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Overall conclusions and recommendations

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GENERAL INTRODUCTION

This report represents the final conclusions and recommendations from the GeoERA Geoconnect^{3}d project. The aim of Geoconnect^{3}d project was to develop and test a new methodological approach to prepare and disclose geological information for policy support and subsurface management. This report summarises the results from each case study / pilot area, synthesising the lessons learnt for each of them, giving recommendations of further work for future projects.

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1 INTRODUCTION

The subsurface plays nowadays an important role as it provides essential resources: drinking water, hydrocarbons, raw materials and heat, etc., as well as the capacity for large-scale fluid storage (natural gas, liquid or liquefied hydrocarbons). Yet, the use of the subsurface is expected to increase even more in the coming years, mainly because of the energy transition, with new types of subsurface uses adding to the existing ones. Among these prospective uses, we can mention the storage of energetic vectors (compressed air, H_2, CH_4, etc.), of wastes, of CO_2, of heat, new types of mining or energy resources exploitation. The question arises whether these new uses would generate potential conflicts in the utilization of the subsurface, which would threaten their economic or technical viability.

Although the subsurface is vast, only fractions have suitable geological conditions for subsurface development, with many technologies requiring similar geological conditions to operate. Salt formations provide the ideal storage conditions for hydrogen, natural gas, or used for compressed air energy storage. On a larger scale, sandstone formations with a suitable cap rock and good permeability and porosity can be used to store hydrogen, CO_2, natural gas; exploited for drinking water extraction and even geothermal energy production. The increased production and demand for electric vehicles and battery power will drive extraction of rare metals such as lithium from the subsurface.

The transnational nature of the European continental shelf creates specific problems in terms of subsurface competition. Subsurface boundaries do not stop at national borders therefore the subsurface development of one area might have implications effecting other subsurface activities within different countries. These subsurface problems are outlined in Deliverable 5.1 ‘State of the art of subsurface planning and management, and avenues for improvement’.

There is hence the need for a transnational, cross border means of subsurface management within Europe, enabling the sharing and combining of subsurface data. Such collaboration would enable the transnational management of the subsurface, avoiding any conflicts of use for future subsurface development.

In order to manage cross border subsurface managing issues policymakers need a good understanding of the geology and of the reservoirs crossing the borders to adequately predict spatial impact and potential interferences around subsurface projects.

1.1 Project Aims

GeoConnect^{3}d has aimed to develop a tool that can convert geological data into information and critical parameters that can be used for a variety of geo-applications from decision making to subsurface spatial planning. Geological data can include a vast array of complex data held in different databases, although in fact, many geological resources are intrinsically linked. Combining data on different resources can lead to a better understanding of the underlying processes and may help to evaluate the interaction between and the impact of different subsurface activities. The tools that have been developed are the structural framework and geomanifestations methodologies. Both methodologies are described in Deliverable 2.4 (Barros and Piessens, 2020) and summarised below.

1.1.1 Structural Framework

GeoConnect³d has connected models of different scale, detail, and origin by using a fault-centered approach using structural data at different scales. This approach is cross-thematic, cross-border and across different geological realms. Subsequently, GeoConnect³d has tied geological data and knowledge to this fault backbone by integrating and envisaging many types of geomanifestations (described below) in a map-based approach. This 2-step approach differs from the conventional geological mapping that focusses on characterising and mapping the spatial distribution of geological units, usually in a section view approach (seismic and well data), and in which faults are often considered as features of secondary importance.

1.1.2 Geomanifestations

Geological data can inform us of past and present geological processes occurring within the subsurface. Collecting this available geological information and plotting it within geological maps and models to form a coherent structural framework allows us to form a detailed understanding of regional geology and the available data and research that has been conducted in the specific area. This level of knowledge is more than literature that collects the thematic information. Rather, it represents the pre-project state of understanding of the regional geology, and comprises the required context to, for example, understand the potential relations between different subsurface activities and their vertical or lateral footprints.

A **geomanifestation is defined** here as any distinct expression of an ongoing or past geological process at surface or at depth. Examples include seismicity, gas seeps, anomalous water chemistry in groundwater and springs, thermal anomalies, non-sedimentary mineral occurrences, jumps in hydraulic head, overpressurised zones and geomorphological disturbances.

1.2 Testing the Methodology

The methodologies have been applied to two regional case studies in order to determine if the methodologies are successful in their aim when applied to geologically complex areas and at multinational scales. The two case studies include the Roer-to-Rhine graben (further referred as R2R) and the Pannonian Basin (further referred as PM). Two pilot studies have also been selected in order to provide an alternative test of the methods deployed within the main case studies. The pilot studies include the island of Ireland and the Molasse basin (Bavaria, Germany). Although these pilots do not have a trans-national context for geoenergy development and management, this was an important task as the GeoConnect³d methods must be applicable to diverse geological and regional contexts. The implementation of the structural framework (further referred also as SF) and geomanifestations (further referred also as GMs) methodology within a large scale, country wide case study is useful to determine how diverse the methodology is, and how it copes with such large amounts of geological data. It should be noted that the focus of the pilot studies was more on implementing the SF, and GMs were added rather as an experimental afterthought.

1.3 Evaluation Board

An evaluation board was set up in order to critically analyse the more generic and methodological approaches of the pilot areas and case studies. A questionnaire was produced by BRGM, providing a criteria to review the case studies, to define how "successful" they are, and how/if the methods used can be further optimised to tackle subsurface management questions. The evaluation board comprised BRGM, RBINS-GSB, CGS, GSI, PIG-PIB, GSS and GeoZS. An evaluation board meeting was held in order to discuss the main points raised in the questionnaire. The evaluation questionnaires for each case study/pilot are included in Appendix. This report contains references from the evaluation questionnaires.

1.4 Scope of Report

This report represents the final conclusions and recommendations from the GeoERA Geoconnect³d project. It summarises the results from each case study / pilot area, synthesising the lessons learnt in each case study, giving recommendations of further work for future projects.

2 SUBSURFACE MANAGEMENT

One of the main aims of the Work Package 5 of the GeoConnect³d project was to assess the actual status of subsurface planning and management in Europe and to provide overall recommendations regarding these processes.

For this purpose, it was necessary to set up some basic definitions to ensure a common understanding of used/created concepts. The underground space itself, understood as the whole space beneath the Earth surface, where natural mineral resources as well as groundwater reserves are hosted, was the one to start with. Further concepts and terms necessary for understanding of novel subsurface management organization and needs were presented and explained in the D5.1 report (Konieczyńska *et al.,* 2020).

For clearing the message of this report two definitions need to be recalled: I) subsurface use[1] nowadays needs to be understood as every activity conducted from the land surface or in a geological space that affects big volumes of underground formations such as extraction of resources (drinking water, mineral raw materials, heat, etc.) or large-scale storage or disposal (natural gas, liquid or liquefied hydrocarbons, carbon dioxide, radioactive waste, etc.); 2) subsurface management means all considerations, planning, decisions and actions to allocate specific uses to appropriate subsurface locations. It is important to remember that management process needs to include prediction of complex and interacting effects on (1) targeted space/formation, (2) neighborhood, especially confinement and also (3) protected compartments/entities (like groundwater, soil, ecological functions, humans' wellbeing).

To successfully employ subsurface systems, possible mutual influences of intended usage options with other existing or planned uses of subsurface should be considered. Optimised use of subsurface must include avoiding/resolving conflicts and looking for potential synergies. All mentioned here starts from and depends on proper recognition and understanding of geological structures and processes that take place within (both in the geological history and today).

It must be noted that first need for planning and management of underground activities was identified in shallow subsurface, where engineering applications mainly in urban areas took place. The GeoConnect³d project does not refer to these kind of activities and this shallow part of subsurface space, which have been already sufficiently managed both in scientific and technical aspects. The area of interest of the project reaches depths of several kilometers and concerns huge volumes of geological structures.

General situation in EU countries

Traditional use of geological space in Europe (as all over the world) was limited to mining activities. Extraction of mineral resources (coal, lignite, salt, barite, gold, silver, copper, later oil

[1] Synonyms: subsurface/underground + application/activity/project/ undertaking/use/development

and gas, etc.) has been performed in all European countries for centuries with little attention paid on any other than short term economic aspects of the activity. So called mining damage and other negative impacts were identified as a problem due to rising awareness of European societies in XXth century and interdisciplinary research approach implemented in the area of Earth and Environmental sciences.

Nowadays challenges derived mainly from increasing energy demand and climate protection goals give a place for new applications in geological space. Subsurface compartments already have been used as a storage for energy carries like natural gas or permanent waste disposal place. The possibility of permanent underground storage of CO_2 captured to diminish substantial emissions to the atmosphere also has been proven in a number of pilot and demonstration projects (e.g. for Europe, the Sleipner and Snohvit projects in Norway[2]). Seasonal heat storage has been studied in shallow geothermal projects in many countries, such as the Neubrandenburg installation in Germany). Bigger scale heat storage possibilities are also investigated (see the Heatstore project[3]), as well as hydrogen storage (Teeside in the UK) or compressed air storage (e.g. the ALACAES project in Switzerland[4]) - novel clean energy carriers. Even direct energy production may have a chance to go underground as shows the pilot pumped storage power plant constructed in closed coal mine near Ostrava[5] in the Czech Republic.

New applications in the underground space can generate new problems resulting not only from direct geology based limitations but also from potential conflicts/interactions between projects conducted in the same or neighborhood space. Moreover, as the subsurface has no borders (except for natural structural and lithological ones), sustainable use of it may require wide cooperation of a number of authorities of different regional, national and international levels. Within the GeoConnect³d project we attempted to identify all parties interested and involved in subsurface use planning and management across project Partners countries and we tried to look through existing European and Member States regulations and procedures in planning, assessment, licensing and controlling deep underground applications.

The survey conducted among project Partners showed that there are different patterns employed in long chain of spatial planning, environmental and technical procedures related to the use of subsurface across countries. The subsurface use management is a process which combines many procedures which are in the competence of various institutions and authorities, in many cases established yet to serve traditional resources mining. The diversity of authorities and differences in the competence are derived from national and local legislation, different in

[2] The Global CCS Institute has created a database of worldwide CCS facilities, policy, regulatory, storage and emissions data, available on https://co2re.co/

[3] https://www.heatstore.eu/

[4] https://alacaes.com/technology/pilot-plant/

[5] https://energnet.eu/wp-content/uploads/2021/02/4-Pawera_Experimental-Underground-Pump-Hydro-Facility_Paris_081119_final_web.pdf

each country, as well as different patterns in organization of state, regional and local administration. In general, subsurface management is still not identified as a uniform issue, and particular aspects of it are scattered across many different pieces of regulations which in many cases creates gaps and space for misinterpretation of actual needs of effective and responsible procedures.

Similar situation, though not so directly influencing development of particular activities, is in the European legislative. Subsurface use aspects are partially covered by a number of European directives (see D5.1 report), but even in case of those referring directly to a certain type of underground application, like the so called CCS directive[6], the need of complex, coherent approach to subsurface use is not identified. There is a need for regulations which will not only focus on possible use of subsurface but also on its protection against pollution or damage of resources (meaning also as opportunities) that cannot be exploited at present but may be of a significant value in the future. This seems to become more urgent as it is more and more evident that the use of the underground space will be necessary to achieve the climate goals related to the New Green Deal or the climate package Fit for 55.

Several stakeholders meetings and workshops organised and served by the GeoConnect³d project revealed also a strong need for assistance in the field of geological background knowledge and expertise in modelling induced behaviour of geological space. The European geological survey organisations (GSOs), gathered in the EGS, are willing to deliver dedicated services to support decision making processes on each of the required administration levels. The tools proposed by GeoConnect³d may be regarded as the first step towards a more complex cooperation in the safe and efficient use of underground space in Europe in the future.

[6] Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006

3 STAKEHOLDERS' VIEWS

Communication with stakeholders and direct knowledge sharing was identified as an important aspect already in the GeoConnect^{3}d preparation stage. Therefore, during the project implementation a series of workshops and seminars have been organised to present the project's approach and ambitions as well as for better understanding of actual needs of particular groups of stakeholders. Feedbacks from these meetings have been carefully reviewed in order to make sure that efforts undertaken stay in line with common expectations and needs. The results have also helped to define remaining gaps and directions for future development of work started in the GeoConnect^{3}d project.

3.1 Mid-term GeoConnect^{3}d workshop, June 2020

This workshop was composed of a series of four webinars which focused on four specific themes separately, in order to attract different stakeholder groups. These themes were: geoheritage, groundwater, geothermal energy and subsurface management. The goal was to discuss the first three themes in the perspective of subsurface management, inviting attendees to join the final session which would bring all themes together. The webinars attracted over 200 attendees from geological surveys, universities and governmental institutions, including policy-makers; there were a further 500 views of the recorded sessions in the project's YouTube channel. During the live sessions, the audience was encouraged to share their views through various interactive polls.

There was a general strong agreement that subsurface management is a pressing issue that should be discussed more. Polls accepting free text comments from the audience about integrating subsurface uses into the case studies revealed a need for discussing and disclosing information about subsurface interactions instead of separating the discussion in different themes depending on the use.

After presenting preliminary GeoConnect^{3}d results, including parts of the areas of interest and the pan-European structural framework as a broad contextualisation of the different themes of the webinars, there was an overall positive reception of the approach by the audience, especially in the final webinar dedicated to subsurface interactions and management (Figure 1). The biggest concern raised was about the lack of accessibility of the results by non-specialists due to the need of previous familiarity with maps and models, and the use of technical language. This and other concerns mentioned were discussed and a few solutions were incorporated with the evolution of the project.

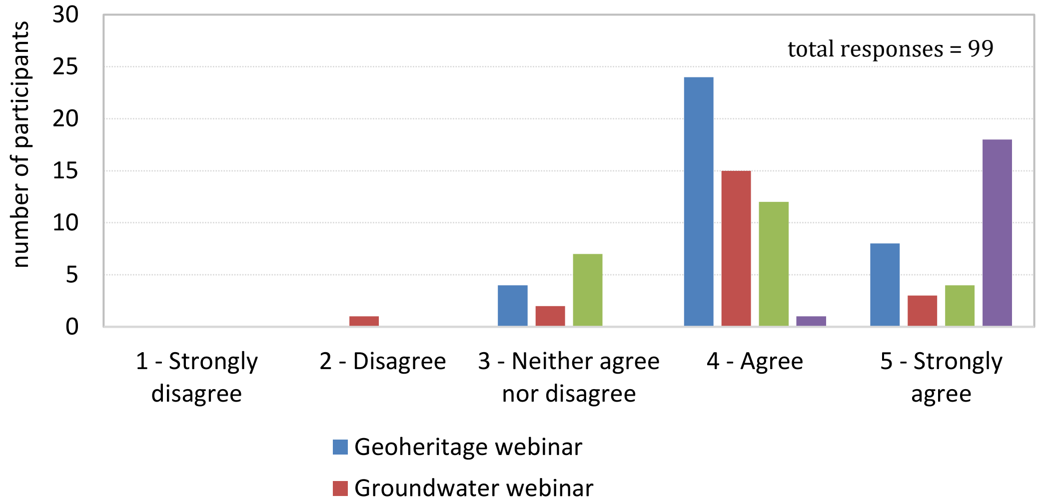

Figure 1: Results of the live poll: "How do you agree with the following statement: the way GeoConnect³d presents geological information is easy to understand".

3.2 Mid-term GeoERA webinar series, November 2020

A few months later, this series of 5 webinars presenting the progress of GeoERA attracted over 600 participants of varied backgrounds and expertise. The audience was encouraged to share their views through various interactive polls in each of the 5 sessions. These were not project-specific questions, as with the GeoConnect³d workshop in June, but broader cross-thematic questions.

As a general observation, unharmonised and incomplete data were highlighted as the largest obstacles to the exploitation of geological information (Figure 2). Overall, after the presentations of preliminary results by all different projects, the audience picked harmonised data and publicly available information and maps as the most relevant/useful products or achievements of GeoERA across its themes. Standardisation and integration of information across Europe, and a focus on user friendly tools, were the most mentioned suggestions to increase accessibility of results in EGDI.

Specifically within the Geo-Energy theme, harmonisation, compilation and thematic integration were once again emphasised as the most important steps to ensure access to subsurface information (Figure 3).

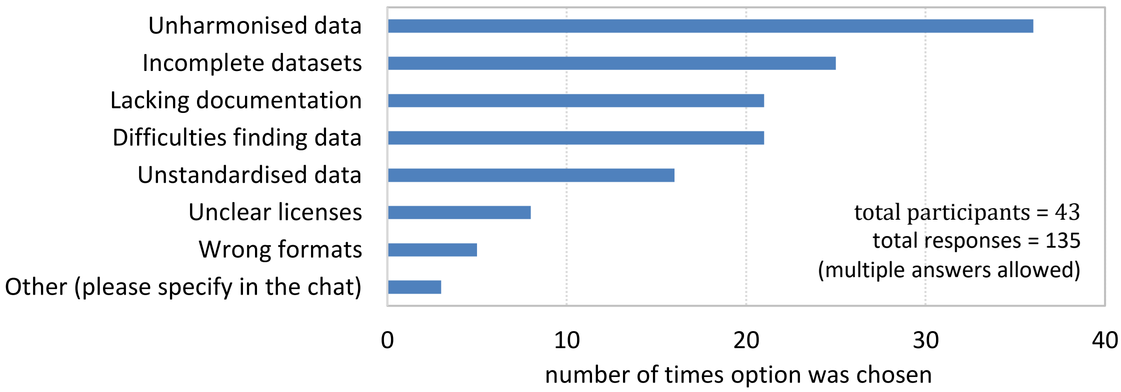

Figure 2: Results of the live poll "Where do you see the largest obstacles to the exploitation of geoscientific information?". Comments sent for the option "Other": 1) Conceptualisation, as already mentioned in the talks, as this is key to understanding and relating geological information.; 2) Visualization and evaluation of information uncertainties.

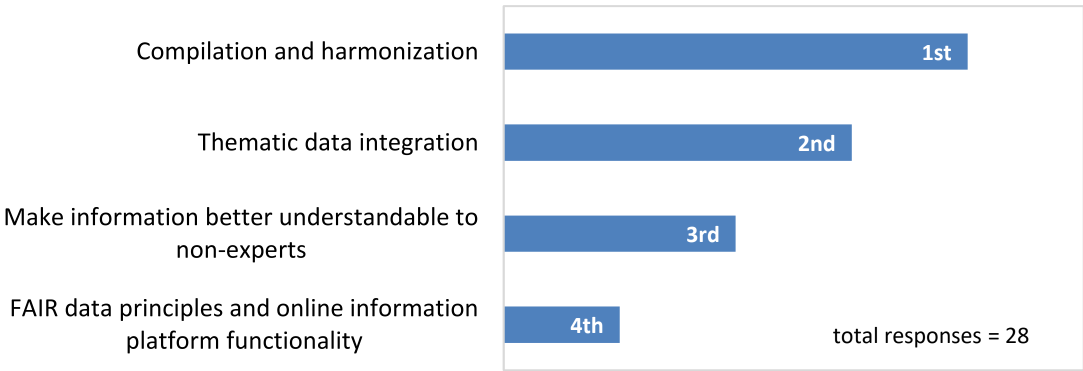

Figure 3: Results of the live poll "What is needed to ensure access to subsurface information in support of the clean energy transition? Rank from most to least important".

3.3 Final GeoConnect³d stakeholders' workshop, June 2021

The final workshop of GeoConnect³d, as a side session of the Geoscience, Policy and Society international event, attracted 43 participants from geological surveys, universities, private sector and government. In this workshop, various polls were opened to the audience, and the group of questions was also open after the session for one extra week to receive further input from the audience that watched it live or in the project's YouTube channel.

Regarding the audience opinions on subsurface management in Europe, there was still a strong agreement about its importance in the development of the energy transition (Figure 4), and they highlighted as main known management issues the ones related to underground storage (energy, CO_2, H_2), and multi-resource conflicts (Figure 5).

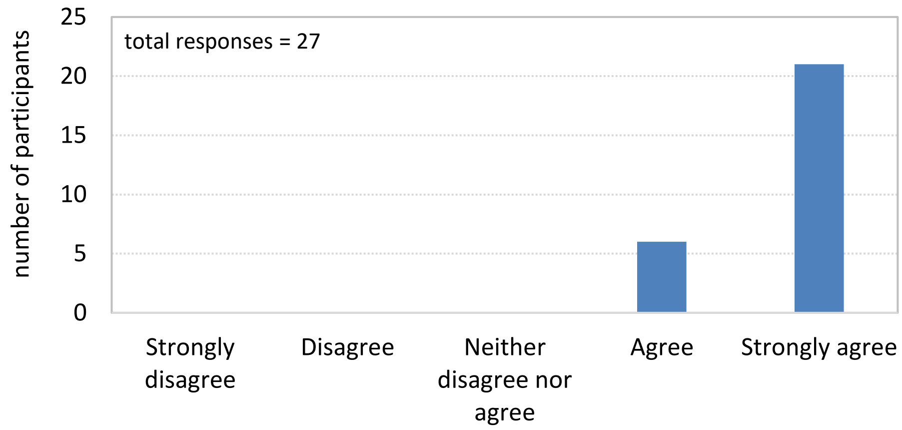

Figure 4: Total results (live and post-webinar) of poll: "How do you agree with the statement: Subsurface management is a key issue in the development of the energy transition in Europe.".

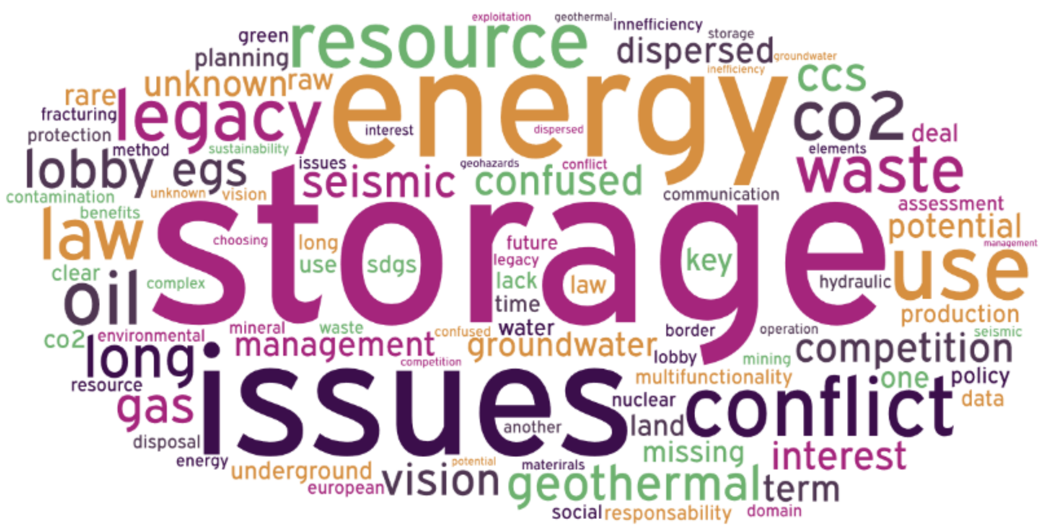

Figure 5: Word cloud resulting from the poll: "Which keywords come to your mind related to subsurface management issues within Europe?".

Presentations of some of the project's results demonstrated the structural framework, the geomanifestations and possible contributions to policy challenges in the different case studies. The acceptance to the structural framework model was comparable to the mid-term workshop (Figure 6). But the main achievement was to showcase some of the suggestions from the mid-term workshop had been incorporated in our results, with e.g. the use of geomanifestations to assess conflicts and synergies between subsurface uses (Figure 7).

Opening a poll to receive free text comments by the audience about the pros and cons of the GeoConnect³d approach, encouraging comments were made about its usefulness to show harmonised geological information across borders (especially for R2R and PB), for communication with non-specialists with some background, and that it successfully provides a framework to synthetise surface and subsurface data. Pitfalls mentioned include the lack of 3D information and the limited application of timing to the concepts presented. Also through free text input, when asked about the opportunities of this approach in view of a European-wide subsurface management policy, the audience mentioned the establishment of international standards and the use of the approach to achieve consilience when handling the subsurface.

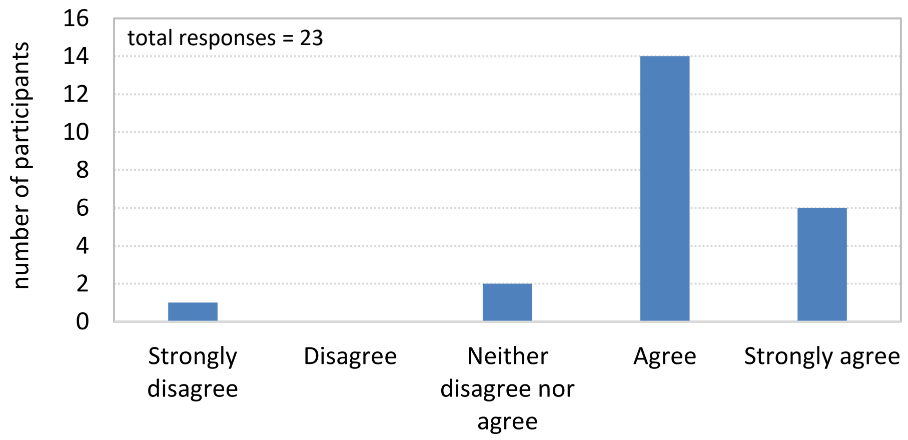

Figure 6: Results of the poll: "How do you agree with the statement: the Structural Framework approach is a useful way to constrain subsurface geology."

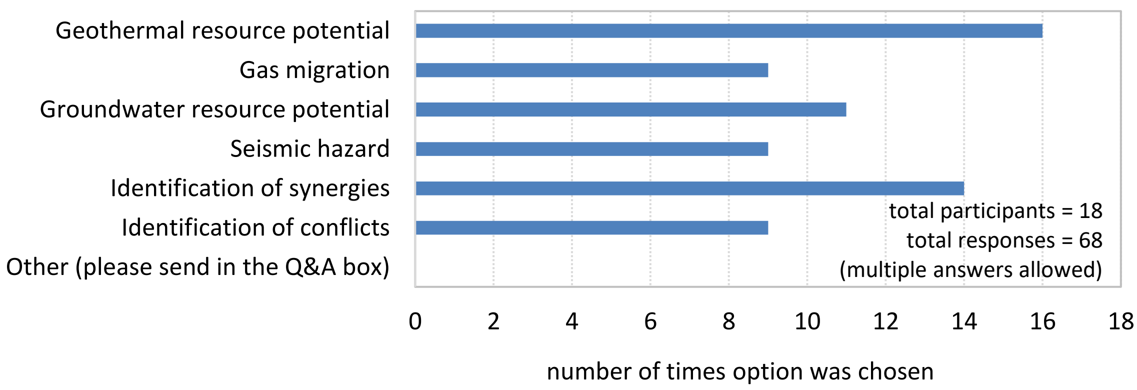

Figure 7: Results of the poll: "For which application(s) is the geomanifestations approach most useful?.

The results of the interactions with stakeholders during these different online events demonstrate a few resonant points. The need for and value of harmonised, standardised, cross-border geological information to support subsurface management was the strongest message by the different audiences. It is also clear that there is an interest in achieving comprehensive, cross-border, cross-thematic management of the subsurface, a goal currently blocked by the lack of Europe-wide accessible information.

Particularly for GeoConnect³d, the views of the audience from preliminary to final results presented one year apart (June 2020 and June 2021) were consistently positive. A rewarding outcome from the interactions with stakeholders was to incorporate external suggestions to the methodology and case studies, and to later demonstrate that it was possible to achieved higher level of comprehensiveness in geological models, opening post-project opportunities towards integrated, harmonised and standardised geological information that can be truly useful for subsurface management.

4 TESTING THE METHODOLOGY

The following section contains a synthesis of the lessons learnt from each case study/pilot. The synthesis is prepared based on reports D5.2a and b (two pilot case studies) and D5.2c and d (two regional case studies), and evaluation board discussions.

4.1 Roer-to-Rhine

A detailed description of the application of the structural framework and geomanifestations methodologies on the Roer-to-Rhine (R2R) case study is available in 'Deliverable 5.2c - Lessons learnt from the R2R case' (Van Daele *et al*., 2021). Below is a brief summary of the report with references made by the evaluation board. The partners who participated in evaluating the R2R case study included: BGR, CGS, GSS, GeoZs, GSI and PIG-PIB.

The main objective of the Roer-to-Rhine case study was to implement and test a workflow to facilitate cross-border and cross-thematic evaluation of geological resources and applications, supporting subsurface management and policy for the exploitation of geo-resources. R2R focussed on the border regions between Belgium, The Netherlands, Germany, Luxembourg and France. Although the study area was limited in extent, the complex deformation history of the area generates multiple geological domains extending over multiple borders, allowing for a regional exercise that was a realistic analogue for a pan-European exercise.

4.1.1 Structural Framework

The SF methodology in the R2R case is a very powerful tool to structure and display data, ensuring geology can be easily interpreted by stakeholders. With the incorporation of zoom levels, large scale geological structures can be combined with detailed geological data. Modelled data can be linked with literature concepts; cross boundary structures can be integrated and larger-scale structures can be distinguished from smaller-scale structures.

4.1.2 Structural framework related technical challenges

4.1.2.1 Structural framework related lessons learnt by R2R team

The main technical challenge involved the variation and quality of data used within the case study involving multiple partners. Partners worked individually within each area of legislation. The approach that was followed differed significantly from partner to partner because of large differences in available information and the geological complexity of different areas within the project. For example, Flanders and the Netherlands are characterized by a generally simple shallow geology and have also been mapped in 3D to great detail aiding the production of the SF. On the other hand, in Wallonia only local scale 3D models are available and the strata are very strongly deformed and faulted. This difference altered the application of the methodology in each area, initially hampering the application of the SF.

4.1.2.2 Structural framework related assessment from evaluation board

General comments

The general comments from the evaluation board assessment also discussed the large variation and quality of data used within the case study. GSI suggested, when making a SF with different partners 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. This would enable the easy interpretation and harmonization of methodological approaches between other partners.

In order to enable users to determine the accuracy of the data and areas in need of further study, the BGR suggested the utilization of a scale-dependent uncertainty analysis describing for every drawn element at every scale an estimation of the representation error.

Qualitative evaluation– Structural Framework

The evaluation questionnaire was prepared in a way to highlight specific areas of disagreement within board member evaluations, potentially displaying areas of strength and also fundamental limitations with the methodology. The distribution of answers to each question regarding the R2R structural framework is shown in Figure 8 below. Evaluation questionnaires are available in Appendix I.

As shown within Figure 8, all questions show relative convergence. Question 1) shows a convergent pattern with partners either strongly or somewhat agreeing with the statement that the structural framework has been successful in making the geology of the area more understandable.

Question 2) demonstrates the majority of partners either strongly or somewhat agreed with the statement that structural framework has been successful in providing a coherent geological context for subsurface applications. The PIG-PIB somewhat disagree stating: *'It looks like the first step only, giving the idea of geological structures across several countries sharing them, but the SF itself is not sufficient to provide the information of possible subsurface application - it does not provide the 3D models of subsurface, not allowing for assessment of space available. Yet GMs provide in this case some ideas on possible applications and their limitations.'*

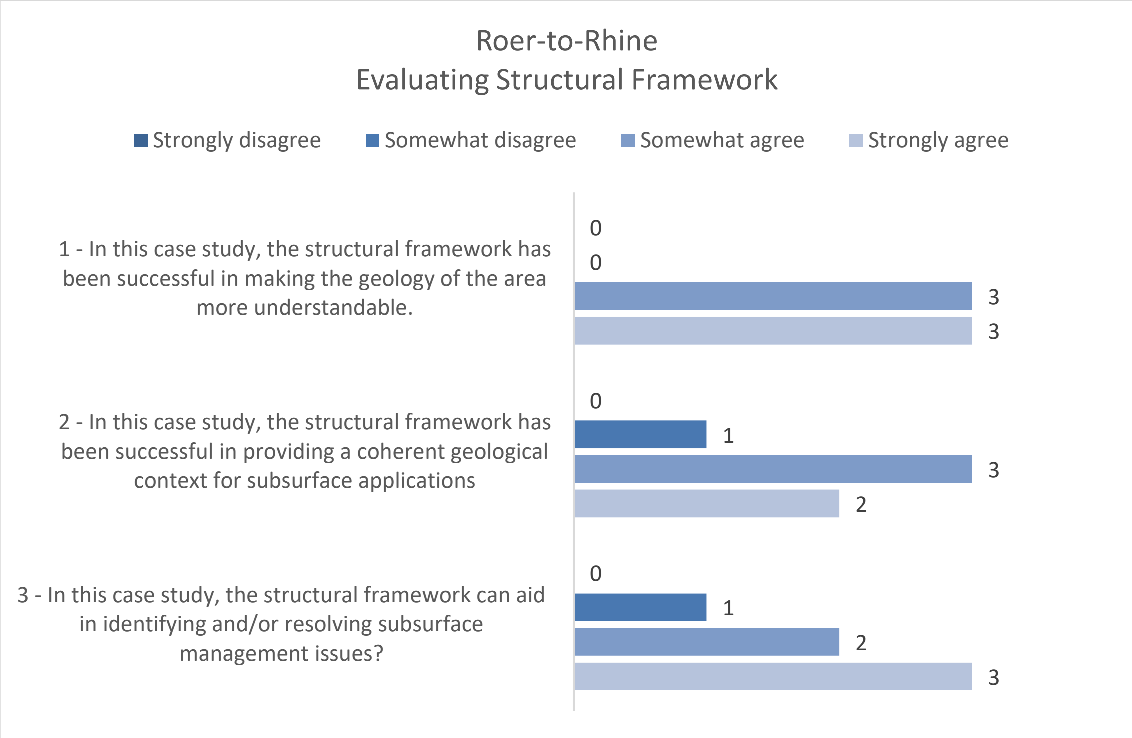

Figure 8 : Results from the evaluation questionnaire: Roer-to-Rhine, Evaluating structural framework

Question 3) also demonstrates the majority of partners either strongly or somewhat agreed with the statement that structural framework could aid in identifying and/or resolving subsurface management issues. The CGS strongly agreed stating: *'Thanks to the structural framework, the study contains signal information on potential for various kinds of subsurface use, as well as on some issues such as possible risks or conflicts of interest. The use of information from the structural framework indicates areas where more detailed research and studies can be elaborated.'* Only the PIG-PIB somewhat disagreed stating: '*Structural framework presented in the case studies may be somewhat helpful in identifying problems related to the use of subsurface. In particular, information on faults and their occurrence in the geological units of the analyzed area. But the lack of 3D visualisation, little information on limits and units properties and not clear instruction how to use SF together with vocabulary file, where hierarchical and non-hierarchical relations are defined and where more data are possibly accessible does not give the strong knowledge to identify and solve possible management issues.'*

4.1.3 Geomanifestations

The geomanifestation types inventoried in the R2R study using in the GeoConnect³d methodology 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. Adopting the concepts of geomanifestations offers a new and cross-thematic way of interpreting geological data, from which many insights can follow. The report states that the application of the geomanifestations has potential to identify sweet spots for preferential exploration of the subsurface in a costefficient way, without risky and expensive exploration campaigns such as seismic surveys or drillings.

4.1.4 Geomanifestation related technical challenges

4.1.4.1 Lessons learnt by R2R team – geomanifestations

Similarly to the challenges faced by the implementation of the SF, the complexities associated with retrieving and managing data from multiple countries sometimes lead to data bias, with some partners utilising different approaches than others. Some areas contain very few data points, merely meaning that they have been explored or covered to a lesser extent in many cases, not that the geomanifestations are not present. In order to maintain a common approach, partners should have ensured sufficient coordination during the application of the methodology, although an element of data bias might always be evident due to data availability problems.

4.1.4.2 Assessment from evaluation board – geomanifestations

General comments

General comments within the evaluation questionnaire often relate to the reliability and interpretation of geomanifestation data when dealing with large areas and many different authors. The GSI stated: *'As the authors note themselves, the bias introduced through different partners taking different approaches to documenting geomanifestations would need to be addressed.'*

The CGS stated that one of the main problems was the reliability of the existing geomanifestations inventories in the studied area. Interests of countries of the region were normally focused on different elements therefore spatial coverage of existing data repositories differed between them. Accurate interpretation would have been time-consuming. The interpretation of the geomanifestations still needs experts' involvement and in many cases statistical and spatial analysis not only on a particular underground project scale, but broader. Incorrect interpretation of these geomanifestations may lead to erroneous conclusions.

In order to gather a greater understanding of the project area's geomanifestations, the BGR suggested to incorporate a list of geomanifestations, detailing which geomanifestations were excluded and why. This would potentially explain to the user the reason for and regional / local differences in geomanifestation types, helping identify any regions which are lacking data and in need further investigation.

Qualitative evaluation – Geomanifestations

The distribution of answers to the evaluation questionnaire regarding the R2R geomanifestations is shown in Figure 9 below.

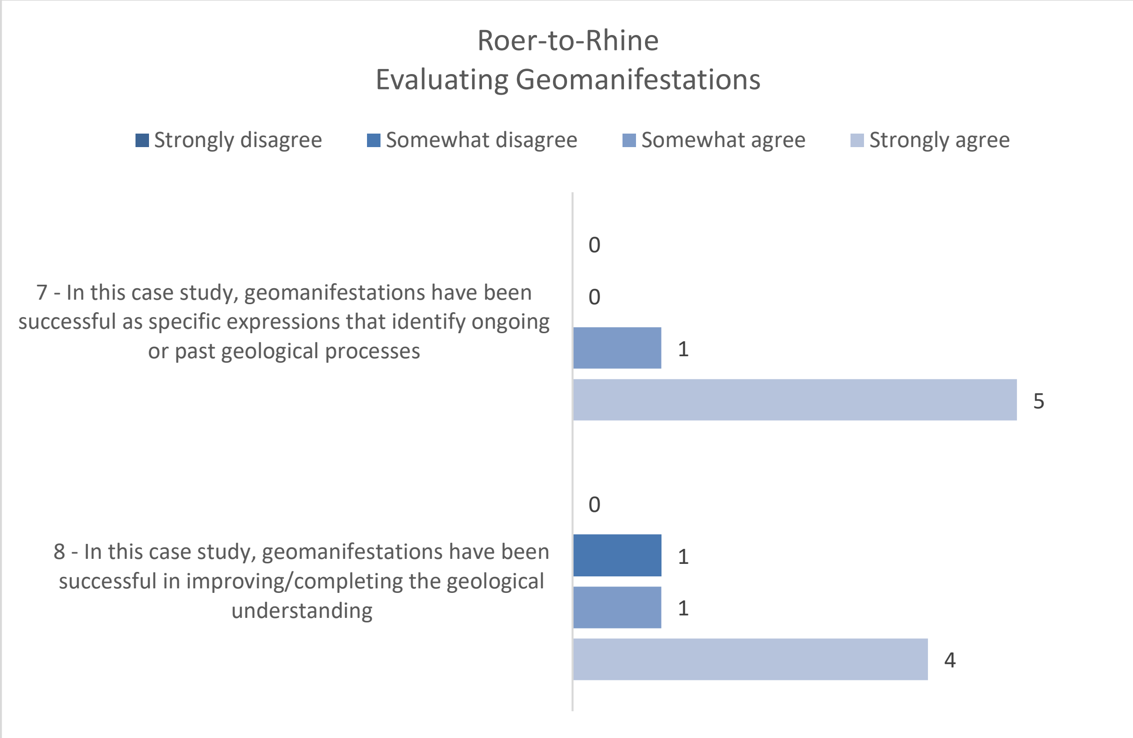

Figure 9 : Results from the evaluation questionnaire: Roer-to-Rhine, Evaluating geomanifestations

As shown within Figure 9, all answers show relative convergence. Question 7) demonstrates a convergent pattern between partners with the majority strongly agreeing with the statement that in this case, geomanifestations were successful as specific expressions that identified ongoing past geological processes. GeoZS strongly agreed stating: *'Geomanifestations are the result of past/recent geological processes below the surface. With the knowledge of their existence and location we have very good insight in the geological history and geodynamics.'*

The majority of partners also strongly agreed with the statement that in this case study geomanifestations were successful in improving/completing the geological understanding. The BGR somewhat disagreed stating: *'Most of the structural patterns were already sufficiently known and the here presented geomanifestations should be seen more as additional confirmations of certain structures in the subsurface. Again, several other examples showed that lineations or clusters of geomanifestations can also indicate structures that are not yet more precisely known, or can concretize the geometry of larger structures that are not precisely determined.'*

4.1.5 Structural framework and geomanifestations integration

The distribution of answers to the evaluation questionnaire regarding the integration of the structural framework and geomanifestations within the R2R project is shown in Figure 10 below.

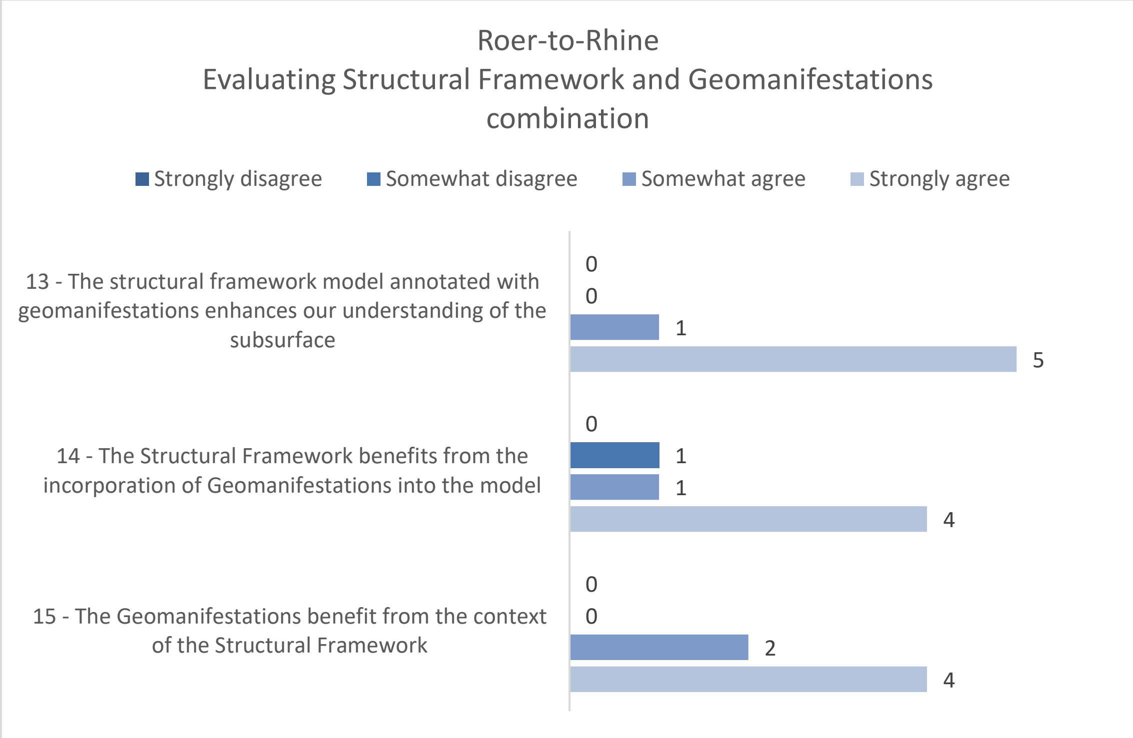

Figure 10 : Results from the evaluation questionnaire: Roer-to-Rhine, Evaluating structural framework and geomanifestations in combination

As shown in Figure 10, question 13) demonstrates a convergent pattern between partners with all partners agreeing with the statement that the structural framework model annotated with geomanifestations enhances our understanding of the subsurface. The GSI stated: '*As well as confirming and refining the spatial features of the SF, the geomanifestation provide further information about the features themselves, e.g. which faults are permeable or not, which are downwelling cold water and which have uprising warm water etc.'*

Question 14) shows that the majority of partners agreed with the statement that the structural framework benefits from the incorporation of geomanifestations into the model. However, the BGR somewhat disagreed stating: *'This depends on what the structural framework should ultimately represent. A comprehensible scalable representation of today's tectonic pattern of a region or the representation of elements that somehow manifest today. But that does not necessarily make these structures equally important for characterizing the structural framework.'*

Question 15) again demonstrates a convergent pattern with all partners agreeing with the statement that the geomanifestations benefit from the context of the Structural Framework. The PIG-PIB stated: *'Spatial analysis of gathered GMs with reference to SF features definitely gave new views on their origin, performance and enable their use as an indicators for geological* *and other processes and in the future can be probably used also as conflict/synergies indicators too.'*

4.1.6 Overall evaluation for Roer-to-Rhine case study

The overall application of the methodologies to the Roer-to-Rhine case study have been rated by each evaluation board partner. Figure 11 shows the result from the evaluation. Each evaluator gave a rating out of ten, with 10 being positive.

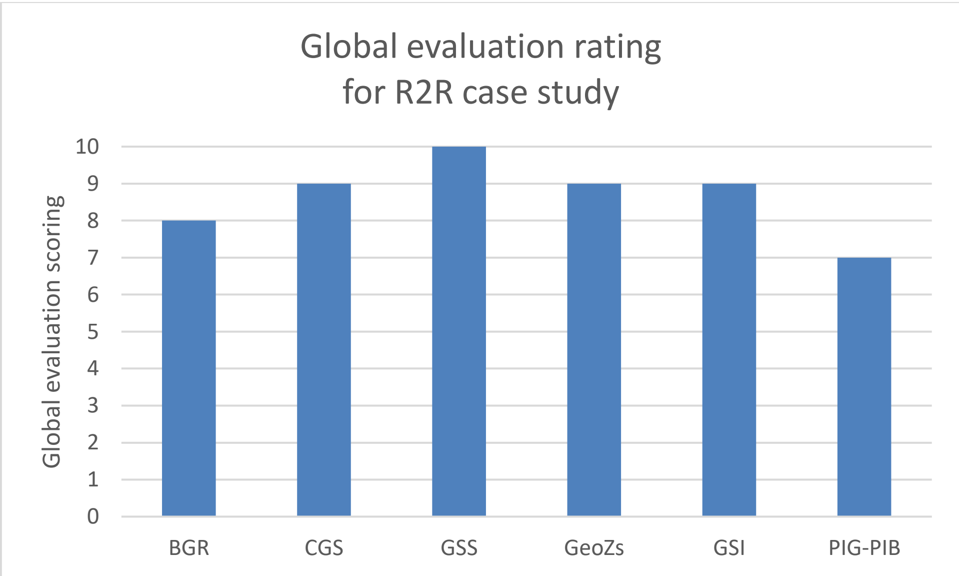

Figure 11 : Results from the evaluation questionnaire: Roer-to-Rhine, Global Evaluation Rating

As shown in Figure 11, the R2R case study was rated positively by all board members with a range of ratings between 7 and 10 and a mean rating of approximately 8.7. Below are some comments from board members:

The PIG-PIB stated: '*The R2R exercise showed which kind of data is needed for proper preparation for subsurface space management and tried to put this data together in a manner that one type of data can contribute to the knowledge the other types bring. This was supposed to create easy to read picture benefitting from all kind of information available. The unknowns about linking the vocabulary sheets with the SF and GMs spatial features make it hard to say if really all that has been described in the report really CAN be deduced from the system (which still is not in operation). The shortages of the 3D presentation, which results in lack of knowledge of depth and thickness of presented SF elements in our opinion is the main disadvantage which hinder the use of the SF in subsurface planning process.*

The innovation of use of a broad range of GMs in relation to SF features seems to be very promising, but needs still a lot of work to enable its use in a unequivocal manner, which really would allow for beneficial contribution in subsurface management at least at some stages of planning.'

4.1.7 Directions for future development (Roer-to-Rhine)

As stated in the lessons learnt report, the structural framework and geomanifestations databases for the R2R area were developed largely at the same time and quite independently from each other. Therefore, additional sources of information often had to be used for the interpretation of the geomanifestations as the structural framework was still work in progress. Due to time restrictions, the extensive integration between the two methodologies could not be applied. Future work could focus upon the enhanced integration of both methodologies.

Within the evaluation questionnaire many board members highlight the need for future projects to enhance the harmonisation between the two methodologies. The BGR state some geomanifestations like mantle Helium have a closer relation to important deep reaching structures than other geomanifestations. The structural framework needs to be customized for different applications and different geomanifestation categories in order to enhance their harmonization. BGR highlighted that the creation and analysis of a structural framework requires a completely different expertise than the analysis of specific phenomena/geomanifestations. Future works could now concentrate on the harmonization of these fields, ensuring both methodologies are beneficial to each other.

Other avenues which future projects can incorporate the link between various geomanifestations. The BGR stated that the methodology has focused upon the link between the SF and geomanifestations, the link between several geomanifestations among themselves can be an area of further study.

The PGI-PIB comment that 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.

4.2 Pannonian Basin

A detailed description of the application of the structural framework and geomanifestation methodologies on the Pannonian Basin (PB) case study is available in 'Deliverable 5.2d - Lessons learned from the Pannonian Basin' (Rman *et al.*, 2021b). Below is a brief summary of the report with references to evaluations made by the evaluation board. The partners who participated in evaluating the PB case study included: CGS, GSI, PIG-PIB and VPO.

The Pannonian Basin is a young Neogene basin system on the top of a complex Paleo-Mesozoic crystalline and sedimentary sequences within the Alpine-Carpathian-Dinaridic orogene system. The Pannonian Basin is a geologically well-defined structure and comprises areas of 9 countries with Hungary lying in its centre, surrounded by the territories of Slovakia, Austria, Slovenia, Croatia, Bosnia and Herzegovina, Serbia, Romania and Ukraine. This specific position raises specific challenges.

- Challenges such as a varying level of subsurface knowledge in different basin areas; different harmonised geological nomenclature (e.g. different formation names that impede regional stratigraphic correlations); varying data policies implying data availability between countries were identified.
- The political situations in PB countries create differing energy policies. EU Member States have to follow specific energy policies and climate action plans with mandatory targets and measures. Non-member states have their own energy strategies.

4.2.1 Structural Framework

The structural framework was applied to the Pre-Cenozoic basement, with the basement top as the reference level. Below this level a multistage structurally deformed and very diverse unit hierarchy system can be found with well-defined limits. The selection of the pre-Cenozoic as the reference horizon allows the deeper geology to be displayed in a clear and understandable way.

4.2.2 Structural Framework Related Technical challenges

4.2.2.1 Structural framework related lessons learnt by PB team

As described above, the methodology was not applied to the thick layer of Neogene basin fill, which was a deliberate choice, not a restriction of the method. This deep area of sedimentary sequences compressed a largely homogeneous unit. Separating this part of the basin into sub-basins would have proven a very complex task due to only the slight differences in basin infilling processes and lithology, preventing the successful application of the methodology. But the area of Neogene basement fill was still considered important when considering subsurface management issues. Various geo-energy resources, deep geothermal energy, rich thermomineral waters, and conventional and unconventional hydrocarbons occur frequently in these formations and are widely used.

The thick Neogene fill also represents a challenge when applying the SF to the Pre-Cenozoic basement below it. The Pre-Cenozoic extends from surface outcrops to depths of 5 km. At these depths, the SF was heavily reliant on geophysical data, however this data in some parts was patchy and of poor quality. As mentioned by the GSI, areas lacking in data presented themselves for further study.

4.2.2.2 Structural framework related assessment from evaluation board

General Comments

The lack of SF application to the overlying basement fill was a common area of discussion within the evaluation criteria. Other issues discussed involved the uneven distribution of geophysical data and the different and not-harmonised geological nomenclature within the area providing challenges for data harmonisation. Key points are discussed below.

Qualitative evaluation – Structural Framework

The distribution of answers to each question regarding the PB structural framework is shown in Figure 12 below. Evaluation questionnaires are available in Appendix II.

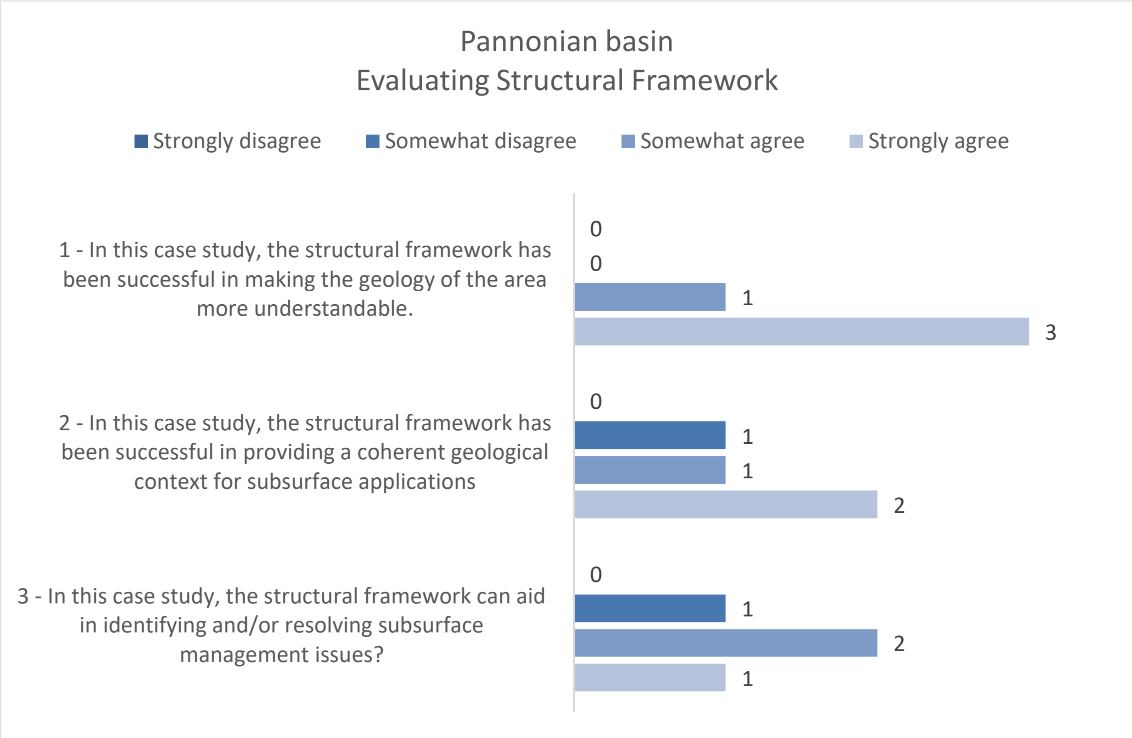

Figure 12 : Results from the evaluation questionnaire: Pannonian Basin, evaluating structural framework

As shown in Figure 12, question 1) shows a convergent pattern with partners either strongly or somewhat agreeing with the statement, demonstrating that within this case study the structural framework has been successful in making the geology of the areas more understandable. GSI have stated: *'The selection of the pre-Cenozoic as the reference horizon allows the deeper geology to be displayed in a clear and understandable way that only a structural framework could achieve.'*

Question 2) demonstrates a slight distribution of answers, ranging from somewhat disagree to strongly agreeing with the statement that structural framework has been successful in providing a coherent geological context for subsurface applications. The CGS somewhat disagreed stating: *'The subsurface applications are mostly related to the basin sediments, so the SF applied to the bedrock can only have a limited role in providing the needed geological context.'*

Question 3) also demonstrates a distribution of answers with answers ranging from somewhat disagree to strongly agreeing with the statement that structural framework can aid in identifying and/or resolving subsurface management issues.

Many comments within the evaluation board also suggest that the lack of SF application to the Neogene basin fill does not provide a coherent geological context for subsurface applications. The CGS stated: *'the subsurface management issues are mostly related to the basin fill while the SF was applied to the bedrock, so the support of the SF itself to identifying and resolving these issues is limited.'*

4.2.3 Geomanifestations

Within the Pannonian Basin, geomanifestations were studied only in three pilot areas and not within the whole project area. A wide range of geomanifestations were identified and are described in detail in Deliverable 4.2 'A joint report on geomanifestations in the Pannonian basin.' (Rman *et al.*, 2021a). There are numerous geomanifestations associated with the thick sedimentary succession of the basin fill and cannot be linked to tectonics directly. geomanifestations were therefore grouped into two categories, geomanifestations with clear structural links; and geomanifestations with indirect links to structural framework.

4.2.4 Geomanifestation Related Technical challenges

4.2.4.1 Lessons learnt by PB team – Geomanifestations

Data availability, quality and present levels of understanding vary enormously among different areas and at depth. Care must be taken when choosing, conjoining and interpreting this information, especially in transboundary areas with different national datasets. Finding original raw data, and subsequent reinterpretation using modern methods is a time consuming task. Availability of deep geophysical data is a problem especially in areas with hydrocarbons exploration and production. These datasets are often confidential and kept by oil and gas companies.

Due to time restraints the SF and geomanifestations were produced in a parallel fashion and largely separately. Both methodologies should be jointly interpreted in order to gain best possible results.

4.2.4.2 Assessment from evaluation board – geomanifestations

General Comments

Similar to a comment made by BGR to the R2R case study, the GSI and CGS believed that the PB study gave the impression that current knowledge and understanding of the subsurface was used to apply the structural framework and interpret geomanifestations. The work focuses on providing a better understanding of both concepts.

Qualitative evaluation – Geomanifestations

The distribution of answers to the evaluation questionnaire regarding the PB geomanifestations is shown in Figure 13 below.

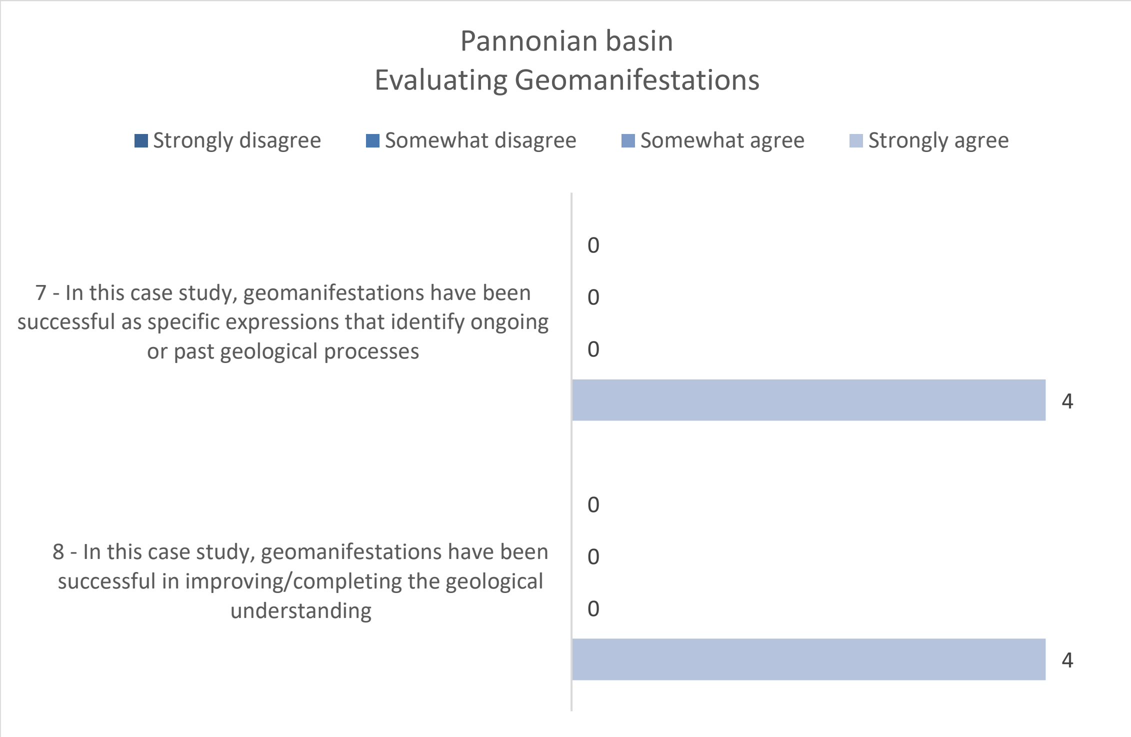

Figure 13 : Results from the evaluation questionnaire: Pannonian Basin, evaluating geomanifestations

As shown within Figure 13, all evaluators found that the geomanifestations were successful as specific expressions that identify ongoing past geological processes and also were successful in improving/completing the geological understanding.

VPO have stated: *'…fundamental processes like convection cells and the numerical modelling of temperature variation with depth could be identified/realized based on the inventory of thermal water occurrences. Also, general water geochemistry data (e.g., in Bosnia and Herzegovina) provide valuable hydrogeological information. The collected Geomanifestations are a great help for predicting geological potential more accurately.'*

4.2.5 Structural framework and geomanifestations integration

General comments

As stated in the lessons learnt report, the methodology enabled the collaboration between a multidisciplinary team of experts, integrating diverse data sets into a big picture scenario. The potential evaluation of subsurface issues within the study area is greatly enhanced, especially when combining the SF with geomanifestations e.g. active fault zones and deep fluid emissions, regional convection in fault zones, etc. The process has highlighted how essential it is to understand the processes and sources of geomanifestations (e.g. faults and reservoirs in the basement rocks), to enable their successful long-term exploitation.

The distribution of answers to questions in the evaluation questionnaire regarding the integration of the structural framework and geomanifestations within the PB project is shown in Figure 14 below.

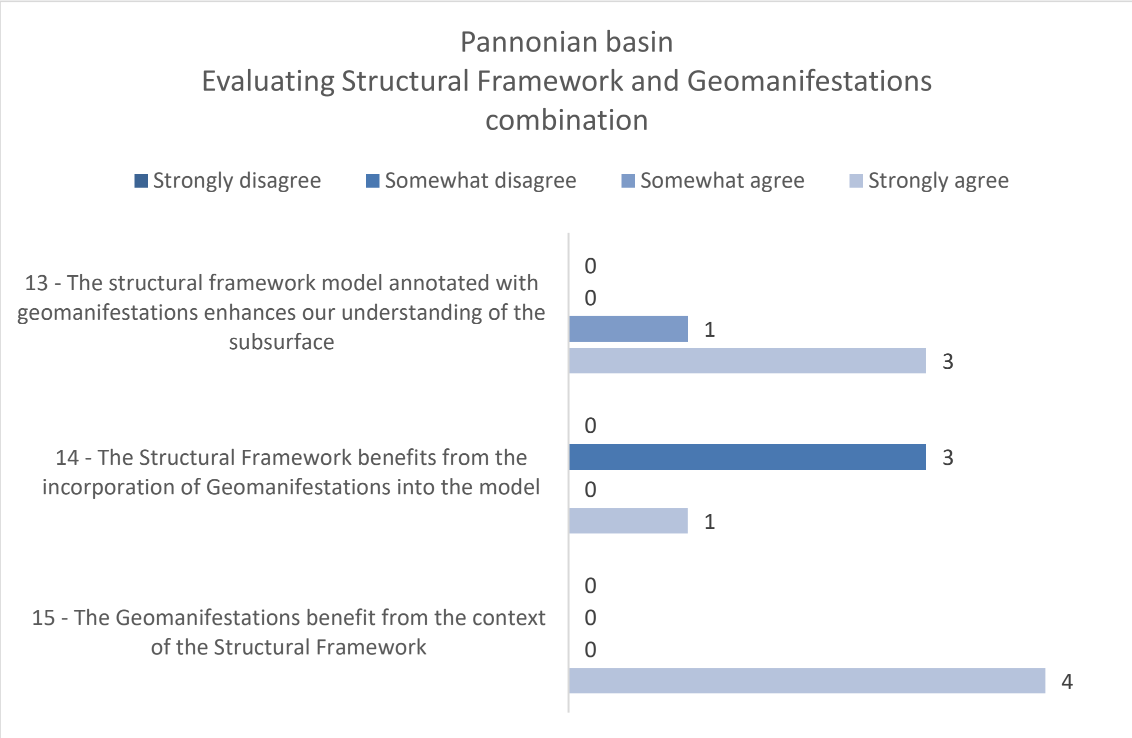

Figure 14 : Results from the evaluation questionnaire: Pannonian Basin, evaluating structural framework and geomanifestaions in combination

As shown in Figure 14, all partners agreed with the statement that the structural framework model annotated with geomanifestations enhances our understanding of the subsurface. The PIG-PIB stated: *'It's clearly stated that only joined SF/GM data revealed clear interconnection of some geological processes (of which most were already assumed, but not so much interpreted in the past), e.g. active fault zones and deep fluid emissions, regional convection in fault zones, etc.'*

The majority of partners disagreed with the statement that the structural framework benefits from the incorporation of geomanifestations into the model (Question 14). The CGS somewhat disagree stating: *'The approach of the authors was rather to explain / interpret* *geomanifestations as "manifestations" of the structural framework. A few examples of benefits that geomanifestations might provide to the SF are indicated but not described in more detail.'*

However, all partners strongly agreed with the statement that the geomanifestations benefit from the context of the Structural Framework (Question 15). VPO stated: *'The Structural Framework is the main aspect that is taken into account for the interpretation of the Geomanifestations. The occurrence of most Geomanifestation types is linked to regional fault zones, although for some of them, the Neogene sedimentary cover (which is not included in the SF) is also of importance.'*

4.2.6 Overall evaluation for Pannonian Basin case study

The overall application of the methodologies was rated by each project partner. Each evaluator gave a rating out of ten, with 10 being positive. Figure 15 shows the result from the evaluation.

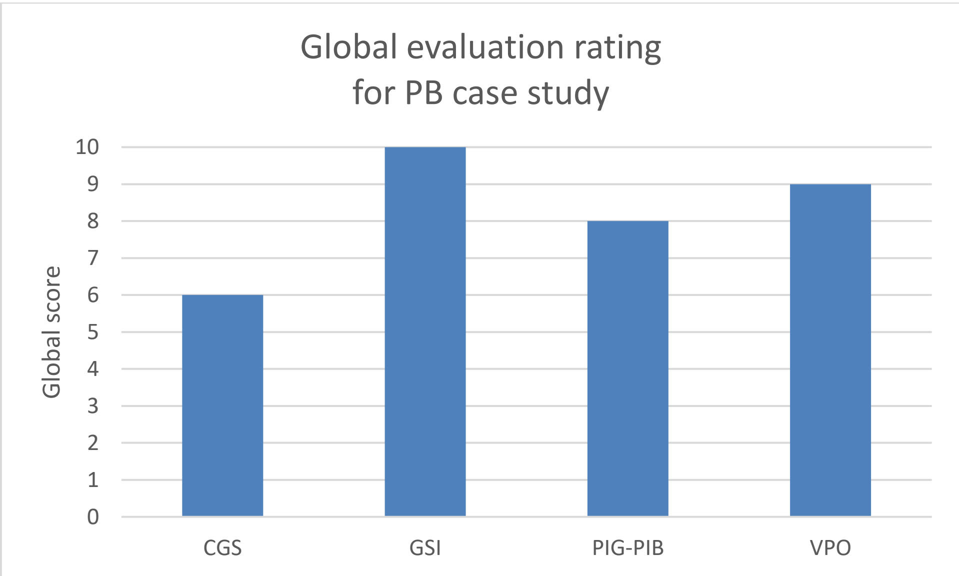

Figure 15 : Results from the evaluation questionnaire: Pannonian Basin, global evaluation ratting

The PB case study was rated positively by all board members with a range of ratings between 6 and 10 and a mean rating of approximately 8.3. Below are some comments from board members:

The GSI, which gave the highest rank, stated: *'I think this area is a great proof of concept for the combination of geomanifestations and SF. This is a good first pass, providing plenty of opportunity for refining the techniques of developing SF and Geomanifestations data bases and for interpreting them.'*

CGS, giving the lowest grade, stated: *'The pilot case study areas were well selected and thus provided a strong case for further development of this approach as a suitable tool for decision-making and subsurface spatial planning. On the other hand, the authors were able to apply the structural framework only to the Pre-Tertiary basement, and not to the basin fill itself. This, in our opinion, represents a significant limitation of application of the methodology to the Pannonian Basin area, and probably also to other areas with similar geology.'*

4.2.7 Directions for future development (Pannonian Basin)

As stated by the authors, in future it is essential to extend the information to 3D, to regionally link the geomanifestations and extent of fault zones to the elevation and geological formation in which they occur or in which they originate.

In this case study, geomanifestations were only inventoried for three sub-areas of the Pannonian Basin. VPO suggest an expansion of the case study towards the whole Pannonian Basin might increase the impact and applicability of the GeoConnect³d databases significantly.

The acquisition of new and good quality data (geophysical data) in relation to the deep subsurface structures would greatly benefit the SF. The GSI stated that the SF relies heavily on geophysics rather than established historical mapping. Communicating a confidence, such as a data density map would enable the user to determine where data is rich, and where further data is required / confidence in accuracy is less.

4.3 Ireland

A detailed description of the application of the Structural Framework and Geomanifestations methodologies on the Irish case study is available in 'Deliverable 5.2b - Lessons learnt from applying the GeoConnected Structural Framework; the Irish case study' (Russell *et al*., 2021). Below is a brief summary of the report with references to evaluations made by the evaluation board. The partners who participated in evaluating the Irish case study included: BRGM, GSS, GeoZs, CGS, PIG-PIB and VPO.

Ireland has a complex geology, created and modified during several tectonic cycles. The geology of Ireland, for resource evaluation can be understood only with an understanding of the characteristics and displacement history of the faults. The large area of coastline surrounding Ireland also offers specific challenges. Ireland, therefore, provides a good test case to validate and refine the methods developed in GeoConnect³d.

4.3.1 Structural Framework

The structural framework in this case can be viewed at 3 different levels with geological detail increasing level by level from: level 1 (1:10M – 1:2M), level 2 (1:2M – 1:500k) and level 3 (>1:500k). The multi-scale nature of the structural framework is potentially a powerful tool for visualising the gross structural character within a geological map together with the detail and complexity of specific features of interest.

4.3.2 Structural Framework Related Technical challenges

4.3.2.1 Structural framework related lessons learnt by Irish team

In the Irish the SF provided a pre–interpreted geological map making it easier to interpret for non-specialists. The structural framework of Ireland simplified the geology picture with focus on Carboniferous reservoirs rocks, neglecting the young quaternary deposits or other "noise" features and show the continuation of the basement units over the island. The SF allows for clear distinction between faulted blocks and conformable or unconformable contacts. Features which are readily apparent from the structural framework, would require careful study of the geology map for a user not familiar with the region. The user also does not need to understand the implications of the lithology descriptions on a traditional geological map.

Constructing the structural framework was a relatively straightforward process; the problems were confined to making the decisions that lead to the construction. Practical issues we encountered when constructing the framework mainly featured the coast line. The different source materials from onshore to offshore were attempting to display different features and unifying these differences into a single limit in the framework was a difficult process. Another practical consideration was that the structural framework could not display folding, and in areas where the geology is controlled by folding this weakness left the framework looking unfinished.

The lessons learnt report also discussed the effect of user created bias during the construction of the SF. Constructing the framework is a reductive process and is an inherently biased view or interpretation of the existing understanding of the geology. The decisions on what to display or leave out of the framework will determine the direction of the bias. This is very common in not only the produced structural frameworks but also with all types of geological mapping. Maps produced are the producer's interpretation of the subsurface environment. The decision from the Irish team to focus on the Carboniferous geology of Ireland has meant that a large proportion of geology has been left out, changing the usability of the SF. As an example, if the Irish team decided that the SF would be to investigate shale gas, the Namurian sedimentary sequences in Ireland would not have been omitted from the framework and instead be the focus of the study. The structural framework is therefore a means of communicating to stakeholders about a specific geological scenario. It is not a library of geological data which a stakeholder will have to interpret themselves. The idea of the SF is that this element of interpretation has been done already by a team of experts. The user will / should be aware that these decisions have been made and why.

4.3.2.2 Structural framework related assessment from evaluation board

General Comments

A common point of discussion from the evaluation questionnaire was that the scale of the structural framework of Ireland is perhaps too coarse for application to subsurface management issues. As discussed in the evaluation board meeting, the scale of the structural framework depends on the type of subsurface management at issue, and the SF would be tailored to fit this specific issue at hand. The question of scale should therefore be determined early in the development of a structural framework, if the specific application of the SF is to resolve a specific subsurface management issue at hand. The issue of scale will therefore again introduce a certain level of producer's bias.

The simplification and removal of 'noise features' also provided a point of discussion. VPO stated: *'Although the omission of a large proportion of faults makes the geology more understandable and visually very strong, it also quite severely hinders the applicability of the SF, both for tackling subsurface management issues, as well as for understanding the processes behind the inventoried Geomanifestations.'*

Qualitative evaluation – Structural Framework

The distribution of answers to each question regarding the Irish structural framework is shown in Figure 16 below. Evaluation questionnaires are available in Appendix III.

As shown in Figure 16, Question 1) shows a convergent pattern with partners either strongly or somewhat agreeing with the statement, demonstrating that within this case study the structural framework has been successful in making the geology of the areas more understandable. The CGS stated: *'Use of the structural framework allows for "simplification of the geological picture" of the country compared with the standard geological map, which can support the understanding of basic geological structure, especially for non-specialists. The level of detail adapted to various zoom levels seems to be very useful in this respect.'*

Question 2) demonstrates a distribution of answers with answers ranging from strongly disagree to somewhat agreeing with the statement that structural framework has been successful in providing a coherent geological context for subsurface applications. The VPO strongly disagree stating: *'A more local SF approach in 3D is recommended to be useful for (site-specific development of) subsurface applications, but other than that, no links between the SF and relevant subsurface applications are mentioned in the report.'*

PIG-PIB somewhat agree stating: *'It is stated that in the whole country scale the SF is too coarse to be useful for subsurface management in case of particular projects. But the idea of SF and the methodology of its building can be useful in bigger scales for particular applications.'*

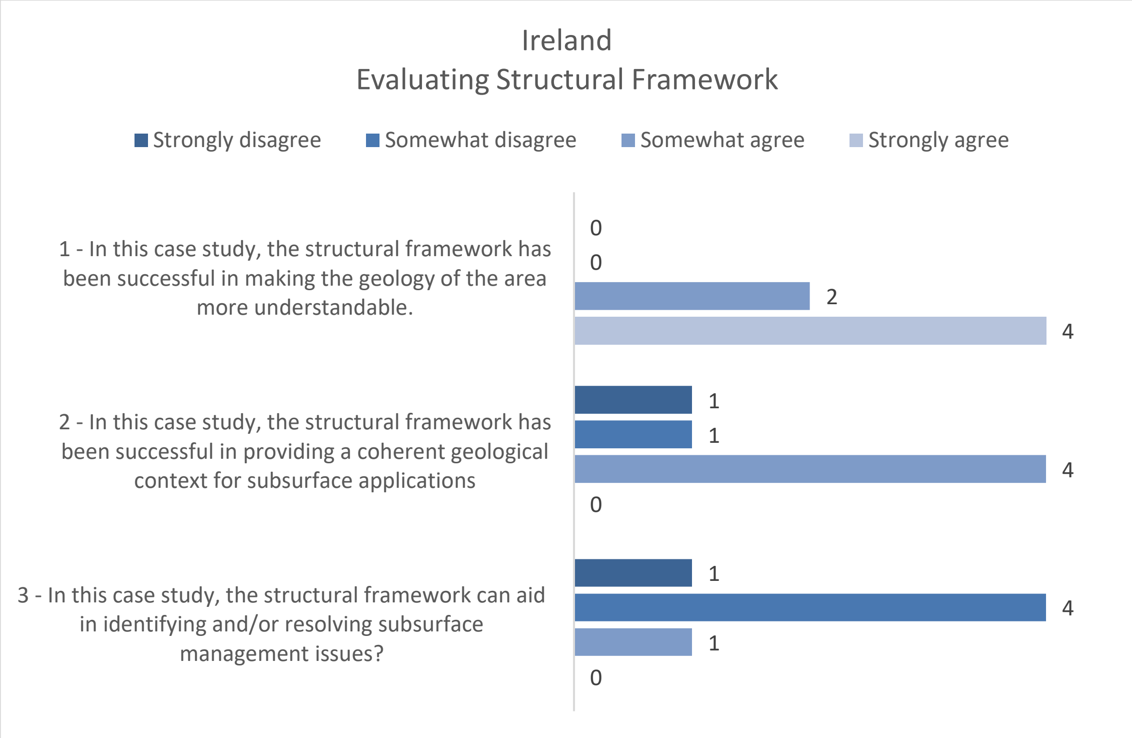

Figure 16 : Results from the evaluation questionnaire: Ireland, evaluating structural framework

Question 3) shows a broader distribution of answers with answers ranging from somewhat disagree to somewhat agreeing with the statement that structural framework can aid in identifying and/or resolving subsurface management issues. Again, the majority of answers here focus on the large scale of the SF being too coarse a tool for subsurface planning applications. VPO stated: *'…Smaller scale SF's (in 3D) would be required to answer specific questions about subsurface management issues.'*

4.3.3 Geomanifestations

The data selected to test the geomanifestations method were already edited, cleaned and stored in databases of Geological Survey Ireland and the Irish National Seismic Network. The geomanifestations selected included: mineral occurrences, karst features, warm springs and earthquake foci.

4.3.4 Geomanifestation Related Technical challenges

4.3.4.1 Lessons learnt by Irish team – Geomanifestations

The bias in the structural framework makes the useful interpretation of geomanifestations more difficult. For example, the structural framework focuses on the basin and shelf features of the Carboniferous and effectively displays the major faults that controlled basin formation, but many later features do not appear. This feature of the framework means that some trends in mineral localities related in time to basin formation, such as Pb-Zn, can be observed, while karst features that may be controlled by later structures do not display a relationship to the structural framework. For a structural framework to offer insight into a geomanifestation dataset it needs to incorporate all features that are, or may be, relevant to a specific geomanifestation and at an appropriate scale. In order for other geomanifestation types such as karst features to display a relationship with the structural framework, first of all the scale of the structural framework would have to be reduced significantly to a basin scale in order to include not only the basin forming faults, but the majority of the faults in the basin as well as fracture networks and join sets. The addition of this detail into the structural framework would allow the user to determine correlation with karst features.

4.3.4.2 Assessment from evaluation board – Geomanifestations

General Comments

In general many evaluation board members considered the lessons learnt report to be lacking a sufficient level of detail when discussing the application of the geomanifestation methodology.

As discussed within the evaluation board meeting, many geomanifestations do not correlate with the Irish SF. During these situations, geomanifestations can be used in order to determine if the SF is lacking in any detail. If certain geomanifestations are not showing any specific relations with the SF, then there may be elements of the SF that are missing. Geomanifestations can be a way of determining the accuracy of the produced SF.

Qualitative evaluation – Geomanifestations

The distribution of answers to questions in the evaluation questionnaire regarding the Irish geomanifestations is shown in Figure 17 below. Both questions show a broad distribution of answers between evaluation members. As mentioned previously, the lack of detail in the lessons learnt report is frequently mentioned by evaluators.

Question 7) demonstrates a broad distribution of answers to the statement that geomanifestations have been successful as specific expressions that identify ongoing past geological processes. CGS stated: *'There are good examples of geomanifestations provided; the description of their relationships to geological processes is, unfortunately, too brief.'*

Question 8) again demonstrates a broad distribution of answers to the statement that geomanifestations have been successful in improving/completing the geological understanding. PIG strongly agree stating: *'Geomanifestations, as they appear, they always add to understanding geology of the area, if not understanding, at least improving the recognition. The same in this case.'*

VPO somewhat disagree stating: *'…The rationale of selecting the respective Geomanifestation types is well explained, but it cannot be deduced from the report if the case study was successful in finding answers on these research questions (e.g., correlation earthquakes – faults – depth).'*

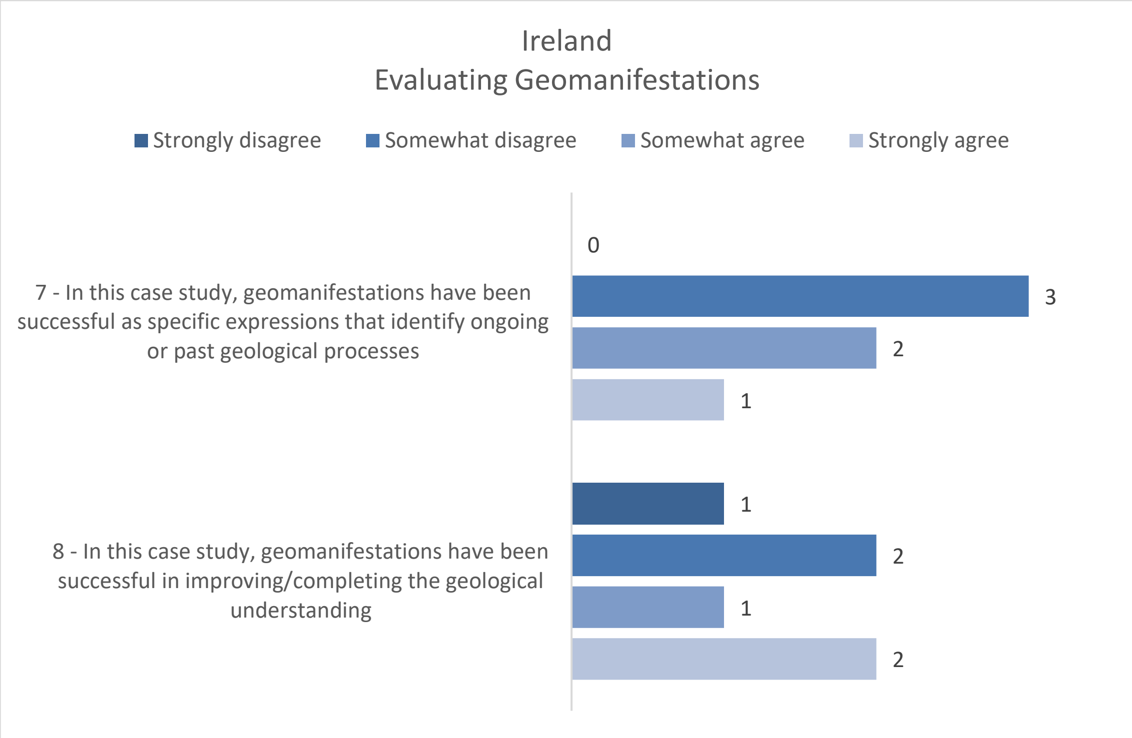

Figure 17 : Results from the evaluation questionnaire: Ireland, evaluating geomanifestations

4.3.5 Structural framework and geomanifestations integration

General comments

A description of the issues associated with the integration of both methodologies is explained in chapter 4.3.4.1 . Due to repetition, it is not thought necessary to add further detail to this section. GeoZs have stated: *'… joint interpretation of SF and GM should be done and clearly explained…. This part was not properly presented.'*

4.3.6 Overall evaluation for Irish pilot study

The overall application of the methodologies have been rated by each evaluation board member. Figure 18 shows the result of the evaluation.

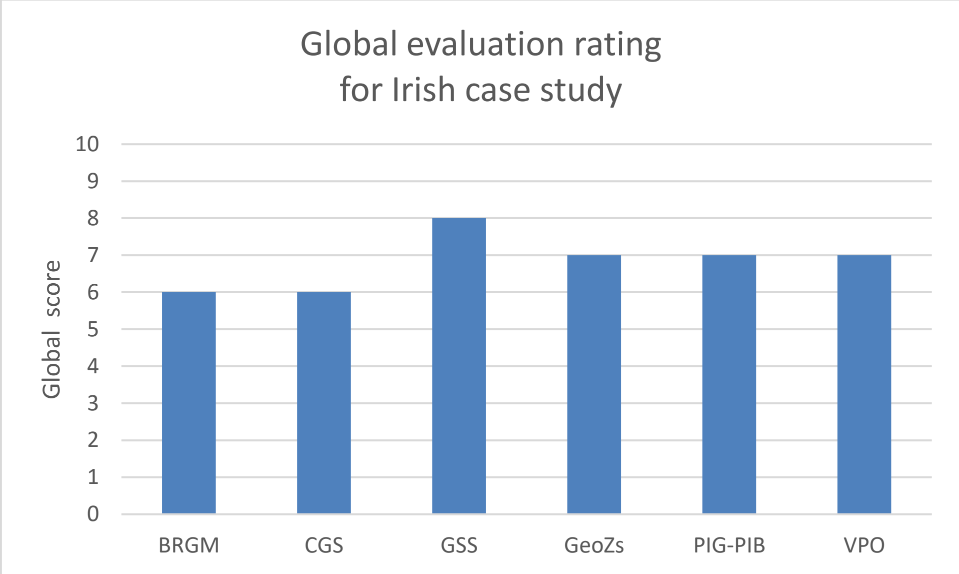

Figure 18 : Results from the evaluation questionnaire: Ireland, global evaluation

As shown in Figure 18, the Irish case study was rated similarly by all board members with a range of ratings between 6 and 8 and a mean rating of approximately 6.8.

PIG-PIB have summarised the application of the methodology: *'The case study showed that on the country scale the SF allows for presentation of main geological features - structures and tectonics which may be relevant for subsurface applications. This can give a general view, but for particular cases there is a need for more detailed resolution to enable decision making based on the SF only. Also connections between SF and GMs are not necessarily straightforward and inclusion of a GM may or may not add on to the whole view. GM need to be chosen with some relation to a particular case - planned activity, and need to be related to the part of subsurface to be directly or indirectly influenced by this activity. If there is no connection/possible influence between GM and subsurface activity, the knowledge of its presence do not add much to the whole view (e.g. karst features in strata overlying a potential reservoir to be used).'*

4.3.7 Directions for future development (Ireland)

To combat the inherent bias in a structural framework, it is recommended that the structural framework method is applied to a specific goal. For example, a structural framework built to interpret karst features of a particular catchment would focus on facies and faults of all sizes, rather than basin forming faults at regional scale.

A national scale structural framework may be too coarse a tool for site specific subsurface planning applications. At a national level, the structural framework will pose and answer questions about the large scale geology, and coarse geomanifestations trends will be apparent.

To answer a specific sub-surface planning question, a series of small scale structural frameworks made using a variety of different decision trees could give a fuller picture to answer specific questions.

4.4 Molasse Basin

A detailed description of the application of the structural framework and geomanifestations methodologies on the Molasse Basin case study is available in 'Deliverable 5.2a - Lessons learnt from Molasse Basin and other realms in Bavaria' (Diepolder, 2021). Below is a brief summary of the report with references to evaluation made by the evaluation board. The partners who participated in evaluating the Molasse Basin case study included: BGR, BRGM, GSS, GeoZs, GSI, CGS, PIG-PIB and VPO.

The Molasse Basin**,** also called the North Alpine Foreland Basin, developed along the northern margins of the emerging Alpine orogeny. As a result of the Alpine thrust, the footwall of the Molasse Basin dips southward to depths of more than 5,500 m. Due to this significant depth, and despite having just an average geothermal gradient, certain parts of the Austro-German Molasse Basin bear more than 30 examples of the successful utilization of geothermal energy (up to 150°C) from low enthalpy, karstified and faulted limestone systems. Recent development setbacks clearly show that the entire system is not fully understood yet and the role of the fault network has been substantially underrated.

The methodologies concepts have been applied in two areas of different geological settings in Bavaria: the Molasse Basin and the exposed Variscan basement of Saxothuringian Zone, west of the Franconian Line.

4.4.1 Structural Framework

The adoption of the structural framework is based on the present knowledge of the tectonic structures and their relationship with respect to the different tectonic phases. Mapped in various scales or inferred from indirect evidence, the SF compilation does not strive for giving a full inventory of tectonic features but aims at stressing the contextual relationship of the fault network and its relation to the geological units.

4.4.2 Structural Framework Related Technical Challenges

4.4.2.1 Structural framework related lessons learnt by the Molasse Basin team

Tectonic features within the Molasse Basin are hidden under a thick succession of young sedimentary sequences. The tectonic features are therefore difficult to trace and detect from surface exploration techniques. The exploration of the deep subsurface has however been driven by hydrocarbon and geothermal exploration and is considered well explored compared to the younger shallow overlying sediments.

4.4.2.2 Structural framework related assessment from evaluation board

General Comments

General comments related to the technical challenges of the structural framework largely involve the issues associated with the availability and consistency of input data. PIG stated that scattered data on detailed recognition focusing on hydrocarbons prospection and geothermal project areas is one of the main issues within the project. Many partners also discuss the problems related to the thick sedimentary deposit overlying the framework, as mentioned above.

Qualitative evaluation – Structural Framework

The distribution of answers to each question regarding the Molasse Basin structural framework is shown in Figure 19 below. Evaluation questionnaires are available in Appendix IV.

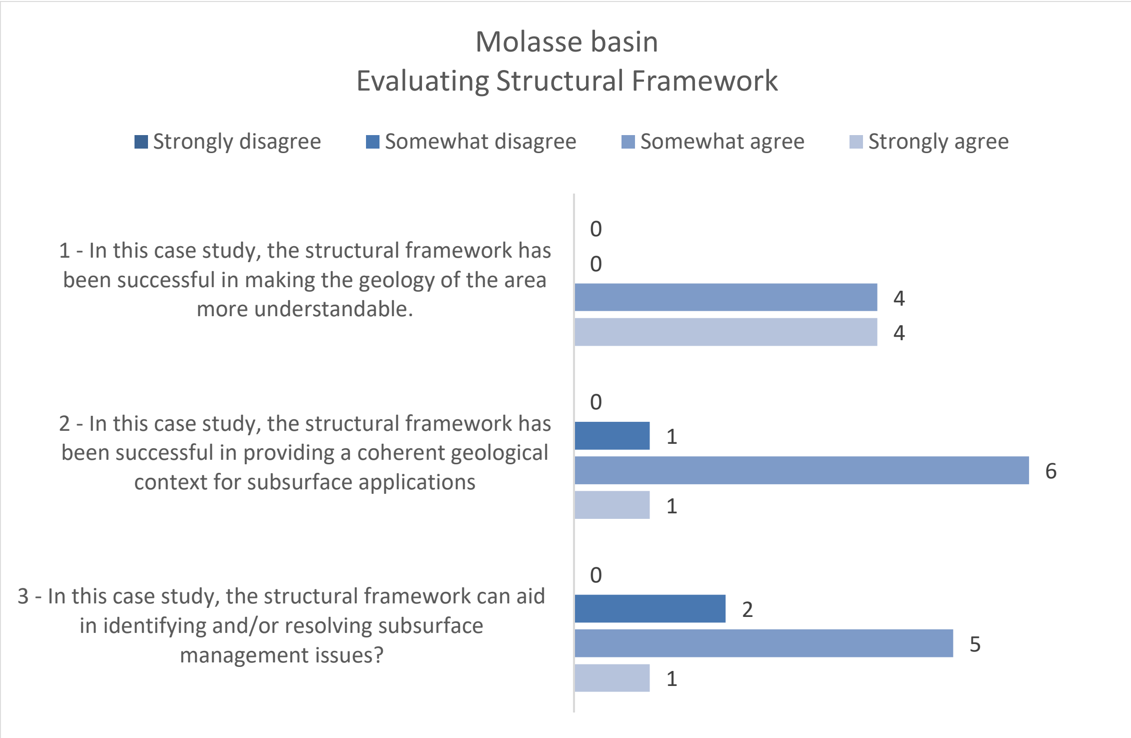

Figure 19 : Results from the evaluation questionnaire: Molasse Basin, evaluating structural framework

As shown in Figure 19, Question 1) shows a convergent pattern with partners either strongly or somewhat agreeing with the statement, demonstrating that within this case study the structural framework has been successful in making the geology of the areas more understandable. The GSI stated: '*The structural framework in this area streamlines the geology, synthesizing many years of interpretation into a high level overview of the geological domains.'*

The majority of partners somewhat agreed with the statement that structural framework has been successful in providing a coherent geological context for subsurface applications (Question 2). BRGM stated: *'The structural framework identifies large scale fault systems and* *demonstrates their relationship to the geological units in Bavaria. These fault systems make up an important compartmentation of prospective reservoirs, potentially highlighting areas of potential subsurface development.'*

Question 3) demonstrates a broader distribution of answers ranging from somewhat disagree to strongly agreeing with the statement that structural framework can aid in identifying and/or resolving subsurface management issues.

4.4.3 Geomanifestation Related Technical challenges

4.4.3.1 Lessons learnt by the Molasse Basin team – Geomanifestations

General Comments

The most obvious issue related to the application of the geomanifestations methodology is that the Molasse Basin is almost completely bare of geomanifestations which can be directly related to the structural framework. Virtually all geomanifestations observable in the Molasse Basin are the result of glacial and inter-/post-glacial processes sculpting the landscape. The second study area in North East Bavaria has a dense area of geomanifestations which can be interpreted to be directly related to the fault system. This area was therefore considered appropriate to test the geomanifestation methodology.

4.4.3.2 Assessment from evaluation board – Geomanifestations

General Comments

As discussed above, the deep sediment fill made it very difficult to interpret the deep seated geomanifestations. This was generally regarded to be the main issue related to the application of the methodology within the study. The BGR stated that before the method is applied on a large scale in a time-intensive manner, predictions of success for the analyses of specific geomanifestations should be made on the basis of exemplary small-scale studies.

Qualitative evaluation – Geomanifestations

The distribution of answers to questions in the evaluation questionnaire regarding the Molasse Basin geomanifestations is shown in Figure 20 below.

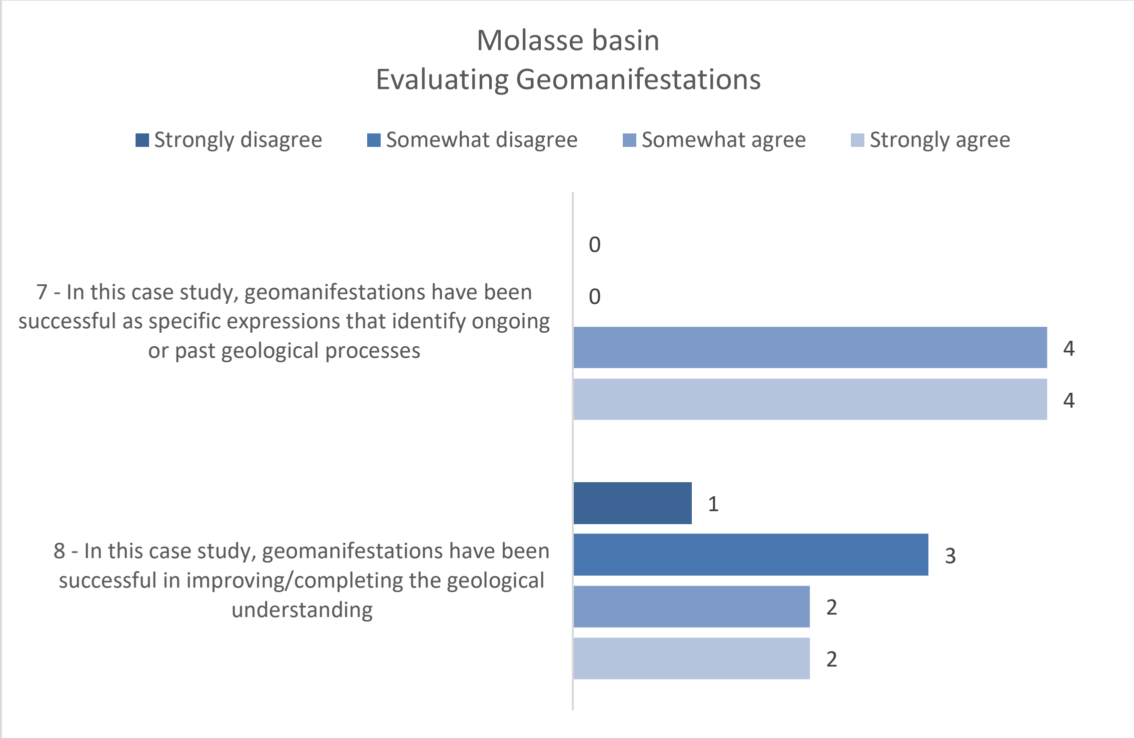

Figure 20 : Results from the evaluation questionnaire: Molasse Basin, evaluating geomanifestations

As shown in Figure 20, all the evaluators either strongly or somewhat agreed with the statement, that geomanifestations have been successful as specific expressions that identify ongoing past geological processes (Question 7).

Question 8) demonstrates a broader distribution of answers with the statement that geomanifestations have been successful in improving/completing the geological understanding. BGR somewhat disagree stating: *'As the authors also noted, the structural patterns were already sufficiently known and the here presented geomanifestations should be seen more as additional confirmations of certain structures in the subsurface.'*

4.4.4 Structural framework and geomanifestations integration

4.4.4.1 Lessons learnt by the Molasse Basin team

General comments

When trying to link geomanifestations with the structural framework. The thick sedimentary fill of the Molasse basin has masked the tectonic features of the basin meaning there are no direct conduits for fluid circulation to take place within the sediment overburden. Geomanifestations can therefore not be related to the structural framework at depth or at the surface. The methodology was therefore considered unfeasible and unsuitable for geological areas of this type.

4.4.4.2 Assessment from evaluation board – Geomanifestations

Many cases have discussed the use of geomanifestations in order to further our knowledge of the structural framework within the subsurface. Due to the complexities associated with the deep basin fill, none of these geomanifestations can be traced from surface exploration. Therefore in the case of the Molasse basin, the knowledge of the structural framework, (initially based solely on conceptual models of the basin evolution) has been used to detect geomanifestations related to the structural framework. The confirmation / localization of a geomanifestation thus is more retrocognition and proof of the conceptual model applied.

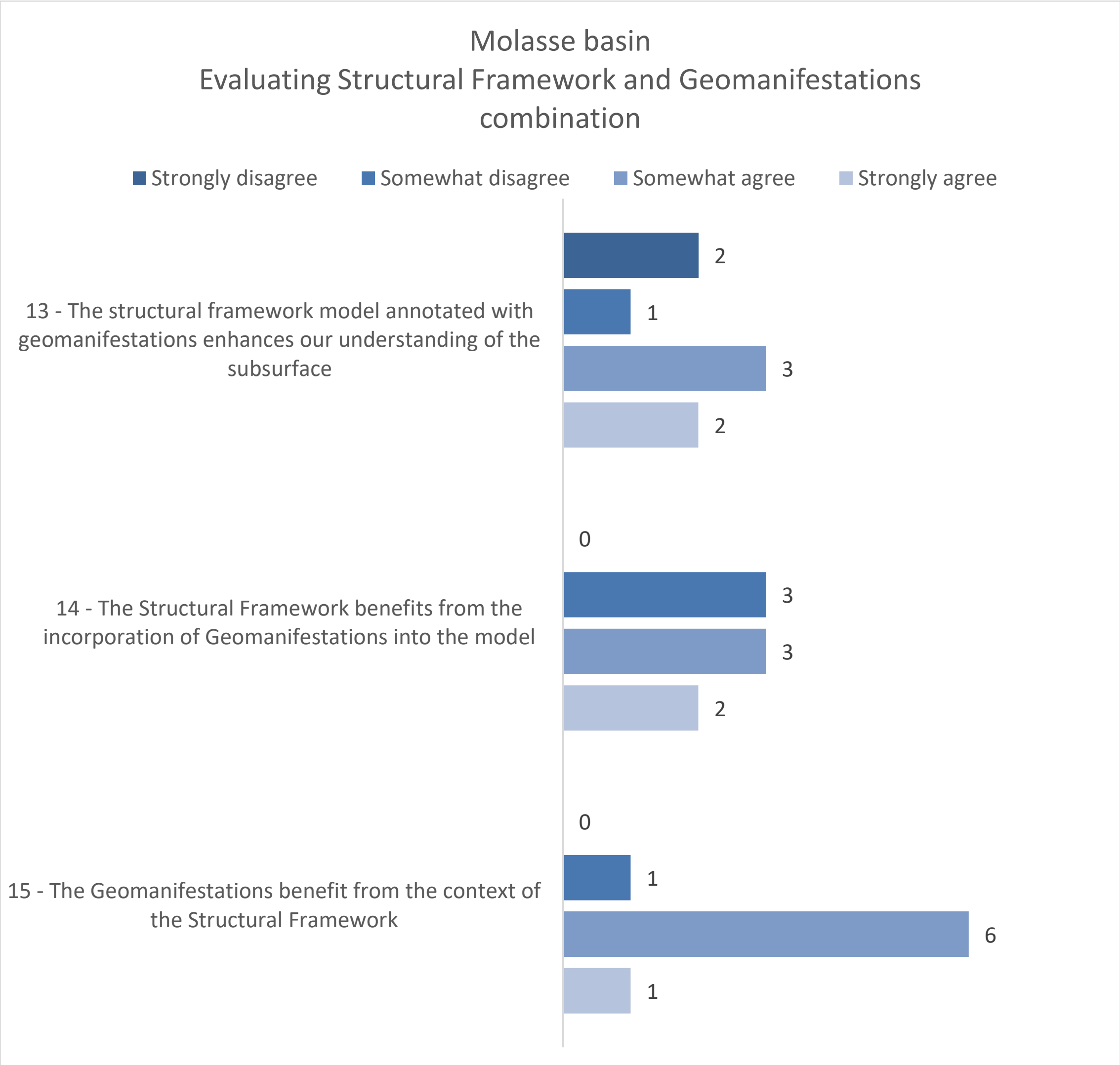

Figure 21 : Results from the evaluation questionnaire: Molasse Basin, evaluating structural framework and geomanifestations in combination

The distribution of answers to within the evaluation questionnaire regarding the integration of the structural framework and geomanifestations within the Molasse Basin case study is shown in Figure 21.

Question 13) demonstrates a highly divergent pattern among partners. The GSI strongly disagreed with the statement that the structural framework model annotated with geomanifestations enhances our understanding of the subsurface: *'The information provided by both geomanifestations and the structural framework improve the ability to communicate the current understanding of the subsurface, rather than improving the understanding itself.'* On the contrary, VPO strongly agreed, stating: *'The combination of the SF and the geomanifestations database certainly improves the understanding of the Bavarian subsurface, both in terms of the location of faults and their permeability.'*

Question 14) also demonstrates a divergent pattern among partners. VPO somewhat agree stating: *'The geomanifestations, though limited, can help to revise and evidence the conceptual tectonic framework, and improve the understanding of past or on-going kinematic processes (e.g., seismicity along the Tachov Fault Zone).'*

Answering Question 15), the majority of partners somewhat agreed with the statement that the geomanifestations benefit from the context of the Structural Framework.

4.4.5 Overall evaluation for Molasse Basin pilot study

The overall application of the methodologies have been rated by each project partner. Figure 22 shows the result from the evaluation. Each evaluator gave a rating out of ten, with 10 being positive.

As shown in Figure 22, the Molasse Basin case study was rated between 4 and 9 with a mean rating of approximately 6.9. Below are some comments from board members:

PIG have stated: *'The SF presented in the case study was prepared based on the existing maps, interpretations and harmonization already done in the past (at least it seems to be like this). No discussion on aggregation criteria is presented (but maybe not needed). Neither the way how to use it in planning and management procedures is suggested. The scope of GMs that had been identified in order to add something to Molasse basin geological knowledge in our opinion was too scarce, but maybe there is nothing else indeed (we have not got sufficient knowledge to judge)…'*

The Czech Geological Survey stated: *'We agree with the author that combining the Structural Framework and Geomanifestations can be a powerful tool for revision and evidencing the conceptual geological framework and the tectonic history of the area. This apparently works specifically well in areas where crystalline bedrock is exposed or covered by a thin overburden only. However, the methodology seems to be struggling in domains where the bedrock is buried under thick strata of overburden. The study successfully tested applicability of methods and* *approaches developed in WP3 and WP4 on a pilot study, even though the Bavaria case study cannot be considered "smaller-scale", and obviously required a lot of effort…'*

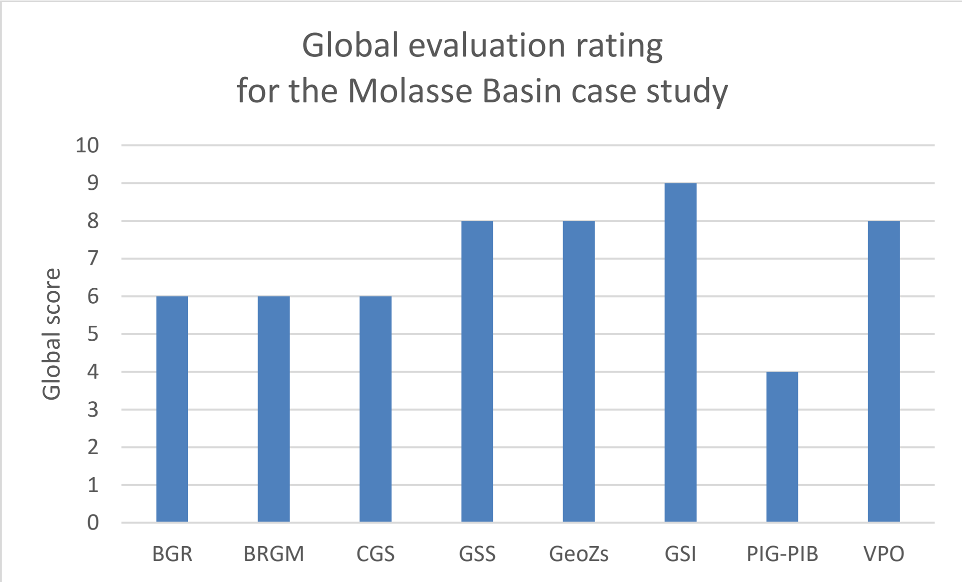

Figure 22 : Results from the evaluation questionnaire: Molasse Basin, global evaluation

4.4.6 Directions for future development (Molasse Basin)

Future work for the Molasse basin recommended in the evaluation questionnaires focus on the further refinement and detail applied to the structural framework.

VPO stated: '*Maybe it would be worthwhile to include the recent sedimentary cover in a bit more detail in the SF...'*

GSI stated: 'I think the structural framework units could be further refined, the Central Foreland Molasse Basin, for example, is presented here as a very large homogenous unit.'

GeoZs stated: *'SF for the Molasse Basin and NE Bavaria is in general well explained both scientifically and practically. However, more detailed structural frameworks (SFs) for particularly interesting areas and sites would be highly appreciated in the future.'*

5 DISCUSSION AND CONCLUSIONS

The GeoConnect³d project has developed and applied a new methodology on four locations, by four different groups. This allows for a relative thorough evaluation of the usefulness of different aspects, as well as the level of maturity of those methodologies through internal assessment.

The level of ambition was high, in that in just over 3 years' time a methodology was developed for setting up a structural framework, combining it with the new concept of geomanifestations, and ultimately applying those for subsurface management issues.

To understand the different evaluation results, it is important to realise that the four different case and pilot studies strongly differ in geological setting, complexity of the team, level of financing, and use of the subsurface.

A final element to take into account is that the results of the different case studies were at the time of evaluation, not yet available on the digital platform. Evaluation was done based on the reports provided, and on GIS packages provided, but without providing full functionality. Thus, the GeoConnect3d project highlights the need for close collaboration between the technical group taking care of the implementation, and the content and methodological research groups. This aspect is taken into account in the CSA projects currently in development.

5.1 Added value of structural framework

Most of the evaluators have a thorough background in geology, but were not familiar with the specific geology of the areas they evaluated. In that sense, the SF seems to be (very) successful in understandably summarizing the geology of each of the study areas, as can be learned from the systematically positive scores provided for question '*…, the structural framework has been successful in making the geology of the area more understandable'*. The most positive clarifying remarks specifically indicated the SF as the tool of choice to display geology in a clear and understandable way, showing the clear benefits compared to traditional approaches.

Comments that were made in this context, is that only part of the geology was shown, which is actually the case for three of the study areas (PB, Ireland, Bavaria). This was each time by design for possibly valid reasons (timing, application…), and the SF does indeed allow to single out part of geology for thematic or other reasons. The repeated remarks from different evaluators do indicate that one must be careful to do so, especially towards an expert audience that expect a full and coherent geological context instead of limited preselected insight.

What the evaluators effectively suggest for these areas, is to stack information of deeper and shallower geology such as basement and basin fill. This is indeed possible in a structural framework and has been foreseen by introducing 'reference surfaces' that vertically position and group limits and units. This is available in the final online product, and allows the user to turn different reference surfaces on or off, and inspect how geology changes with depth, and even how fault traces change. However, at this stage, the evaluators were not able to use a portal where this was already included.

The need for integration of true 3D models is mentioned several times, somewhat contrary to the relatively widespread perception that 3D models by themselves are too complex to be useful for wider audiences. Possibly this is because of the expert-level of evaluators. In any case, GeoConnect³d did start out with the ambition to see a seamless integration of 3D models in the 2D framework, but had to accept the technical limitations for actually realising this.

5.2 Added value of geomanifestations

The use of geomanifestations as additional data was evaluated in two perspectives: (1) do they add information on geological processes, and (2) do they improve or complete the geological understanding. The results here differ for both questions, and especially for the different areas.

For the larger case studies, evaluation is positive, and even unanimously very positive for PB. Both smaller pilot studies show mixed to even negative evaluations. Overall, geomanifestations were better appreciated to demonstrate geological processes, rather than complement geological understanding.

Interpreting the explanations left by the evaluators, this seems to go back to the design stages of the project. The concept of geomanifestations was from the beginning central to the larger case studies, and some work went into brainstorming on which of those would be useful to include. The interest of the pilot studies was more on implementing the SF, and GMs were added rather as an experimental afterthought. Several of the expert comments, both of the evaluators and the involved researchers, reflect this and stress that GMs must be more than an additional arbitrary data layer. They must be chosen in context of the regional geology and the processes want to be highlighted. It also should not be assumed that plotting geomanifestations will automatically result in self-evident conclusions, some discussion is needed. The portal tries to accommodate for this with hierarchically organised and fact sheets linked to the GIS environment, but since the portal was not operational, it is unclear if this solution meets the user expectations.

Some evaluators, possibly depending on their specific background and regional familiarity, did consider certain examples of geomanifestations as illustrations of established knowledge, rather than leading to new insights. Even if subjective, this is an important distinction, with the first linking more to using GMs for communication and the second for actually deepening insight.

A fundamental issue linking directly to the areas chosen as well as the generic use of geomanifestations, is that certain or even all expressions can simply be absent from certain areas because deeper processes do not reach the surface to leave any indications. This may not always be initially clear, as is shown by some examples of mapping out geomanifestations that are typically ignored, and it was suggested that larger studies where effort to collect data are significant, should start out with smaller trial areas. In that case, care has to be taken because some of the test areas show that relatively subtle differences in geological context, including the obvious depth to bedrock, can determine the usefulness or even presence of certain geomanifestations.

This brings us to a next issue of potential, possibly even likely bias in geomanifestations. This can be due to geological, geographical or other causes. In cross-border situations or when relying on historical records, this includes availability of information or differences in the way data is collected, classified or summarized. Especially when relying on literature and other existing data, finding the right balance between using only harmonizable data, or using the maximum amount of data available, is difficult, and can certainly be optimised based on the experience gained.

5.3 Combining structural framework & geomanifestations

Two elements were specifically identified by the evaluators as elements not or not fully exploited in the current study. Firstly, all studies mainly look at patterns of a specific type of geomanifestation, even when several were collected. Clearly, the path of studying the relation between different geomanifestations is worth exploring, as this can e.g. bring insights to which degree underlying processes are linked.

Secondly, given the broad perspective of geomanifestations, researchers with very different specialisations can be brought together in joint research, enabling the collaboration and formulation of ideas. It is suggested that setting up such joint platform has a huge potential for future projects, especially when based on, or combined with a SF to further expand the expert portfolio, as well as more closely link the process related geomanifestation studies.

This does bear the question of how SF and GM mutually have been supportive in the four different test cases. Combining both in one application was found to improve the overall product for the larger case studies, but opinions were mixed regarding the smaller pilots. This seems to be due to the added value of the geomanifestations that was evaluated similarly.

More specifically, it was asked if including geomanifestations improved the presentation or comprehensibility of the structural framework. Interestingly, this was only found to be true for the R2R area, with an on average neutral or negative opinion for the other areas, including the PB. This is at first surprising, because the geomanifestations by themselves were considered to be of very high value. The lesson here seems to be that, as has already been remarked, the geomanifestations must be well chosen and matched to the geological context of the structural framework. For the PB, the basin fill was not visualised in the structural framework, which was felt to be the missing link between the basement and the geomanifestations. For Ireland, similar issues arose, and in addition also the level of detail of the SF that was considered too low with respect to the GMs shown.

The mirror question of whether the structural framework was beneficial context for geomanifestations was, in contrast, answered very positive for the PB. This shows that the two can be combined in a very useful way, but it needs to be considered what the exact purpose is. In this case, the SF of the PB basement seems to clearly and satisfactorily gain in meaning when graphically combining with the geomanifestations. Understanding this in the planning phase clearly requires reflecting on these subtleties.

5.4 Addressing subsurface management

The farthest reaching ambition was to apply the new methods, and in particular the SF, to the topic of subsurface management. The evaluation was split in two parts: does the SF provide the geological context for subsurface applications, which refers to SF as a communication tool, and does it help in identifying or resolving subsurface issues, which is using the SF for actual subsurface management. Although the evaluators were on average positive on both questions, it was mostly found that this part was insufficiently developed by both the case and pilot studies. In general, all of the issues identified above have a bearing on this outcome and were often repeated by the evaluators. This includes the appropriate level of SF detail for certain applications or issues, the need to include all relevant parts of geology, and also to more clearly position and address the potential or actual subsurface applications in the SF. This seems to indicate that, even if the SF has been successfully developed and applied, none of the test areas reached the stage where it could be successfully demonstrated as a subsurface management tool. Looking at the different comments left by both authors and evaluators, this is not a fundamental shortcoming, but rather something that has proven not to be achievable within the time and funding frame of the project.

Looking beyond this, one remark considered if the combined SF-GM approach would ultimately allow users to draw their own conclusions, and how this conclusions would differ based on the expert level of the user. This is an important consideration, and the project’s standpoint has been (and remains) that the goal in this respect is to present geological information in such a way and with the right level of context and interpretation so that it becomes less abstract, allowing to address and discuss subsurface issues with a larger group, but one in which experts are always present.

5.5 Additional lessons

Some additional advice that can be added to the lessons learned, regards increasing the detail of the uncertainties for elements of the SF, and especially when developing a SF with multiple teams, to define the vocabulary more up-front to come to a better and more uniformly organised hierarchical structure. Regarding the latter, a lesson not explicitly mentioned is that building a first vocabulary is a very iterative exercise and experience seems to be key in order to come to a stable hierarchy early on in the project, with clear guidance to all partners involved to come to a uniform final product. The project did certainly bring to the fore several experts that could take up a leading role.

5.6 Conclusion

The overall scoring of the evaluators is interesting, as they seem to be influenced by different personal expectations. The motivation of lower marks in particular are useful to take into account in the future, and quite aptly summarize some of the major concerns. The Pannonian Basin mostly lost points because of not including the full geology in the structural framework. Ireland systematically lost points on not providing the right scales to link the SF to geological applications, or to the geomanifestations, and also the Molasse Basin suffered from similar considerations. For R2R possibly the lack in uniformity both for the SF and for the GMs could be the main point to improve.

Most important is that none of the evaluators or authors identified fundamental issues from the application of the methodologies in four very different areas by different teams. All comments can be addressed, and used as lessons to improve the content of further work. The methodological approach was found not only to be useful, but often superior to the current ways of working, and hold significant but as yet unexplored potential.

6 RECOMMENDATIONS

The central goal of GeoConnect³d was to build new methodologies, combine them into a new approach, and try them out, because it was strongly felt that the classical ways to bring geology to the tables where subsurface management issues were discussed had reached their limits. Based on analysed evaluations, this goal clearly has been reached, with the central and complementary elements of this approach, the SF and GMs, being recognised as useful and promising. This view is backed by the results collected during the stakeholders workshops.

The important missing step, is to realize much clearer and practical demonstrations with respect to actual subsurface management and related decision making. This should be the central goal of any follow up work, as it would provide the final proof of concept.

Several technical recommendations to strongly consider, many of these beyond the technical or financial possibilities of the GeoERA context, include the inclusion of actual 3D, dimension of time, expanding the geological scope of the SF and the geographic scope of GMs, and combine it with additional products such as data density maps.

Success also lies in careful planning, especially since the approach can be seen as a combination of superficially interesting datasets or unrelated project ideas. This refers to the geological scope of the SF, in relation to the GMs to be used, as well of the scale and level of detail that should match, especially, with a-priori well defined research or subsurface management questions.

Harmonisation and obtaining uniform datasets and data distribution is always a central topic, as also came forward from the stakeholder consultation, and deserves the traditional attention for GMs. Due to the specific properties of the SF, attention here needs to focus on the early stabilisation of the main hierarchical vocabularies, which is most reliably done by involving experienced people. Cooperation guided by the SF has proved to work very well where the mindset for collaboration between teams was present. Stakeholders have emphasized the need for international standardisation when addressing subsurface management, which provides an additional related goal for future development.

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8 APPENDICES

Appendix I: Evaluation Questionnaires for Roer-to-Rhine case study

Appendix II: Evaluation Questionnaires for Pannonian Basin case study

Appendix III: Evaluation Questionnaires for Ireland pilot case

Appendix IV: Evaluation Questionnaires for Molasse Basin pilot case