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The “Hexagon concept”: A fundamental approach for the Geoscientific Spatial Data Compilation and Analysis at European Scale to Define the Geothermal Potential of Variscan and Pre-Variscan low- to high-grade Metamorphic and Intrusive Rocks

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ABSTRACT

Growing interest in the deep geothermal potential of regions outside the classical target zones in Europe comes along with an increased demand for geoscientific spatial data (geodata) on various scales and resolutions to estimate the theoretical and technical geothermal potential of feasible sites. A large number of this data is already provided by European National Research Institutions and Geological Surveys as well as by other European institutions and associations. Furthermore, a rising amount of data and expert knowledge concerning relevant parameters at local scale is been constantly collected within ongoing EGS (Enhanced Geothermal Systems) projects, which have begun on several geotectonic zones.

Nevertheless, most potential maps, platforms, web services, geothermal viewers and parameter databases are mainly adjusted to the needs of high to medium enthalpy targets in volcanic and sedimentary rocks. Yet, investigations which focus on the research and development of medium to low enthalpy unconventional, enhanced geothermal reservoirs are in the need of data about quite different rock types and deeper horizons. Beside the high relevance of existing and planned surface infrastructure, the geothermal potential is mainly determined by subsurface parameters such as rock properties, tectonic and structural features, heat flow and deep groundwater or brines.

A main objective of the European project MEET (Multidisciplinary and multi-context demonstration of EGS exploration and exploitation Techniques and potentials) is to promote the dissemination of small-scale EGS power and/or heat plants by mapping the most promising sites based on relevant surface and subsurface geodata. In the study presented, a review on successful, ongoing and abandoned geothermal projects as well as on different data sources, platforms and formats concerning scientific geodata on various scales is performed. Accordingly, different geotectonic zones comprising low to high-grade metamorphic and/or intrusive rocks with or without younger sedimentary cover in Europe are analyzed to identify, deduce and classify sub zones of certain lithology, structural style and anisotropy in regard to their geothermal potential. The resulting large-scale maps and geodata catalog constitute an important aspect of the MEET geothermal potential mapping approach.

1. INTRODUCTION

The present study is one particular research aspect of the MEET project “Multidisciplinary and multi-context demonstration of EGS exploration and exploitation Techniques and potentials”, funded by the European Horizon 2020 program. The main objective of the project is to boost the realization of low to medium enthalpy geothermal projects all over Europe (Trullenque et al. 2018).

Since May 2018 the 16 involved partners have been investigating optimization strategies for existing geothermal plants, studying and developing green heat- and power-extraction technologies for the conversion of unproductive or abandoned oil & gas wells and exploring unconventional target regions outside high enthalpy zones. In the course of this, the research is focused on Variscan and pre-Variscan metasediments and metavolcanics as well as on granitic and other crystalline rocks also considering EGS-technologies to increase insufficient reservoir permeabilities. These research activities are performed at several demonstration sites and at nearby or distant analogue sites at a local scale. Their outcomes are upscaled and transferred to larger regions and scales to point out similar areas and to find future prospective potential sites in Europe.

In general, the successful realization of a geothermal project in terms of economics and sustainability has to be fed by various disciplines as it is a complex, long-lasting process with several steps. In addition, it has to combine – in contrast to projects dealing with all other forms of renewable energy - surface and subsurface elements. Therefore, a wide range of spatial and non-spatial parameters have to be taken into account.

In the geothermal community and related disciplines, a large amount of this data is available. On local scale, a lot of data is published both as result of site-specific investigations (Parker 1999, Genter et al. 2009) and as summary in review papers (Sass & Götz 2012, Breede et al. 2013, Limberger et al. 2014, Limberger et al. 2018, Schaming et al. 2016, Vidal & Genter, 2018, Reinecker et al. 2019). On larger scales, maps, viewers, data platforms, databases and other information systems offering spatial and non-spatial data of various topics related to geothermal research and associated disciplines and of regional to European scale (ThermoMap, GeoElec, GeoDHEurope, OneGeology) are available. Furthermore, several projects of the EuroGeoSurvey, the GeoEra and the ETIP-DG are dealing with data provision and interlinked challenging questions like data homogenization and standardization (Günther, 2019).

In contrast, spatial and non-spatial data are or were generated, collected or treated within projects of different thematic background, disparate research focus and various approaches. The outcomes are not just diverse in scale, resolution, coverage and completeness, but also in the way of representation, provision, confidentiality and due to the involved disciplines, they might be heterogeneous in the technical language. Therefore, it might be challenging for project teams which will be involved in future geothermal projects to collect in time and at realistic costs an adequate set of complete, reliable and qualitative data. Another obstacle might be the comparison and weighting of the data in terms of quality and relevance, especially if metadata is missing or teams are unfamiliar with the terminology and workflows of geothermal projects. To make it even more difficult, the stakeholder interest and focus might change during the project lifetime.

To support future exploration and exploitation activities all over Europe, within MEET a Decision-making tool (Raos et al. 2019) implementing spatial and non-spatial data is developed and a catalogue of relevant geospatial datasets and their availability is compiled. Moreover, GIS-based analyses are performed to elaborate an updated geothermal potential map of Europe as well as a web-based tool combining those surface and subsurface geospatial data that already exist online. Regarding the data catalogue, the potential map and the web-based tool, these main questions will be answered:

- Which geospatial data-sets have to be the basis of an updated geothermal potential map of Europe and an optimized web-based tool to fulfil the needs of future exploration projects focusing on unconventional sites?
- Which medium- to large-scale geospatial data-sets are available up to now?
- How accessible are the available data?
- How could missing geospatial data-sets be created and implemented in the future?
- What would be an appropriate way to combine, provide and visualize the various geospatial data-sets?

To overcome as much as possible of the abovementioned obstacles and to develop a more holistic approach, the first step of the analysis of the geospatial data is a comprehensive review to understand the complex system of a geothermal project in Variscan and pre-Variscan rocks. The elaborated concept presented in this study will be the mutual base for all following steps and all intended outcomes associated with geospatial data-sets. It will give an overview about a geothermal project and will allow deeper insights in it. The logical but simple scheme will be useful for dealing with various and heterogeneous geospatial data in terms of sorting, classification and weighting and it will be beneficial for comparing existing data representations and data sources.

2. METHODS

Beside analogue and digital literature, websites, web-portals, online-databases and web-viewers, the main input for the proposed concepts are talks with researchers, on-site visits of drill-sites and geothermal plants, MEET internal work-package meetings and general assembly’s as well as exchange with experts from industries and consulting companies.

The bulk amount of heterogeneous information provided by several disciplines and sub-disciplines was sorted and categorized. Furthermore, different geothermal reservoirs themselves were screened and analyzed in detail to subdivide them into their essential but alike components. Several graphical shapes and representations were tested to come up with a flexible and simple but complete scheme that is applicable to all geothermal reservoirs within MEET. Beside the already mentioned two reservoir types (intrusive rocks, low- to high-grade metamorphic rocks), a third reservoir type was taken into consideration: Oil and gas wells drilled to exploit Mesozoic sedimentary rocks which are aimed to be converted for geothermal energy exploitation. Furthermore, these rocks are the target horizon of several geothermal plants in Europe, and the already gained technical and scientific experience and knowledge should be utilized. The subdivision between hydrothermal, petrothermal and other EGS types were not taken into account to keep the approach simple.

Moreover, general rules were defined to find a balance between complexity and simplicity of the concept. In the following paragraphs, the term “parameter” is used for all types of data that are relevant for a geothermal project and that have any kind of spatial reference. At present, it does not have to be a real geospatial data-set, which comprises graphical representations and attributes. In the course of the MEET project, the transition of these parameters into usable geospatial data-sets will be examined and acquired.

In terms of timing, the lifetime of the geothermal project and its associated reservoir are subdivided into natural (pre-technical) and developed (technical) phase. In terms of spatiality, a subdivision between the subsurface and surface is applied to the concept. In this publication, the first part of the concept dealing with the subsurface and their parameters during the pre-technical phase, is presented and aims to answer the following questions:

- Who is generating, collecting and/ or analyzing parameters of the subsurface that are relevant for geothermal potential assessment?
- What are the most common methods to generate these parameters?
- Where are the parameters collected or generated?
- How can the parameters be sorted, categorized and arranged?

3. RESULTS

3.1 Generation, collection, treatment and usage of parameters in the community

During the pre-technical phase that means the prospection and exploration phase of a potential geothermal site, mainly three disciplines are involved in the investigation of the subsurface, which are geosciences (or earth sciences), geophysics and computer sciences (including mathematics) and several related sub-disciplines as listed in Table 1. The first two mentioned disciplines are strongly involved in field-based investigations at the surface and in the subsurface by assessing existing quarries, road cuts and cliffs or drill holes, tunnels, mines and caves near the potential site or in a larger distance but in a transferable and representative combination of rocks and structures. The associated analyses of real objects, such as solids, fluids or gases, are performed in-situ and under lab-conditions, which are always artificial but inspired by natural conditions.

Descriptive methods and interpretations are mainly used in the geoscientific community to document observations or phrase interpretations. A lot of community-based standards, expert knowledge & “thumb-rules” are in use, illustrating the high value of experience within the community. Stochastical, modelling and simulation methods are deployed commonly to limit the high uncertainty in determining the behaviour of the subsurface due to the limited access to subsurface measurements compared to surface data. The collected or generated surface parameters vary in a wide range of properties, such as scale, coverage, resolution but also in their relation to other reference objects, like reference points, lines, planes or volumes.

Table 1: Disciplines & sub-disciplines involved in the data collection or generation process, common methods, major parameter characteristics and data users.

Discipline	Geosciences (Earth Sciences)	Geophysics	Engineering	Computer Sciences (incl. Mathematics)
Sub-disciplines	Structural geology Applied geology Sedimentology Mineralogy Exploration geology Hydrogeology	Surface geophysics Borehole geophysics	Rock mechanics	Geoinformatics Geomatics
Location & Methods	Surface & subsurface mapping	-	-	-
	Surface & subsurface data & sample acquisition On-site testing & experiments Lab tests & experiments			- -
	Literature analysis & compilation Mathematical methods			
Sub methods	Qualitative description	-	-	-
	Quantitative measurements			-
	Estimation (thumb-rules, expert knowledge) Interpretation Synthesizing Standard calculation methods Interpolation& extrapolation, upscaling & downscaling Modelling & simulation			
Parameter characteristics	Dimension(s) Coverage Scale Resolution Accuracy Dependency (time, pressure, temperature) Reproducibility Time of collection/ acquisition Relevance for geothermal project Relation to point (well head), plane (surface, water level, top of horizon) or volume (reservoir, aquifer, pore)			
Data user	Exploration geologists Drilling engineers Investors Regulators Engineering geologists Discipline-specific researcher PR experts			

3.2 Characteristics of geothermal reservoirs

Schematic block diagrams of the two major and the subordinate geothermal reservoir types of the MEET project as well as their main components are shown in Figure 1. Though each block represents a quite unique rock sequence and related tectonic structures, all three blocks can be subdivided in the same 6 integral parts. These comprise three real objects, which are the static “rock mass”, the mobile fluid phase and mobile gaseous phase, the discontinuities within the rock mass as well as the heat regime and the pressure regime surrounding and penetrating the reservoir. In detail these elements, which are denoted as “compartments” in this concept, can be described like this:

Rock: Comprises the complete solid rock material without discontinuities and is used in this concept similarly to the term “rock matrix”

Fluid phase: Stands for all shallow and deep groundwater, brines, soles and pore water within the system.

Gaseous phase: Represents all gases within the system, which can be air, methane or others.

Discontinuities: Comprises all sedimentary, tectonic or metamorphic structures that act as crucial fluid pathways, such as fault zones, joints, karst cavities or voids and pores within sedimentary rocks. The term “fracture” will be used in this study for all sedimentary and tectonic structures that function as fluid pathways as this definition is commonly used in the modelling community.

Heat regime: Stands for the heat entering the reservoir from a close by or distant source (deep crust, MOHO) or that is produced within the reservoir.

Pressure regime: Represents all the forces that act on and in the reservoir due to the tectonic stress field and lithostatic, hydrostatic or gas pressure.

In the geoscientific and geothermal community different terms are common to describe the subsurface rocks. In this study beside the abovementioned term “rock matrix”, the term “rock mass” is used for the subsurface rock matrix and all discontinuities and the term “reservoir” is dedicated to this part of the subsurface, which is exploited or will be exploited for geothermal energy extraction.

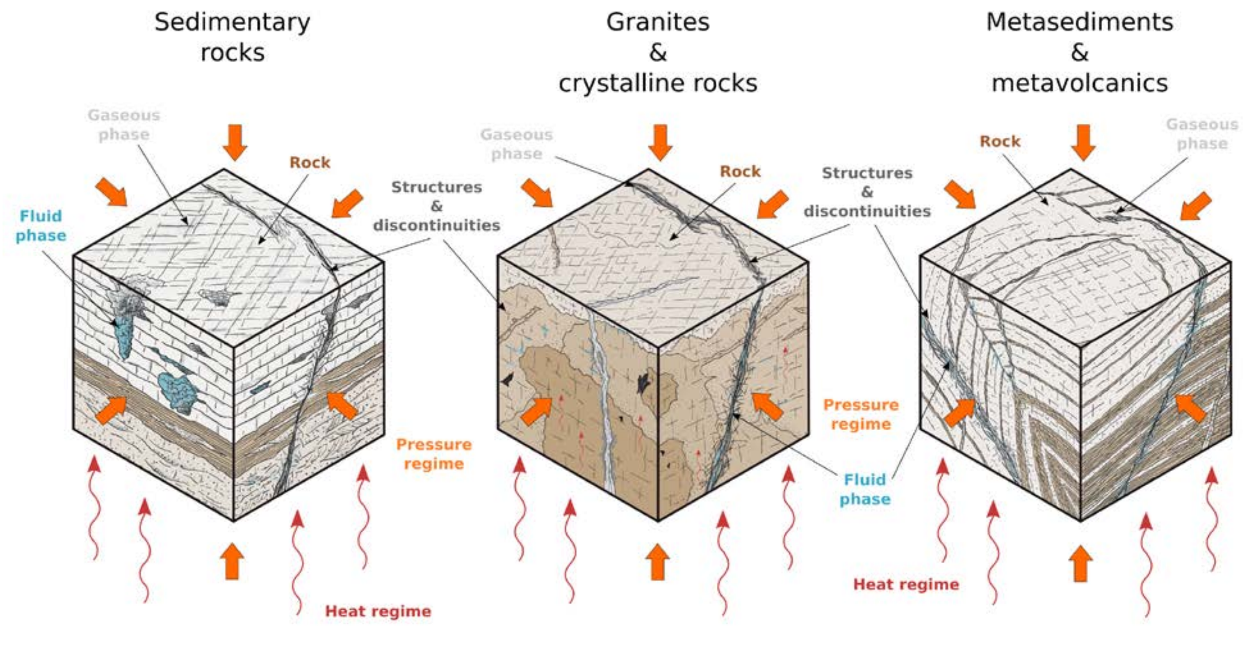

Figure 1: Schematic block diagrams of the two major geothermal reservoir types of the MEET project in intrusive (middle), low- to high-grade metamorphic rocks (right) and the subordinate sedimentary (left) geothermal reservoir types and their main parts.

3.3 “Concept Hexagon”

In the next step, the six different compartments of all three geothermal systems shown in Figure 1 are represented as triangles and combined into a hexagon (Figure 2). The hexagon is overlain by a net of 10 staggered hexagons to reflect 10 major levels of parameter types and associated data generation or collection methods that are relevant for geothermal reservoir characterization.

Even though the levels are numbered and show sharp boundaries, they do not represent strict, staircase-like levels but more general trends from the outer side of each triangle to the inner tip, as it is specified in Figure 3. One trend represents the transition from classical discipline-specific parameters and methods, which are common in geosciences and geophysics, to those, which are relevant for geothermal potential estimation. The other trend stands for a higher informative value of the parameter or the method in terms of geothermal reservoir characterization due to higher accuracy of the value or smaller distance to the potential reservoir.

Typical and common discipline-specific and geothermal parameters are assigned based on their generation or collection method (e.g. from Mussett & Khan, 2000, Gerling et al. 2015, Agemar et al. 2017, National Academies of Sciences, Engineering, and Medicine, 2019) to one of the 10 levels; this is exemplified in Figure 3 for some parameters of the "Rock" compartment. The same parameter can be generated by different methods and therefore be allocated to different levels, representing a differing value of usability and information content. In Figure 3 this case is demonstrated for the parameter "colour", but can be transferred to "metamorphic grade" or "horizon thickness".

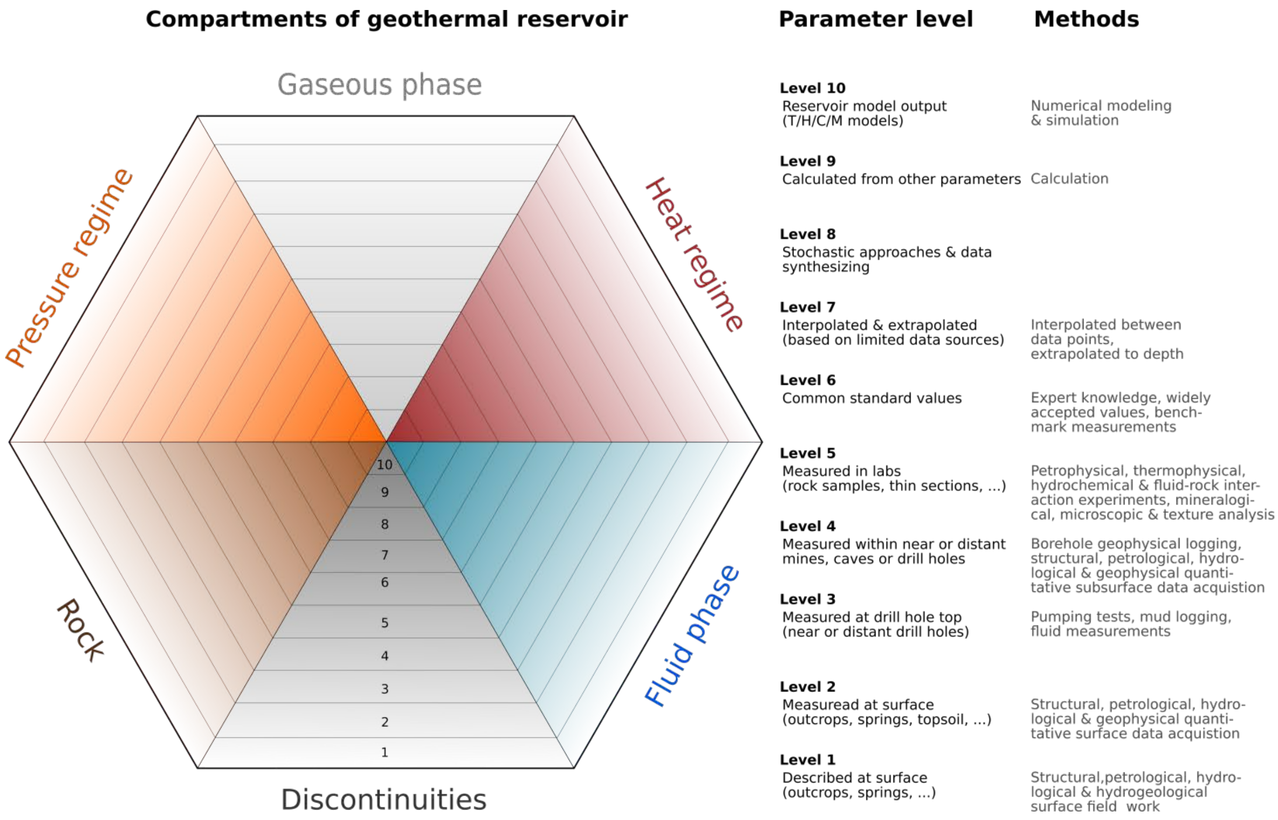

Figure 2: The "Hexagon concept", which is a combination of the 6 triangular compartments representing all major elements of a geothermal reservoir and 10 levels of parameter types & methods relevant and commonly applied throughout the reservoir prospection, exploration and assessment.

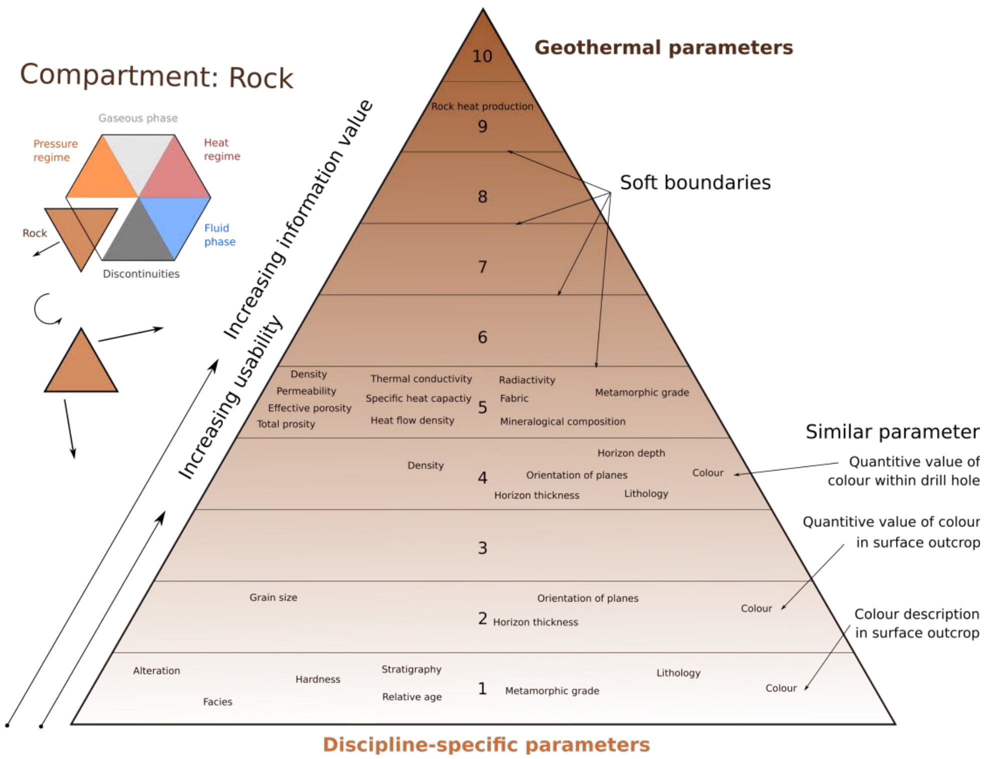

Figure 3: Triangular compartment "Rock" as one of the elements of the "Hexagon concept" filled with exemplary parameters. Large and small arrows illustrate general trends within all compartments as well as point out the case of parameter repetition and soft boundaries between all levels.

3.4 Visualization of complex parameters

By applying the "Hexagon concept", several parameters could not be assigned to one compartment and at least one certain level, as they are influenced by more than one element of the geothermal reservoir, e.g. the parameter "reservoir permeability" is defined by the rock matrix and the discontinuities that limit and separate it to form the "rock mass". Therefore, the primary "Hexagon concept" was used as a base to generate a more complex visualization, which is shown in Figure 4.

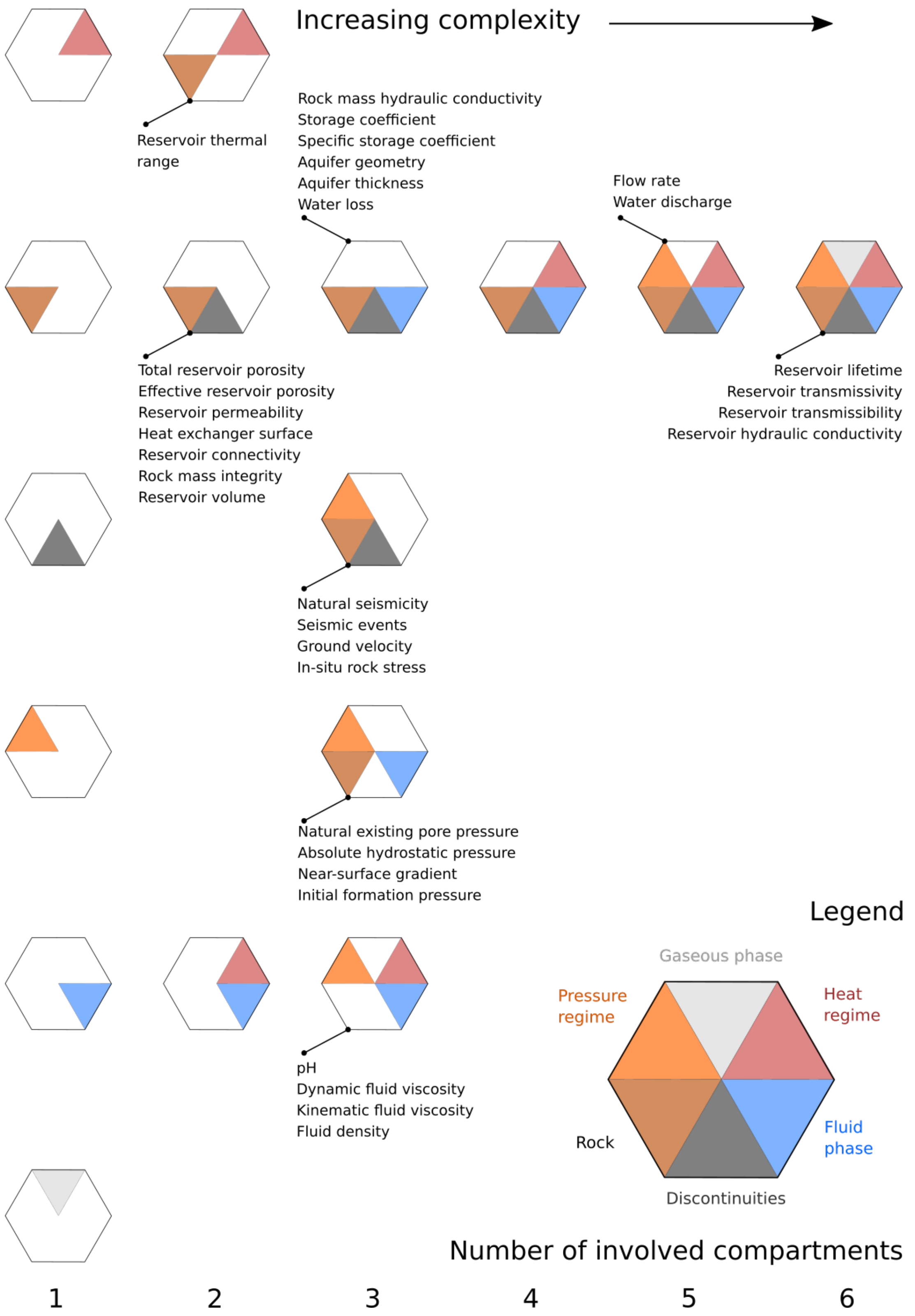

Figure 4: "Hexagon concept" used for the classification of parameters that are influenced by more than one element of the geothermal reservoir. Some exemplary parameters are assigned to the most common combinations of compartments.

Some of the exemplary parameters and their influencing compartments shown in Figure 4 are represented in another form in the upper right corner of figure 5 to express the flexibility of the concept.

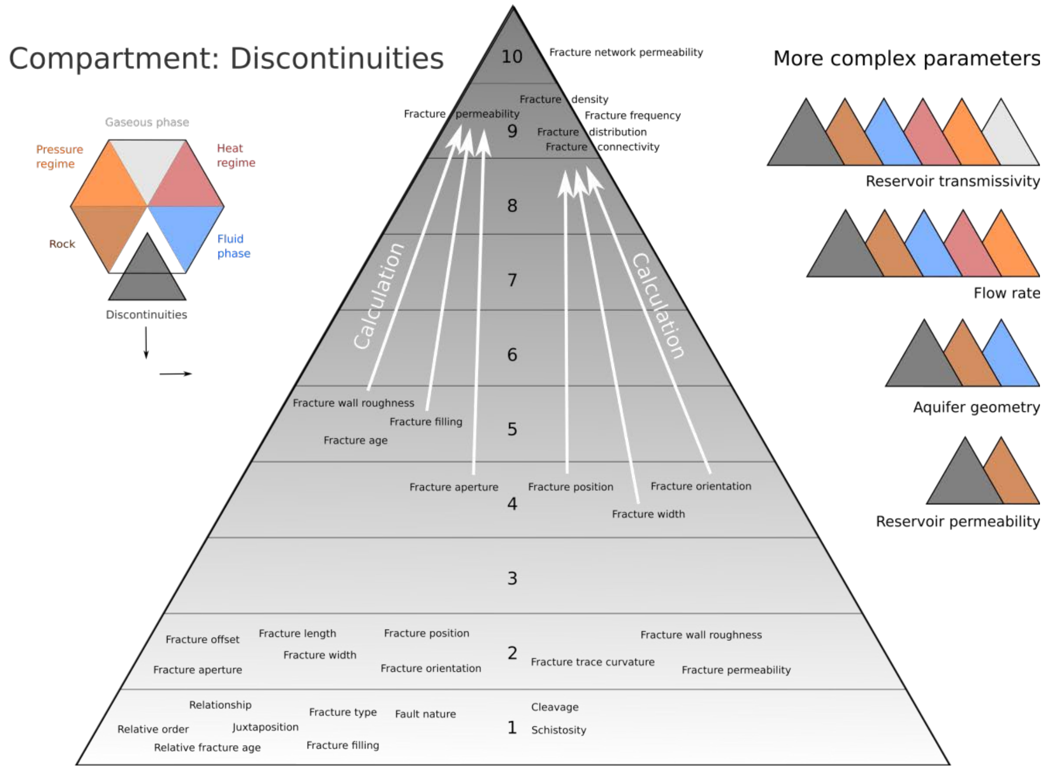

Figure 5: Triangular compartment "Discontinuities" of the "Hexagon concept" filled with exemplary parameters related to tectonic and metamorphic structures. Furthermore, the crossover from one parameter level to another by calculation is marked by arrows. Parameters that are defined by more than just discontinuities in the subsurface are shown in the upper right corner.

3.5 Summarized results

The proposed "Hexagon concept", as shown in Figure 2, is a holistic approach that gives an overview about the two major and one subordinate geothermal reservoir types in the MEET project and that takes all major components of the subsurface system into account. It provides the framework for sorting, categorizing and weighting pure discipline-specific (geoscientific, geophysical or engineering) as well as real geothermal parameters by assigning levels of increasing informative values. The concept can be utilized to identify parameters that are created by several methods or parameter that are named by different terms. Beside these basic functionalities, the concept can be expanded by integrating the most common ways of transition between two or more levels. The various types of transition can range from simple estimation and averaging to complex calculation.

Existing sources of parameters or geospatial data, such as viewer, databases, platforms or maps can be reviewed and evaluated in terms of their informative value or completeness by taking all compartments into account at the same time. By applying the concept, successful, abandoned or unrealized geothermal projects can be analyzed due to their major reasons of success or failure. Furthermore, within an ongoing exploration campaign, based on the concept it can be clarified, if the minimum amount of data is collected to go to the next step. In general, as communication is a major factor of successful project work, the "Hexagon concept" can be adopted as a tool for discussion within interdisciplinary teams or for internal and external Public Relations actions to visualize the complexity of a geothermal project to data producers, stakeholders or the public.

4. DISCUSSION

At first glance, the "Hexagon concept" is a very uncommon approach to analyze a system in earth sciences or natural sciences, as it is mainly based on visualizations and simple shapes and does not inhibit complex calculation paths or digital technologies. On the other hand, the high complexity of such systems have to be simplified and visualized to make it understandable to the wide range of groups and disciplines. Especially, as the time for learning and understanding is quite limited due to the high pressure and workload in contrast to the constantly increasing number of publications and books.

Furthermore, behind the unconventional appearance of the graphical concept, a very flexible and expandable tool is hidden, which can be used to analyze the complete system or aspects in great detail. For instance, the concept can be utilized to categorize and compare several workflows for determining heat-related parameters, as is discussed and summarized by Günther (2019).

The description and classification of the parameters' generation and collection process and the involved disciplines is just based on a limited number of literature and data sources as well as communication activities. But in these meetings, talks and discussions, a wide range of people, who are experts in certain parts of the prospecting, exploration and exploitation processes were involved, such as field geologists, exploration geologists, lab researchers, modellers, operators of geothermal plants, and drilling engineers.

The geothermal reservoirs that are analyzed within the MEET project were subdivided into 6 integral parts. In some cases, there is still a dependency between two compartments due to the complexity of a geothermal reservoir. For instance, the radiogenic heat production of granites is strongly connected to the properties of the rock material. Another example is the conditions of the fluid phase or the gaseous phase, which influence the hydrostatic or the gas pressure. Regarding sedimentary rocks, primary sedimentary fabrics can act as major discontinuities, but can be defined as material characteristics of the rock itself. In these three examples, there is no sharp boundary between these compartments. However, these limitations were taken into account to keep the concept simple and usable.

The 6 compartments of the "Hexagon concept" have the same shape and the same size, but their information value and their weight for the estimation of the potential of a geothermal reservoir might be different. The same size of the triangles was chosen, because each component is relevant for a successful realization of a geothermal plant. The weight of each compartment could be visualized in an adapted version of the "Hexagon concept" by using various sizes.

The ten levels of parameter types and methods were defined to cover all major ways of parameter collection and generation. Their order was set to keep the figure clear and usable but does show just trends. The user should always take into account that there might be more methods or different methods could be applied to generate similar results. Due to clarity, the units and further parameter characteristics like dimension or relevant scale were not visualized but will be implemented in updated version of the concept. The more complex visualizations shown in Figures 4 and 5 are further uncommon approaches. Their usability and meaningfulness must to be tested in the near future during meetings and team discussions.

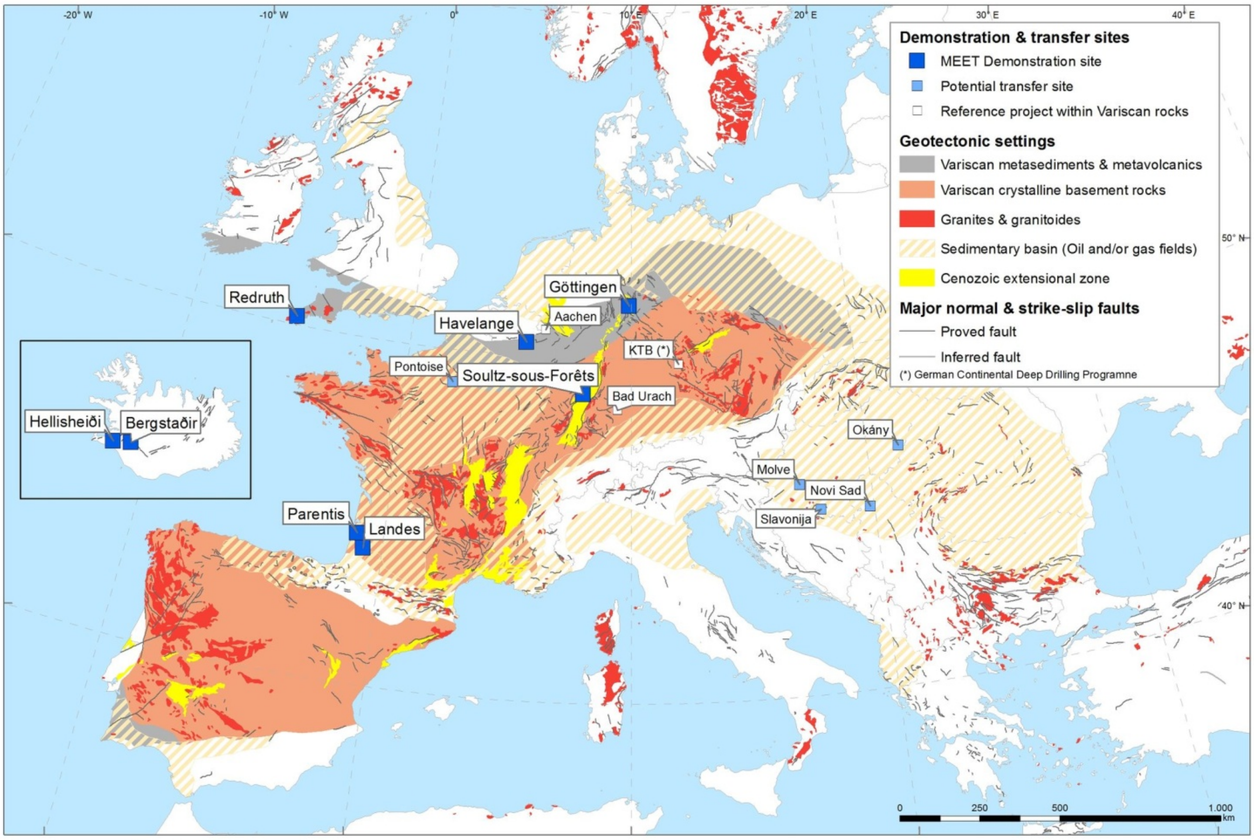

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Figure 6: General map of the major and subordinate geothermal reservoir types as well as the demonstration and transfer sites of the MEET project within the Variscan belt and adjacent areas in Europe.

5. OUTLOOK

Within the next phase of the project, the presented "Hexagon concept" will be filled with more data to provide information about all parameters that are essential for successful project assessment. As mentioned above, several methods will be tested to show certain characteristics of parameters, such as dimension (1D, 2D, 3D) or reference objects. As a second step, the connection between two or more levels will be elaborated in detail.

Regarding the general approach, the concept will be extended to include the "technical phase" of a geothermal project, which starts with the first drilling. Parallel to this, the change of the relevance of each compartment throughout the prospection and exploration process will be analyzed and visualized.

Furthermore, the surface part of a geothermal project will be included by developing another, circular figure that is made up of economic, technical, environmental, political, legislative and social criteria inspired by the United Nations Framework Classification - UNFC 2009 – (UNECE, 2013) At the end, this will be combined with the "Hexagon concept".

Parallel to the mentioned tasks, the proposed "Hexagon concept" will be utilized to compare, evaluate and categorize existing online-data sources as well as published potential maps in terms of their parameter content and treatment of parameters. Based on these results, the compilation of parameters and associated geospatial data will be started by creating appropriate data-sets for each compartment covering the area shown in Figure 6. In the next steps, these mono-thematic data-sets will be combined and merged with the surface concept to provide an integral approach for future users.

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