R area apparently is not (exclusively) spatially related to the Eifel volcanism. Furthermore, the distribution of thermal anomalies neither seems to relate spatially to the other Geomanifestations. That is especially surprising for the Eifel area with its young volcanism. Only few (and relatively small) thermal anomalies are observed in this region. However, thermal anomalies typically seem to occur in areas with high topographic differences, such as the Rhine and Mosel River valleys (FIGURE 23).

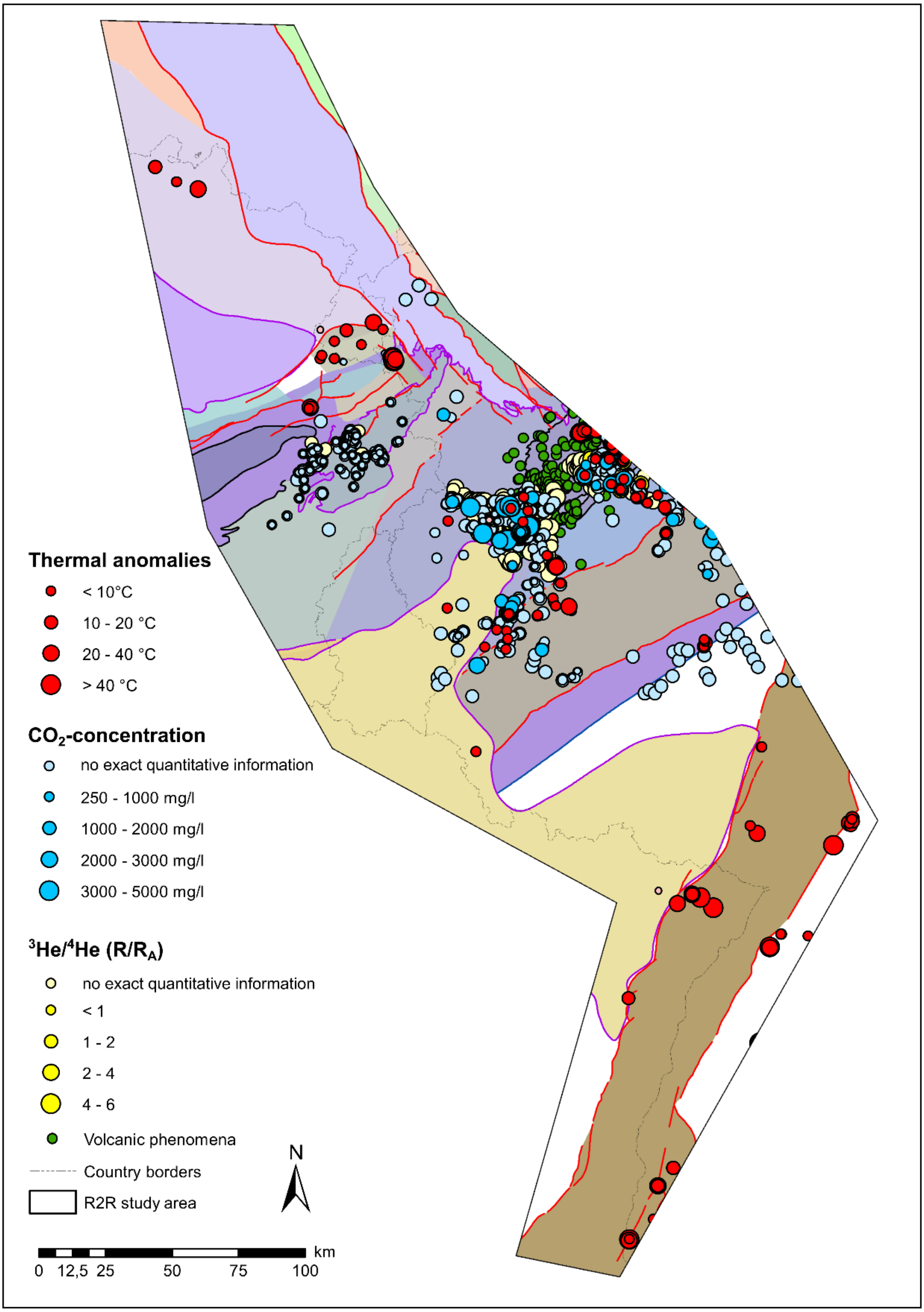


FIGURE 22: GRADUATED OVERVIEW OF THE THERMAL ANOMALIES (RED), CO_2-SEEPS (BLUE), ANOMALOUS $^3He/^4He$-VALUES (YELLOW) AND VOLCANIC PHENOMENA (GREEN) IN THE R2R AREA.

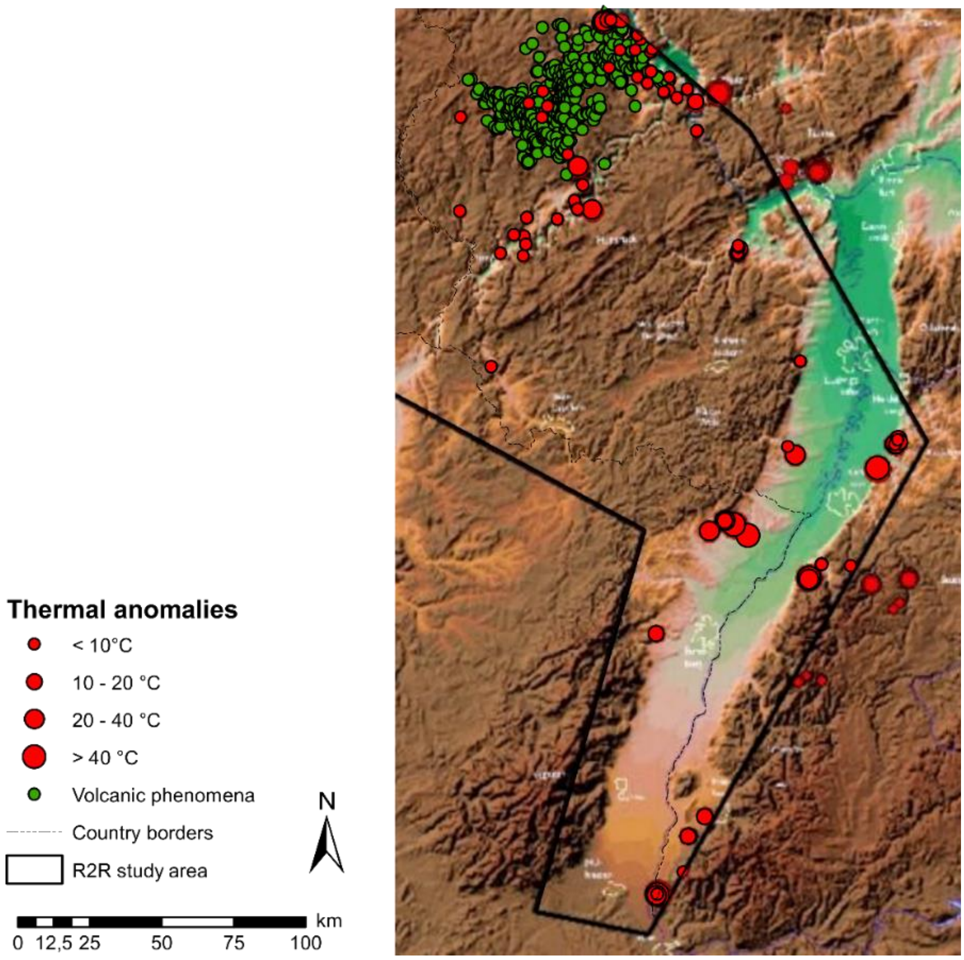


FIGURE 23: THERMAL ANOMALIES AND VOLCANIC PHENOMENA IN THE SOUTHERN PART OF THE R2R AREA, OVERLYING THE TOPOGRAPHIC MAP.

The large-scale spatial correlation between Geomanifestation types allows to derive some broad conclusions. High $^3He/^4He$ generally indicates a significant mantle contribution to the gas budget (Davidson and Emerson, 1990). The He-isotopic composition distribution indicates an important influence of mantle magma in the Quaternary Eifel volcanism. This is also confirmed by the increased extent of anomaly for the CO_2-seeps, as well as the elevated mantel-C flux (May, 2002).

Young volcanism apparently is no guarantee for an elevated heat flux and temperature in the upper crustal layers, and thus geothermal potential. Rather, the correlation between thermal anomaly distribution with strong, large-scale topographic differences (FIGURE 23) suggests that the hydraulic gradient (which is generally low in the Eifel region) and the development of deep groundwater circulation cells are key conditions for efficient heat transport. This phenomenon is especially well-documented for the Upper Rhine Graben. Numerical modelling based on topography-driven hydraulic flow and good transmissivity along aquifers, faults and fractures was able to explain the high thermal anomalies at the west side of the Upper Rhine Graben (Koltzer et al., 2019; Les Landes et al., 2019; Stober and Bucher, 2015), where a series of successful deep geothermal exploitation projects have been or currently are developed (e.g., Soultz-sous-Forêts, Rittershofen, Landau, Wissembourg, …).

Upon zooming in on a **more local scale**, additional patterns emerge for all Geomanifestation types.

Thermal anomalies often appear to occur aligned, mostly along a NE-SW strike. Again, this indicates that faults play an important role in heat transfer through (topography-driven) fluid flow. More specifically, the orientation of these alignments suggests Variscan thrust sheets dominate this process. In addition, in some cases, an interplay between NE-SW and NW-SE faults can be observed, for example in Wiesbaden or Aachen, Germany. In Wiesbaden the thermal anomaly along the NE-SW “Quellenlinie”, parallel to the southern edge of the Taunus-plateau, decreases towards the SW, towards its intersection with the NW-SE (graben) fault (FIGURE 24). Remarkably, the reverse is observed in Aachen, where the thermal (and also chemical) anomaly of the springs along the two NE-SW Variscan thrust faults increases towards the NW-SE deep-seated graben fault (FIGURE 25). Faults can thus either facilitate upward flow of hot water (as in Aachen) or form a conduit for downward flow of cooler water (as in Wiesbaden). In either case, fluid mixing occurs, expressed by the dilution of the anomalous cold or hot signature with increasing distance from the graben faults. These two examples illustrate the complex influence (permeable) faults can have on the water household, and thus also on the geothermal potential, and stresses the importance of local data.

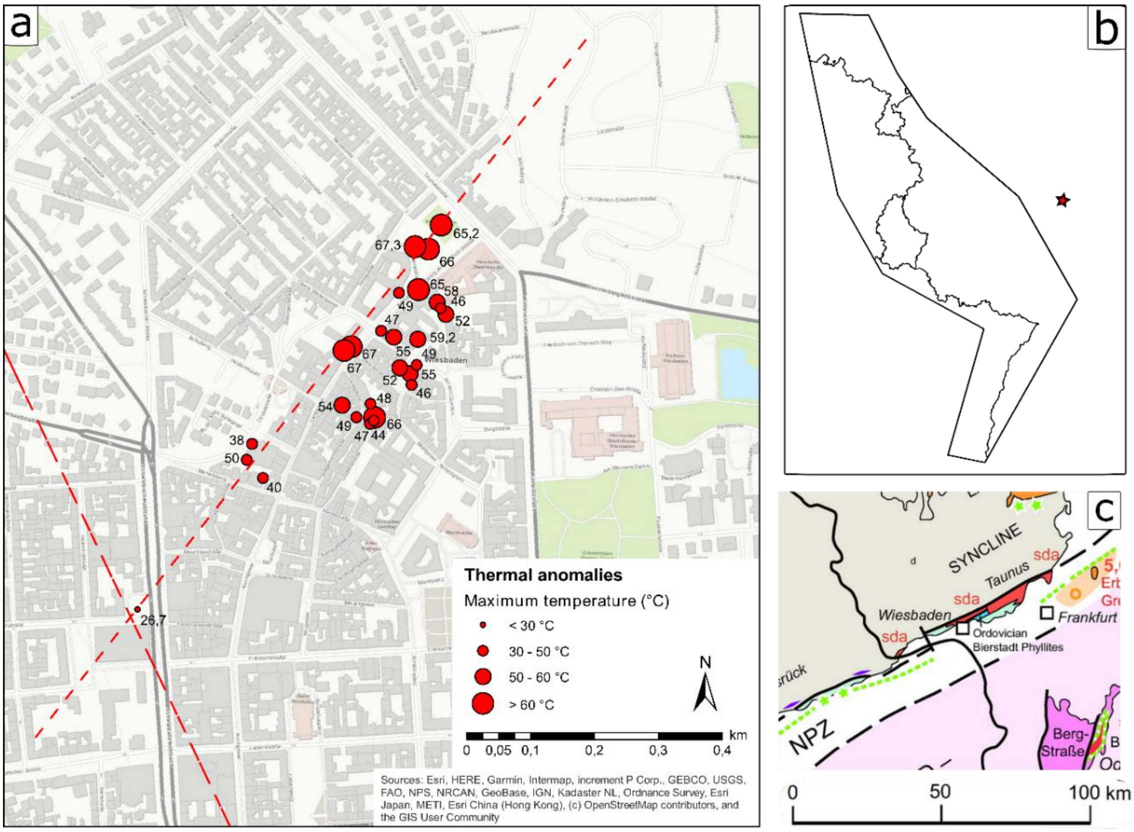


FIGURE 24: ALIGNED THERMAL ANOMALIES IN WIESBADEN, ILLUSTRATING THE INTERPLAY BETWEEN TWO FAULT SETS: (A) ZOOM ON THE THERMAL ANOMALIES IN THE CITY CENTER (BASED ON MITTELBACH AND SIEBERT, 2014), (B) LOCATION OF WIESBADEN JUST OUTSIDE OF THE R2R STUDY AREA, (C) GEOLOGICAL MAP SHOWING THE NE-SW AND NW-SE FAULT TRACES AROUND WIESBADEN (FRANKE ET AL., 2019).

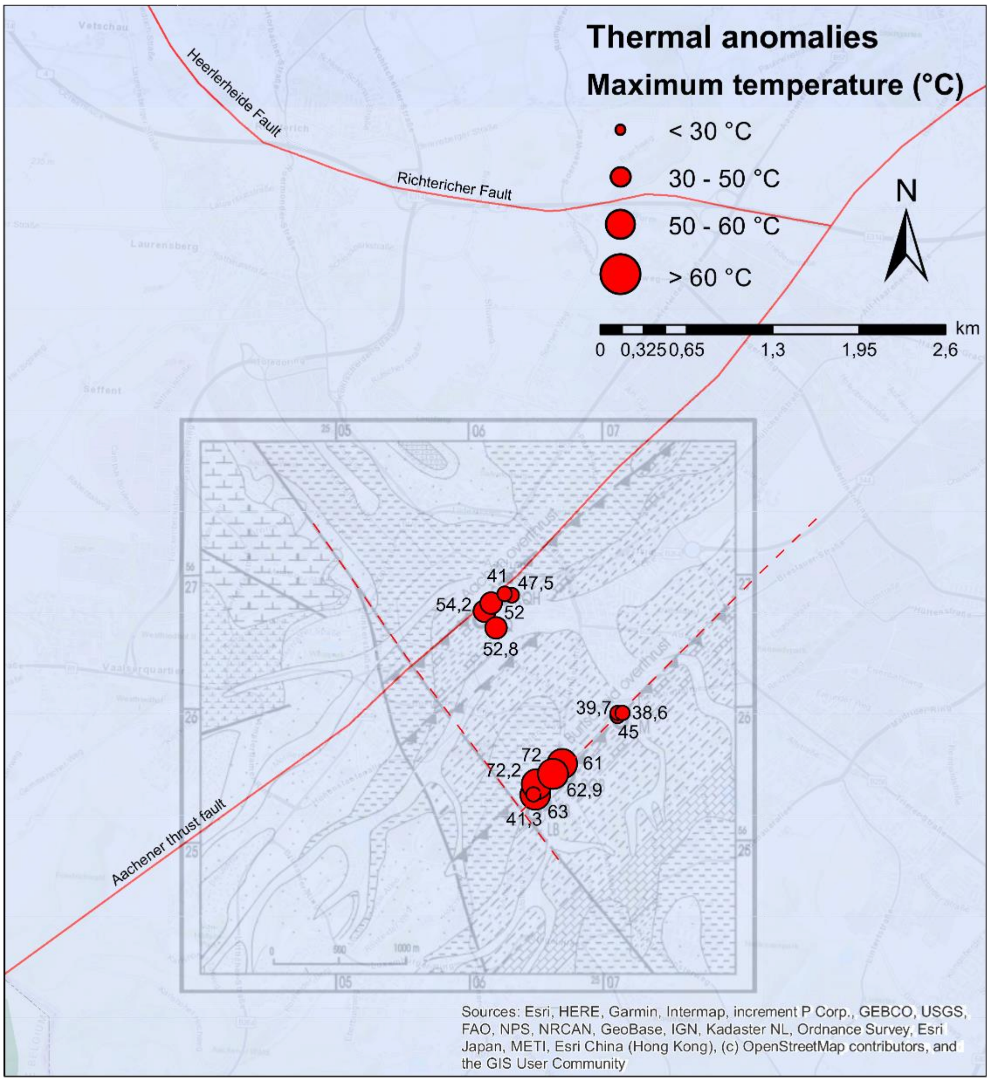


FIGURE 25: ALIGNED THERMAL ANOMALIES IN AACHEN, ILLUSTRATING THE INTERPLAY BETWEEN TWO FAULT SETS. FAULTS IN SOLID RED LINES ARE PRESENT IN THE STRUCTURAL FRAMEWORK. UNDERLYING MAP OF HERCH (2000).

Furthermore, observations like this can be used for guiding further prospection. To continue on the example of Aachen, a similar high thermal anomaly was observed further northwestwards, in Heerlen (the Netherlands). Hot (50 °C) saline water was encountered at a depth of just 250 m, again at the intersection of a NW-SE graben fault with a NE-SW Variscan thrust fault (Kimpe, 1963). In fact, this concerns the same deep-seated graben fault as in Aachen, the Benzenrade fault (FIGURE 26). Further away from this graben-fault, along Variscan structures to the west, smaller thermal anomalies were reported as well (e.g., Thermae 2000 drilling, Wittem spring, …). Although this area generally is not regarded as potentially interesting, targeted research at locations where graben-related and Variscan permeable structures intersect, can point toward “sweet spots” which are worth investigating in more detail for their geothermal potential. Unfortunately, up to date, not all these faults are included yet in the Structural Framework.

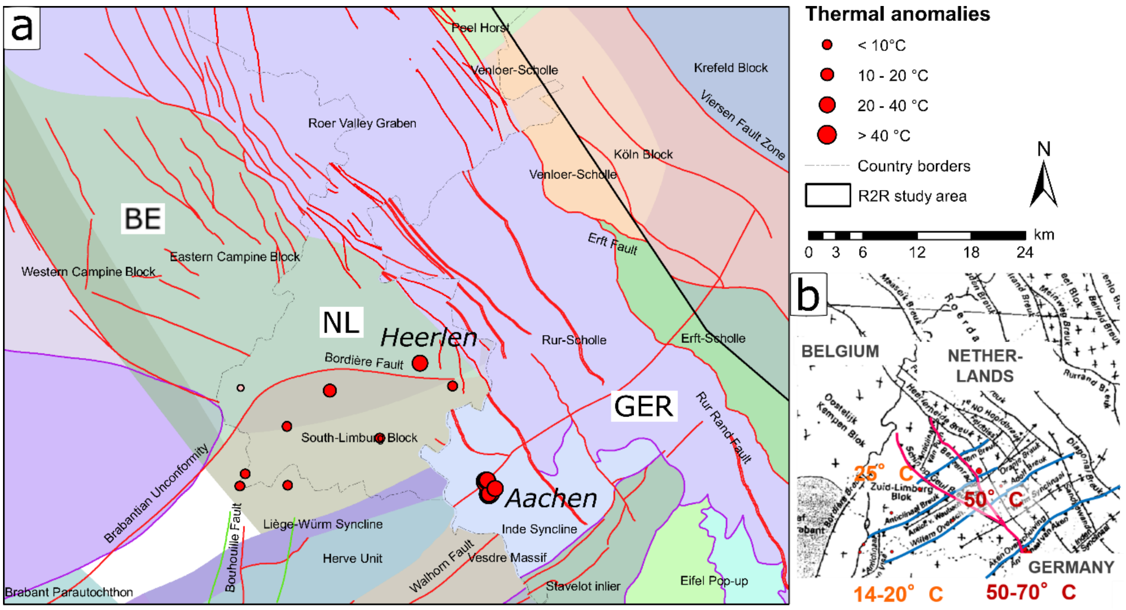


FIGURE 26: CONNECTION BETWEEN THE AACHEN THERMAL SPRINGS AND THE WARM WATER OUTBREAK IN HEERLEN. (A) STRUCTURAL FRAMEWORK AND GEOMANIFESTATIONS DATABASE DISPLAY (B) GEOLOGICAL MAP OF THIS REGION.

Likewise, for the **CO_2-seeps**, rough alignments along the Variscan (NE-SW) structural trend can be observed on the regional scale (FIGURE 27). This focused CO_2-seepage indicates that deep-seated faults likely are involved in 'capturing' mantle-derived or magmatic-related CO_2 and assisting in its migration to the surface (see also May, 2005). On a more local level, the distribution of CO_2-seeps appears —at first sight— to be more random. However, a clear link between CO_2- and groundwater discharge (i.e., rivers, streams, …) has been pointed out by Weyer et al. (2012) in the area of Daun. This observation can be extrapolated to other parts of the R2R area (FIGURE 28). The most well-known examples are the spectacular Andernach geyser at the Rhine bank, and the CO_2-mofettes in the Laacher See. Although the dataset is expected to be slightly biased with regard to the conventional way of surveying for and measuring CO_2-occurrence, focusing on wet rather than dry seeps (as mentioned in §2.2), groundwater migration undoubtedly influences the migration of CO_2, as the latter easily dissolves in groundwater it encounters while migrating upwards, and consequently shares its migration pathway till surface dischargement. In Luxembourg, the combination of the Structural Framework and these insights has allowed the discovery of multiple, previously unknown (dry) outgassing sites in the area around Rosport and Ralingen (NE Luxembourg), and, indirectly, to link these to the large-scale geodynamic story behind it.

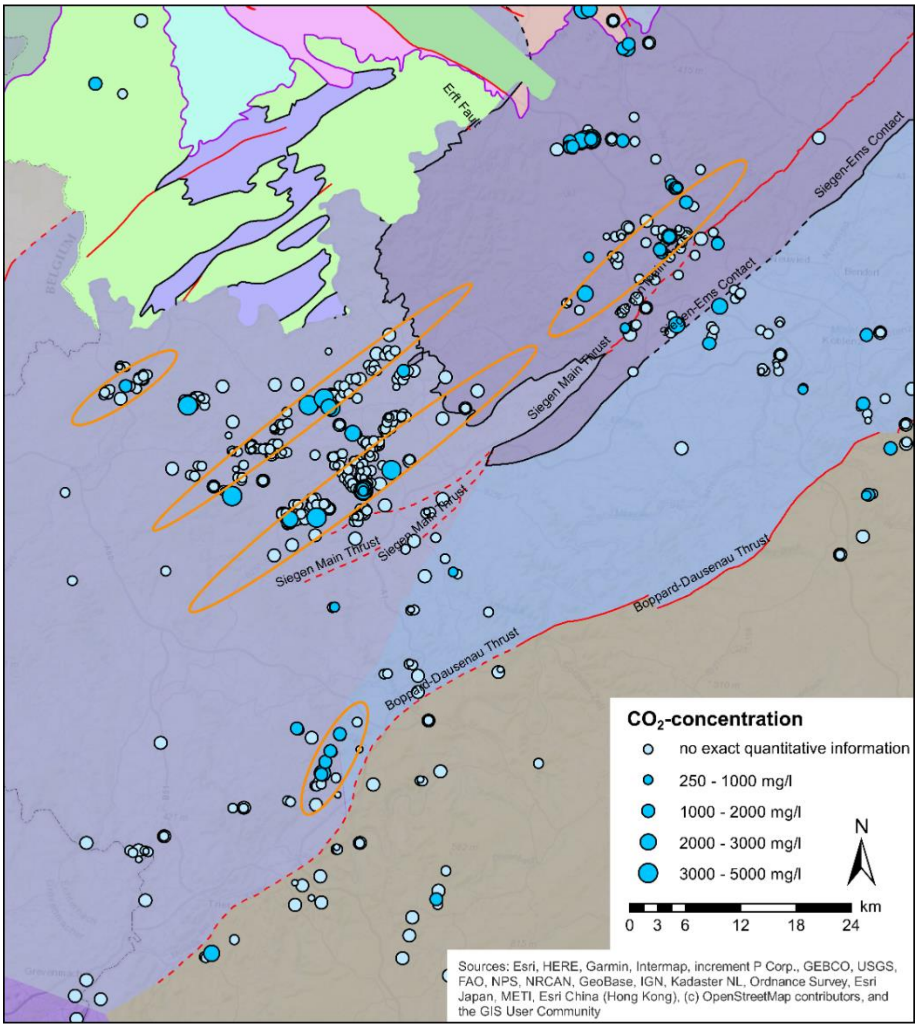


FIGURE 27: NE-SW ALIGNMENT OF CO_2-SEEPS IN THE EIFEL AREA.

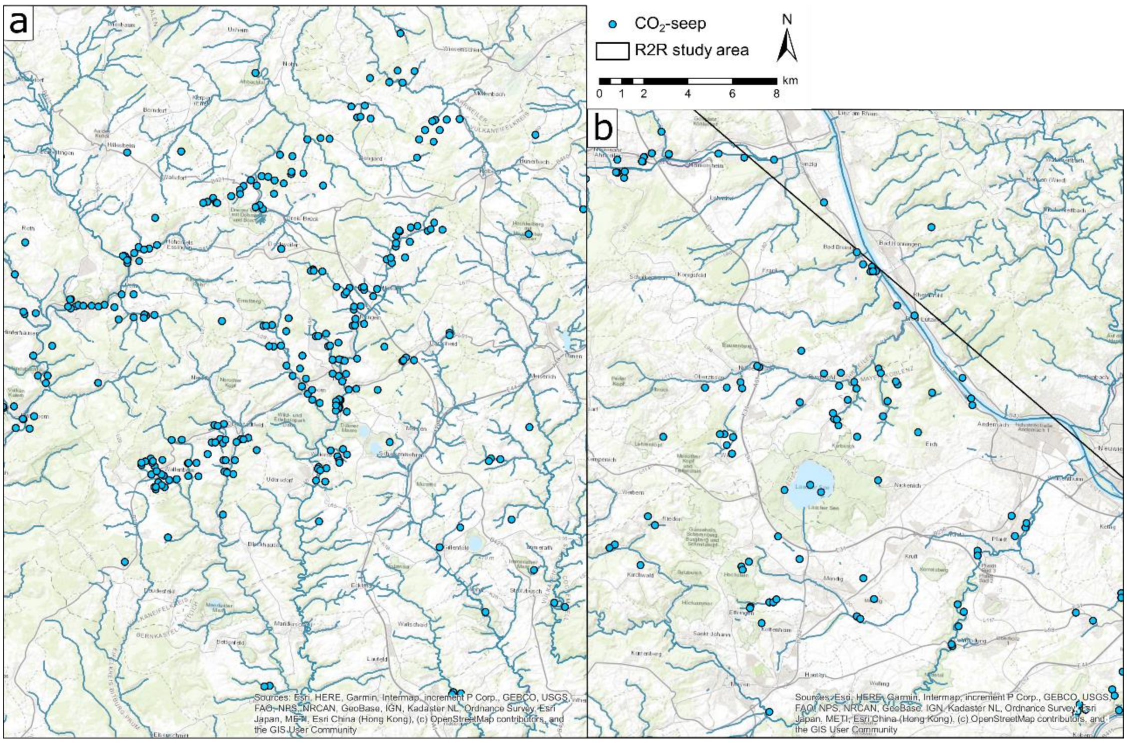


FIGURE 28: SPATIAL CORRESPONDENCE BETWEEN CO_2-SEEPAGE AND GROUNDWATER DISCHARGE (A) IN THE REGION OF DAUN AND (B) IN THE REGION AROUND THE LAACHER SEE (GERMANY).

In addition to this fundamental knowledge on fluid and gas migration processes in the subsurface, also the burial history represents an important geological aspect of an area which can give (indirect) indications on the structure of the subsurface. For the Brabant Massif, a subcrop unit, this information also aids in constraining the thickness of its lithostratigraphic units. The **illite crystallinity** values inventoried for the Geomanifestation database show a first order pattern, seemingly dominated by burial metamorphism, as expected. However, the relatively high number of anomalies requires an additional explanation. At this point, the different published interpretations do not satisfactorily explain these phenomena. Documenting and making this information available, within a geological context (i.e., the Structural Framework), is a first important step in the follow-up research, which is currently still work in progress.

Two episodes of **volcanism** took place in the Eifel, one during the Paleogene (often referred to as Tertiary volcanism) and one during the Quaternary (FIGURE 29). For each period, two geographical clusters of volcanism remnants (volcanoes, maars and calderas) can be distinguished: the Hocheifel (age 42 – 34 Ma) and Siebengebirge (26 – 18 Ma) for the Paleogene, and the West- and Easteifel for the Quaternary (700.000 – 11.000 years ago) (van Overmeeren, 2014). According to the relationship between the time since volcanism, the temperature difference induced and the expected specific heat flow by Dijkshoorn and Clauser (2013), the Quaternary volcanism is too young to have a thermal influence, and the Paleogene volcanism already over peak load (FIGURE 29). This explains the lack of correlation between thermal anomalies and volcanism (FIGURE 23). While the two Paleogene volcanic fields appear as a broad, unconstrained clusters, the Quaternary clusters show a large-scale NW-SE distributional trend. This same trend is observed for the **$^3He/^4He$** and CO_2-anomalies (see above). The NW-SE direction is interpreted to represent two transcrustal fault systems through which magma, as well as mantle-derived He and CO_2, could rise to the surface. This direction also corresponds to the general fault orientation of the Roer Valley Graben which occurs NW of it (e.g., the Feldbiss-fault). The Eifel fault systems were newly formed or reactivated during crustal extension and uplift of the Rhenish Massif, as a side effect of the Alpine Orogeny (van Overmeeren, 2014).

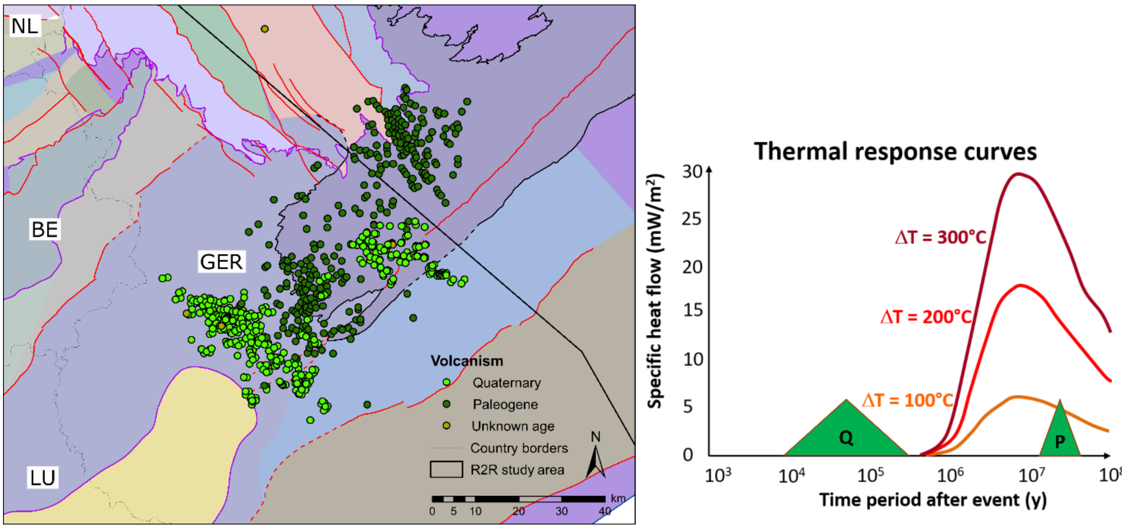


FIGURE 29: TWO EPISODES OF VOLCANISM IN THE EIFEL. (LEFT) SPATIAL DISTRIBUTION OF THE VOLCANIC PHENOMENA. (RIGHT) EXPECTED THERMAL RESPONSE OVER TIME (AFTER DIJKSHOORN & CLAUSER, 2013).

Furthermore, a clear spatial link between the Pb-Zn deposits (**polymetallic veins**) and Structural Framework elements is identifiable in the Herve-Vesdre and Landenne areas, Belgium. Although the deposits are located within the Variscan orogenic front, deposition is post-Variscan and spatially associated with transverse NNW-SSE faults part of the Rhine graben network (FIGURE 30, Dejonghe, 1998). By combining the Geomanifestation Attributes and SKOS Vocabulary, the information of vein age and time of fault activity displayed in the Structural Framework helps to quickly place these deposits in the context of the Lower Rhine embayment. This kind of knowledge enables taking more targeted and data-supported decisions in future research projects or when defining prospection strategies to find additional mineralization sites. In the Oesling area, the Structural Framework and other polymetallic vein observations were of great help to better understand the systematics of the mineralization system, which lead to a new discovery of Mn-mineralization in NE Luxembourg. Also, for this particular case of the polymetallic veins, the Structural Framework and Geomanifestations databases nicely illustrate how they, as interactive tools, allow to translate highly technical scientific knowledge to information in a more understandable way.

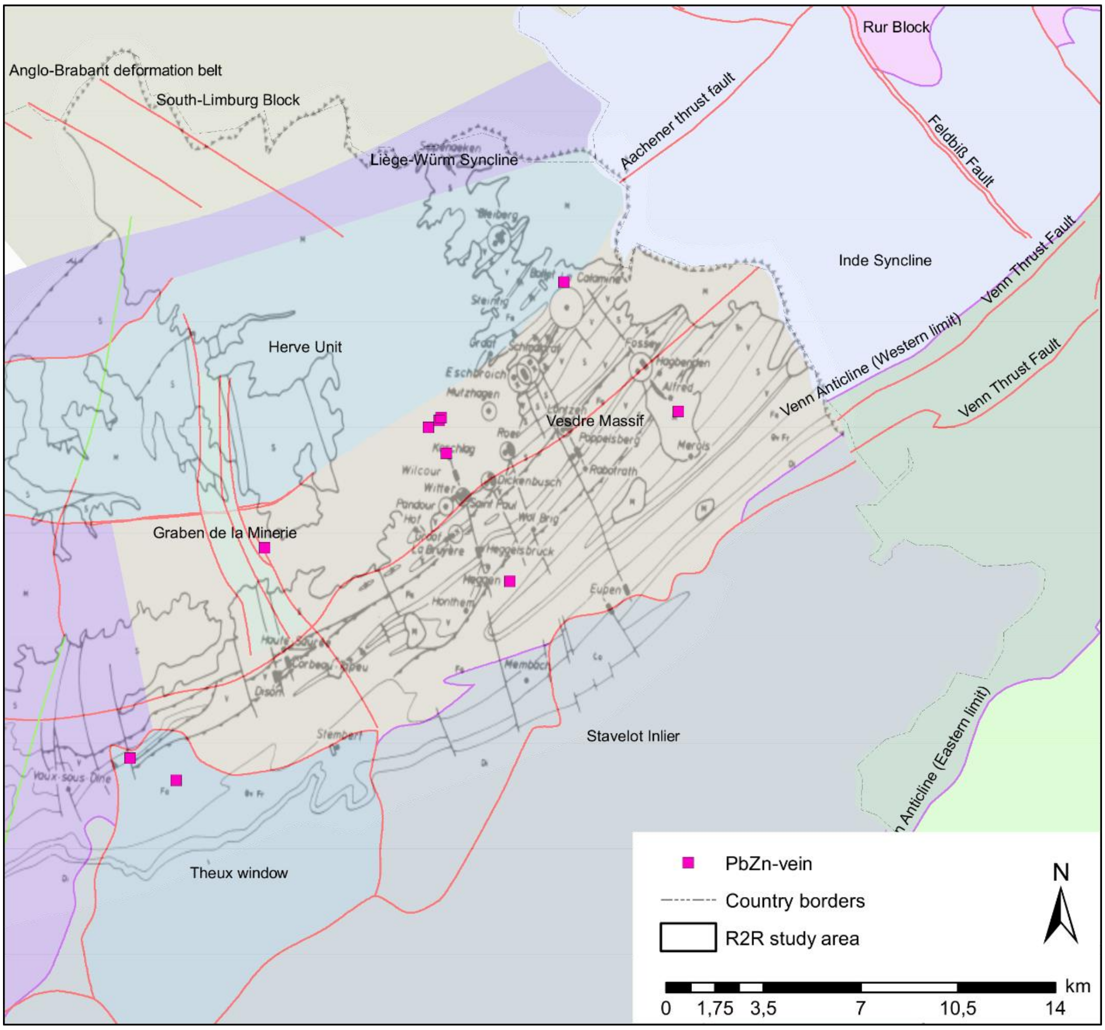


FIGURE 30: STRUCTURAL FRAMEWORK PROVIDING CONTEXT TO THE UNDERLYING MAP OF DEJONGHE (1998). POLYMETALLIC PB-ZN VEINS REPRESENTED BY SQUARES. NOTE THE SPATIAL ASSOCIATION WITH EXTENSIONAL NW-SE FAULTS REPRESENTED IN THE MAP.

Information on **surface movements**, in general, can be an indication for several geological (natural) and induced processes acting in the subsurface. Aseismic slip of faults (e.g., not clearly associated with earthquakes) can be demonstrated on the basis of footwall uplift/hanging wall subsidence. Other relevant causes for surface movement include: peat oxidation, gas extraction, subsurface injection (for geothermal energy production or CCS), heat storage and sinkholes, either due to collapse of abandoned mines or dissolution (karst). In combination with the Structural Framework, outlines of surface movement give a good overview of where surface elevations processes are related to faults and where surface deformation has another origin. The surface movement observed in the coal mine area (Limburg, the Netherlands; FIGURE 31) likely is related to the abandonment of the mines in the mid-1970's. Since then, the ground water pumps, required during exploitation, stopped working, leading to a slowly rising groundwater level (Caro Cuenca et al., 2013), which in some mines is actually reaching total flooding. The mining inspection authorities have introduced a signaling system for ground movement in order to predict and follow up differential rebound of the surface along faults that might result in damages (Jaarplan Staatstoezicht op de Mijnen, 2021).

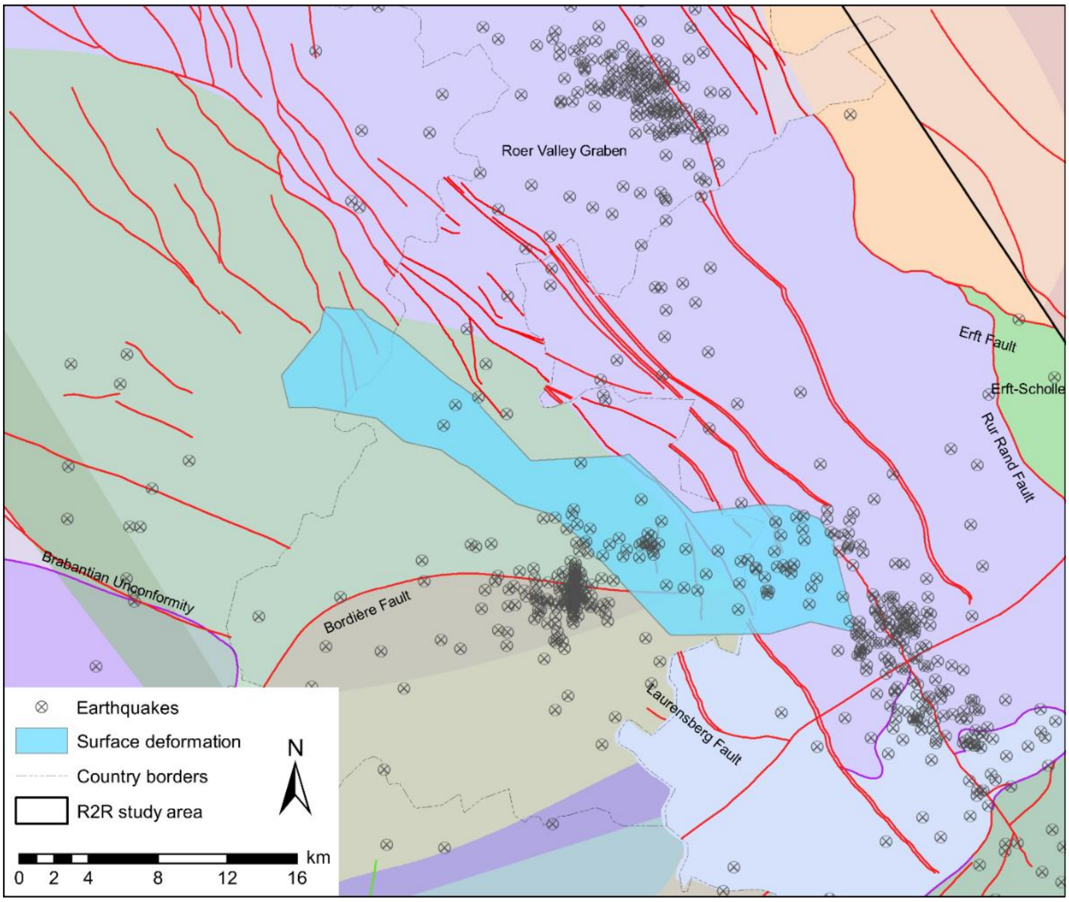


FIGURE 31: STRUCTURAL FRAMEWORK TIED TO THE SURFACE MOVEMENT POLYGON AND EARTHQUAKES IN THE COAL MINE AREA IN SOUTH LIMBURG (THE NETHERLANDS).

The occurrences of **earthquakes** allow the identification of active faults to rule out areas for subsurface exploitation (geothermal energy production, CCS, energy storage, etc.). Although there is a good documentation of both instrumental and historic earthquakes, it is still hard to link earthquake's locations and magnitude to faults. To date, the potential of faults to become active is the subject of many seismic hazard assessments. For this, overlying the earthquake Geomanifestation dataset on the Structural Framework is an adequate first step, i.e., documenting the available earthquake information in a geological context and facilitating communication on this topic.

The interpretation of **collapse structures** in terms of timing and geometry, and linking them with the Structural Framework could generate a better understanding of the tectonic history of an area and help interpreting pathways of deep fluid flow. FIGURE 32 shows that the collapse structures are generally located near or on top of faults. These are all normal faults that were formed during the Jurassic or Cenozoic extensional phases. The general alignment of the collapse structures is NNW-SSE and WNW-ESE, corresponding to the dominant Meso- and Cenozoic fault strike in the area (Deckers et al., 2019). Interesting is a potential (W)SW-(E)NE alignment of a number of collapse structures, as it is almost perpendicular to the Meso- and Cenozoic fault directions.

Most probably, the observed collapse structures can be related to evaporite dissolution, as was suggested by Dreesen et al. (1987). As for their timing, the collapse structures have different upper limits: some die out just above the top of the Dinantian, whereas others continue into the Paleogene. The upper limits of the collapse structures are not random, but bounded by some of the major unconformities which coincide with the main tectonic phases. Three main surfaces by which the collapse structures are topped were identified:

- Several small collapse structures are limited to the lowermost part of the Namurian, just above the top of the Dinantian. These structures can be related to dissolution in the top of the Dinantian when it was aerially exposed just after deposition (Vandenberghe and Bouckaert, 1980). During the subsequent Namurian transgression, these collapse structures were filled. Such small collapse structures, that only developed during an upper Dinantian to lower Namurian hiatus, have not been mapped, as they are limited in vertical and lateral extent. Most of them are probably below the resolution of the seismic data.
- Most collapse structures are topped by the base of the Upper Cretaceous which unconformably overlies the Upper Carboniferous strata. This means that collapse occurred sometime during the large hiatus between the Upper Carboniferous and Upper Cretaceous. As this is such a large hiatus, it is difficult to establish an exact timing for the dissolution phase(s). However, in the Mons area, a major dissolution phase also occurred during this hiatus, which was dated late Early Cretaceous by Quinif et al. (2006). Swennen et al. (2021) also showed that a vein in the Heibaart borehole in the western Campine Basin yielded an age of 113.0 ± 2.6 Ma. This makes a late Early Cretaceous age for a major dissolution phase in the Campine Basin very likely.
- A number of collapse structures continues into the Upper Cretaceous and Paleogene. The majority of the collapse structures that continue through the Upper Cretaceous, also continue through the Paleocene-Eocene boundary and are topped by the base Oligocene reflector. A similar observation was made by Debatist & Versteeg (1999). Since the region experienced large wavelength deformation by the Pyrenean tectonic phase just before the onset of the Oligocene (Deckers et al., 2016), it is likely that dissolution and renewed collapse was related to this phase. The earlier, middle Paleocene Laramide tectonic phase shares similar dynamics as the Pyrenean tectonic phase (Deckers & van der Voet, 2018) and could therefore also have contributed to this Paleogene collapse episode, especially since fracture-filled veins of this age were detected in a drilled section of the Dinantian in the region by Swennen et al. (2021).

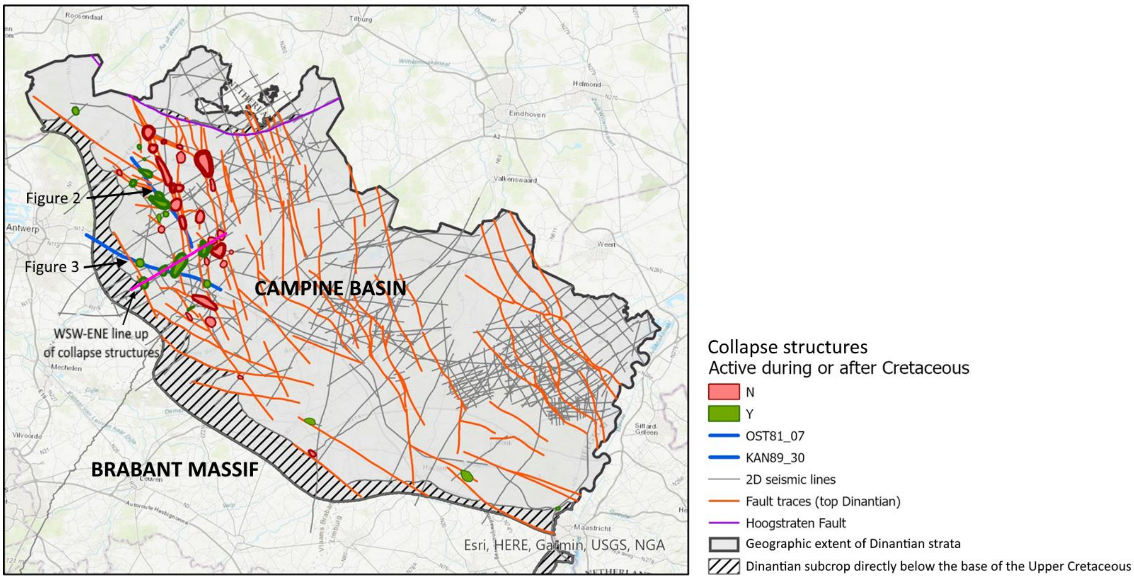


FIGURE 32: OVERVIEW OF THE MAPPED COLLAPSE STRUCTURES IN RED AND GREEN BASED ON 2D SEISMIC DATA (SHOWN AS GREY LINES). GREEN POLYGONS MARK COLLAPSE STRUCTURES THAT REACH INTO THE PALEOGENE (Y). RED POLYGONS REFLECT COLLAPSE STRUCTURES IN THE CARBONIFEROUS THAT ARE VERTICALLY DELIMITED BY THE BASE CRETACEOUS UNCONFORMITY (N). THE VERTICAL THROW OF THE COLLAPSE STRUCTURES IS INDICATED BY THE THICKNESS OF THE CONTOUR LINES: THE THICKER THE LINE, THE LARGER THE THROW. ORANGE LINES ARE MAJOR FAULTS THAT WERE MAPPED FOR THE G3DV3-MODEL AT THE TOP DINANTIAN LEVEL AND ARE INCLUDED IN THE STRUCTURAL FRAMEWORK OF GEOCONNCECT³D.

The analysis of **seismic amplitude anomalies** in relation with the Structural Framework in the context of geothermal projects can (1) provide clues for areas with high geothermal potential hence aiding prospection and (2) give insights in the presence of local gas occurrences, aiding risk-analyses when drilling and preventing blowouts.

3.2.2 Problems

Ideally, the Structural Framework is used as a main source for interpreting the spatial distribution of all Geomanifestation types. Further refinement of both databases then can occur iteratively based on newly obtained insights. Unfortunately, this approach was not possible for the R2R area in the framework of the GeoConnect³d project. The limited timeframe made it obligatory to develop the Structural Framework and Geomanifestations databases largely at the same time and quite independently from each other. Therefore, additional sources often had to be used for the interpretation of the Geomanifestations because the Structural Framework was still work in progress. Additionally, the combination of the Structural Framework and Geomanifestations could only be tested for a subpart of the R2R study area. No detailed Structural Framework was constructed for the southern part of the R2R area, where a lot of Geomanifestations are located (e.g., the Upper Rhine Graben). For these cases, previously published (fault) maps were used as well. However, the Geomanifestations alone can already provide useful insights too (e.g., co-occurrences, link with topography, alignment and trends; see above).

Another important remark is the data availability or data collection strategy. No systematic or uniform field surveying was done to build the Geomanifestations database. Additionally, every partner inventoried its Geomanifestations individually, with or without the limitation to its own territory. Even though a database like this is never complete, the lack of ambition to make the database —for the selected Geomanifestation types— covering the whole R2R study area has a negative influence on its usability. An area with only a few data points merely means that it has been explored or covered to a lesser extent, not necessarily that Geomanifestations are not present, or that this area is less prospective.

3.2.3 Conclusions and recommendations

As illustrated in §3.2.1, multiple valuable new insights have been discovered by tying the Geomanifestations database to the Structural Framework and from the Geomanifestations inventory itself. For example, the key factors governing thermal anomalies were observed to be topographic differences, linked to hydraulic gradients, and the occurrence of faults or fractured rocks. Quaternary volcanism serves as main source of origin for CO_2, as suggested by the close association between the presence of CO_2-seeps and Quaternary volcanoes, maars and calderas. On a regional scale, faults play a fundamental role as migration pathway of CO_2, while the local scale distribution demonstrates the importance of groundwater discharge for bringing CO_2 to the surface. The occurrence of Quaternary volcanism in the Eifel, as well as elevated $^3He/^4He$, seems to be primarily related to large-scale fault systems. Data of total He-concentrations is too sparse to make solid conclusions. The research on the occurrence of polymetallic veins revealed important information on the systematics of the mineralization system, and even led to the discovery of a new, economically interesting, deposit in NE Luxemburg. Anomalies in seismic signatures have proven to be an excellent pathway to explore the subsurface as well. AVO-anomalies give an indication of beds containing a high proportion of fluid or gas, useful both for prospection purposes and a safe exploitation. The collapse structures show a clear link to the geological history of the area, which is indirectly related to its tectonic history and the structure of the subsurface. For the other Geomanifestation types, concrete results look very promising but remain to be cashed in the near future.

The ultimate goal of the Geomanifestation database is to represent a full inventory of Geomanifestations. For all Geomanifestation types, there is still some completion work needed to have the full R2R area covered. Furthermore, it is recommended to keep the database up-to-date and add new information when this comes available with further (targeted) research. The extension of the Structural Framework to include more detailed data of the Upper Rhine Graben is indispensable to interpret the many Geomanifestations related to temperature, CO_2-seeps or volcanism in this area. Also, expansion to other types of Geomanifestations would greatly enhance the applicability field of the database. Specifically, for the bias in CO_2-seeps mentioned above, it would be valuable to include additional data that focusses on dry CO_2-seepage, such as bio-indicators, i.e., plant or animal species that indicate the occurrence of elevated CO_2-concentrations independent of the hydrology (e.g., Berberich and Schreiber, 2013). Lastly, in order to make optimal use of the Structural Framework – Geomanifestations interaction, both datasets should be integrated and revised in an iterative way, facilitating, for example, the creation of a more detailed SF in areas where Geomanifestation patterns suggest a link with local or structural patterns. It is in this interaction that the added value of these databases for exploring the subsurface and gaining more knowledge on the key processes that play in the subsurface (leading to a more sustainable subsurface management) is most powerfully reflected.

4 APPLYING THE STRUCTURAL FRAMEWORK AND GEOMANIFESTATIONS FOR POLICY SUPPORT

As highlighted in §1.3, European legislation dictates that the exploitation of targeted geological structures should not cross international boundaries. Often even **cross-bordering influences** of exploitation are not allowed. Limited geological knowledge or models that stop at the national boundaries thus severely restrict the evaluation of these aspects in the design and regulatory phase of such a project. Therefore, a first application of the GeoConnect³d strategy of building a sound, cross-bordering Structural Framework provides a direct, integrated answer to this high policy need. The Structural Framework promotes the cross-boundary harmonization of geological structures (e.g., fault traces) and provides an easy tool to visualize large scale geological features that continue over multiple countries. For example, the assessment or interpretation of (induced) seismicity data in border regions, such as the Roer Valley Graben, is greatly facilitated with the Structural Framework. However, even if it does not concern a cross-border project, policymakers, as well as project partners, need to be able to assess or predict **spatial impact and potential interferences of subsurface projects**, which requires an in-depth understanding of the geology.

Secondly, the Geomanifestations strategy of inventorying data from different geodisciplines, integrating insights and trying to understand processes allows to increase knowledge in each of the individual fields and can potentially predict sweet spots for preferential exploration. The Structural Framework and Geomanifestations tool thus proves very valuable for gaining a more **fundamental understanding on the structure and characteristics of the subsurface**, an absolute necessity for knowledge-driven subsurface management. Increased geological knowledge, e.g., upward, downward or no vertical flow along a certain fault, contributes to a deliberate and balanced subsurface management, especially when the subsurface volume is limited and where interfering and fragmented use both have to be avoided at all costs. But even beyond that, conceptual insights from well-explored or more 'mature' regions (such as the Eifel region or Upper Rhine Graben, respectively) are transferable to less explored regions, where they can help to better appraise the potential of a subsurface application in a cost-efficient way, as illustrated with the example of Aachen and Heerlen (§3.2.1). In addition, they can serve as useful guidance to determine, without risky and expensive on-site drilling or seismic campaigns, potential 'sweet spots' —in this case for geothermal resources— that deserve further investigation.

Furthermore, the processes and factors related to the highlighted Geomanifestations (see §3.2.1) teach us a lot about the specific applications associated to them. For example, it turns out that hydrological factors and the (local) interplay between fault (sets) are more important factors to consider than the occurrence of young volcanism when evaluating the geothermal potential of a given area. The discovery of new, economically interesting, gas seeps and a Mn mineralization site in NE Luxembourg using the Structural Framework, also illustrates the **prospective value** of the GeoConnect³d approach. But knowledge on the natural CO_2-seeps, serving as a **natural analogue** for CO_2-storage in the subsurface, also has a more indirect impact. The fundamental processes observed to govern the distribution of CO_2-seeps imply that both the presence of (permeable) faults and groundwater flow have to be taken into account when selecting an optimal location (if any) and assessing the long-term effectiveness that can be assumed for such a storage.

Lastly, the Structural Framework and Geomanifestations allow this knowledge to be communicated to policymakers in a straightforward and understandable way. Combining seemingly unrelated data or results in a framework like this enables **streamlined communication** between policy makers and experts on potential issues and results. In particular, the Structural Framework is a great help to initiate focused discussions about applications or thematic issues in the subsurface, e.g., on a specific location or geological setting.

5 CONCLUSIONS

For the R2R area, the combined Structural Framework – Geomanifestations methodology was both developed and applied, which led to several new insights:

- The vocabulary structure following the SKOS system provides a powerful means to structure geological data (both limits and units were integrated in this project). The hierarchical structure and custom properties allow to relate elements in terms of broader and narrower concepts, and units and their limits, each of which contains a clear definition and literature references.
- Zoom levels have significant added value when aiming to explain large-scale geological structures, whilst also maintaining detailed geological data.
- Joining the information contained within the vocabulary structure with the geometry files of the geological limits and units facilitates cross-boundary integration
- As a vocabulary on its own does not have a spatial representation, geological data that is hierarchically structured using a vocabulary does not, and does not need to, automatically provide spatial structure. This is especially relevant when working with units (represented by polygons). The reason for this is that the vocabulary can be structured in a thematic way and different themes might spatially overlap, resulting in map-views that are complicated and difficult to interpret rather than being instructive. When a spatially clear Structural Framework is supposed to be the entry point for the end user, some dynamic filters (e.g., the option to query for specific themes) should be implemented in the spatial viewer that is disclosing the Structural Framework.
- Future versions of a visualized Structural Framework should encompass both the third dimension and the link with timing, as they allow to gain better insight in the geological structure and history of an area.
- Adopting the concepts of Geomanifestations offers a new and cross-thematic way of interpreting geological data, from which many insights can follow. Specifically, it has potential to identify sweet spots for preferential exploration of the subsurface in a cost-efficient way, without risky and expensive exploration campaigns such as seismic surveys or drillings.
- The added value of the Geomanifestations approach is largest when ensuring a complete and consistent database for the entire project area. However, this project showed that constructing such a database is not a trivial task, especially when input originating from different partners/countries needs to assembled and integrated. Also, in this endeavor, new fieldwork or analyses are indispensable to ensure all required data is available in the correct way.
- The Structural Framework and Geomanifestation database for the R2R area were developed quite separately. Unfortunately, the timeframe of the project did not allow for an extensive appraisal of interaction between the two results. Initial results or interpretations of Geomanifestations based on previously published maps, however, look promising. Ideally, an iterative integration and revision approach is applied to ensure the best quality and most up-to-date version of the Structural Framework and Geomanifestation database.

- The application of the Structural Framework – Geomanifestations methodology has significant added value for policy makers aiming to tackle subsurface management challenges. Firstly, it provides a means of communicating geology, hence helping to bridge the gap between experts and policy makers when it comes to understanding the geological structure of an area. Secondly, it helps to assess or predict spatial impact and potential interferences of subsurface projects. Thirdly, the strategy of inventorying and interpreting data from different geodisciplinces allows to achieve a more fundamental understanding on the structure and characteristics of the subsurface, which is essential for knowledge-driven subsurface management, especially when the subsurface volume is limited and where interfering and fragmented use has to be avoided at all costs.

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