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Deep geothermal resources in the Pan-European Atlas of Sustainable GeoEnergy Capacities (GSEU project): The Play-based Exploration Pyramid concept

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ABSTRACT

This work introduces version 1.0 of the Pan-EU Atlas of Sustainable GeoEnergy Capacities (SGC), delivered by the **GSEU (Geological Service for Europe)** project. It details the methodology evolving from the Play-Based Exploration Pyramid (PBEP) concept into a practical approach for sharing harmonized knowledge about deep geothermal energy potential across Europe. This Atlas aims to deliver a standardized and generalized understanding of geothermal resources, emphasizing the potential in the framework of the Europe's sustainable energy transition.

The PBEP concept of the PanEU Atlas of SGC follows a multiscale geothermal exploration approach that systematically narrows focus from a geosystem to local scale, organizing technical and scientific data from broad, low-knowledge areas to highly detailed high-knowledge regions or local targets. It aims to ensure a refined understanding of geothermal plays, improving the identification of potential areas across Europe, spanning four levels (Level 0 to Level 3) and incorporating further refined knowledge in the assessment of geothermal resource. Levels 0 and 1 GIS datasets were published along spring 2025 in the European Geological Data Infrastructure (EGDI) as version 1.0 of the Atlas. Information available includes public data from boreholes and thermal springs (Level 0), which forms the basis for Level 1 - a harmonized map highlighting favourable prospecting areas for deep-origin geothermal resources, classified according to Geothermal Play Types (GPTs). This is accompanied by a catalogue of factsheets for each delineated GPTs across EU (~ 400 in total), summarizing the generalized findings along with a report on description and metadata. This scale-dependent process will continue in version 2 of the Atlas, with Level 2 focusing on identified potential geothermal reservoirs using 1D lumped stochastic estimations for geothermal resources and medium to high heat storage potential into deep aquifers. Finally, Level 3 will provide detailed local-scale evaluations of specific targets, compiling already existing maps and models containing spatial-distributed reservoir assessed information in 2D and/or 3D.

Versions 2.0 and 3.0 are expected to be end by the end of 2025 and 2026, respectively, and will include the additional Level 2 and 3 data layers for deep geothermal resources.

1. INTRODUCTION OF THE CO-FUNDED GSEU PROJECT (2022-2027)

The GSEU is a Horizon Europe co-funded project (Coordination and Support Action) running from 2022 to 2027. It is led by EuroGeoSurveys (EGS), a non-profit membership organisation that represents the Geological Survey Organisations of Europe. EGS brings together a workforce of over 10,000 experts who collaborate through scientific expert groups, task forces, and EU-funded projects — including our

flagship initiative, the Geological Service for Europe (GSEU) project. The European GSEU project realizes the foundation of a Geological Service for Europe grounded in pan-European integration and harmonization of national subsurface data and collaborative research by NGSOs.

The GSEU project brings together a consortium of 49 partners — national and regional geological surveys (NGSOs) — from a total of 36 countries. Its main goal is to develop and make permanently available a pan-European geological data infrastructure and related information services for the sustainable and safe use of our subsurface and its resources.

The project covers different areas of expertise, including Raw Materials, **GeoEnergy Resources,** Groundwater Resources, Coats and Sea, Geological modelling and mapping and the deployment of the European Geological Data Infrastructure (EGDI), all these grouping in several Working Packages (WPs). The (EGDI) platform's map GIS viewer and general search engine (https://www.europe-geology.eu/data-tools/map-viewer/) will become a fundamental element of the GSEU, supporting the delivery of knowledge to policymakers and other stakeholders (Fig. 1).

Figure 1: GSEU project. The Geological for Service for EU (https://www.geologicalservice.eu/

2. THE PAN-EU ATLAS OF SUSTAINABLE GEOENERGY CAPACITIES

The GSEU activities related to GeoEnergy resources are organized within the Work Package 3 (WP3) of the project, which aims to develop and organize pan-European inventories, characterizations, and knowledge related to Sustainable Geo-Energy Capacities (SGC). These include geothermal energy resources, underground capacities for CO_2 storage, and temporary subsurface storage of sustainable energy carriers such as hydrogen, heat, and cold.

In this regard, GSEU WP3 is structured around three key goals (deliverables):

- **Online platform for centralised access to national and international databases** of Sustainable Geo-Energy Capacities.
- **The Pan-European online Atlas of SGECs (Pan-EU Atlas SGC)**.
- **A Knowledge and Competence Hub** to support Geological Survey Organisations (NGSOs) and stakeholder communities.

The **Pan-EU Atlas SGC,** the main product, will provide harmonized and generalized maps and databases, covering geothermal resources and subsurface storage capacities. These products will be based on both the evaluation of existing information and the integration of new national assessments, ensuring consistency and comparability across Europe.

Building upon the outcomes of previous European initiatives — notably the **GeoERA Programme** (a previous Horizon 2020 ERA-NET 2018-2021 conducted by European geological survey organisations with 14 projects covering the geoscientific topics of Raw Materials, GeoEnergy and Groundwater, plus a specific project on Information Management (the EGDI initiative) to support the other projects) — the GSEU WP3 aims to improve the current state of the art through a more integrative and harmonized framework for resource assessment. This will involve the identification of information gaps and needs for future data enhancement. Additionally, WP3 will implement standards, vocabularies, structural frameworks, and **Linked Data principles** developed in GeoERA. All results will be made accessible through a **single open-access gateway via the EGDI platform**, enabling better data integration at both national and European levels. This approach will enhance subsurface management, decision-making support, resource classification, and visualization of harmonized geological data across EU.

This paper first presents the approach agreed upon by the project partners in December 2023 to structure and plan the deep geothermal component of the future **Pan-EU Atlas of Sustainable GeoEnergy Capacities (SGC),** which will be delivered by the GSEU project through the EGDI platform, with the complete Atlas becoming available at the end of the project. However, partial deliveries by layers and updates have been planned between 2025 and 2026 to provide information as early as possible, ahead of the future Geothermal Action Plan for EU, expected by the European Commission in the first quarter of 2026. The second part provides an explanation of the content of version 1.0 of the Pan-EU Atlas, which has been published in Spring 2025, containing the first three datasets.

2.1 The Play-based Exploration Pyramid approach applied to the PanEU Atlas of SGC

In relation to the mapping of Deep Geothermal resources at the EU scale—including Medium and High Temperature Underground Thermal Energy Storage

(UTES)—the GSEU project has adopted a structured, knowledge-based approach inspired by the **Play-Based Exploration Pyramid**, originally developed for the oil and gas sector and later adapted by Moeck et al. (2019, 2020) and also re-used by Weydt et a. (2025) for geothermal applications (Fig. 2). This hierarchical framework organizes the assessment of geothermal potential into three levels of increasing geological detail: **Geosystem**, **Play**, and **Prospect**, which in the GSEU terminology, follows a concept based on levels of knowledge in general terms at EU scale, from low knowledge and high coverage (geosystems) to high knowledge and low coverage (prospects at local scale).

So, the first level of the pyramid - the **Geosystem** level - provides a generalized view of favourable areas for deep geothermal resource exploration. It applies the *catalogue of geothermal play types* defined by Moeck (2014), which classifies geothermal systems based on their geological settings and dominant heat transport mechanisms. These broad areas—comparable to sedimentary basins in the oil and gas industry—are used to map potential across the EU in a harmonized manner, forming the foundation of the GSEU Level 01 dataset.

The second level - the **Play** - refines this classification by focusing on potential geothermal reservoirs within the broader geosystems. This stage evaluates available geological data to identify and delineate potential reservoirs for deep geothermal exploitation and storage, incorporating probabilistic approaches for estimating available base resources and capacities. This constitutes GSEU Level 02, which provides a harmonized, 1D assessment of potential deep geothermal reservoirs and UTES applications.

At the top of the pyramid, the **Prospect** level represents the most detailed scale of analysis. This level compiles spatially resolved data (2D/3D), including reservoir models and site-specific attributes that describe both qualitative and quantitative aspects of the systems. Within GSEU, Level 03 does not generate new prospect-scale data but rather compiles and harmonizes existing datasets from previous national or cross-border projects not yet publicly accessible. It will be progressively enriched with results from ongoing initiatives such as the Go-Forward Horizon Europe project.

This structured, pyramid-based approach allows for a consistent and comparative evaluation of geothermal potential across different EU regions. By grouping geothermal systems with shared geological characteristics, it streamlines the exploration workflow—from broad reinterpretation of existing data at the geosystem scale, through identification and characterization of plays, down to targeted risk assessment at the prospect level—ultimately supporting more informed decisions regarding future drilling and development activities.

At the bottom of the pyramid lies the most fundamental level of information: a database of boreholes, wells, and thermal springs. This foundational dataset serves as the starting point for classifying geosystems into one of the geothermal play types according to their geological characteristics and heat transport mechanisms. From this classification, it becomes possible to identify potential geothermal reservoirs (plays), which may later be evaluated in greater detail at the local (prospect) scale.

This bottom-up methodology ensures that the resource assessment is grounded in real data and becomes progressively more refined through each level of geological understanding—while also allowing the Atlas to be continuously updated and expanded as new information becomes available in the future.

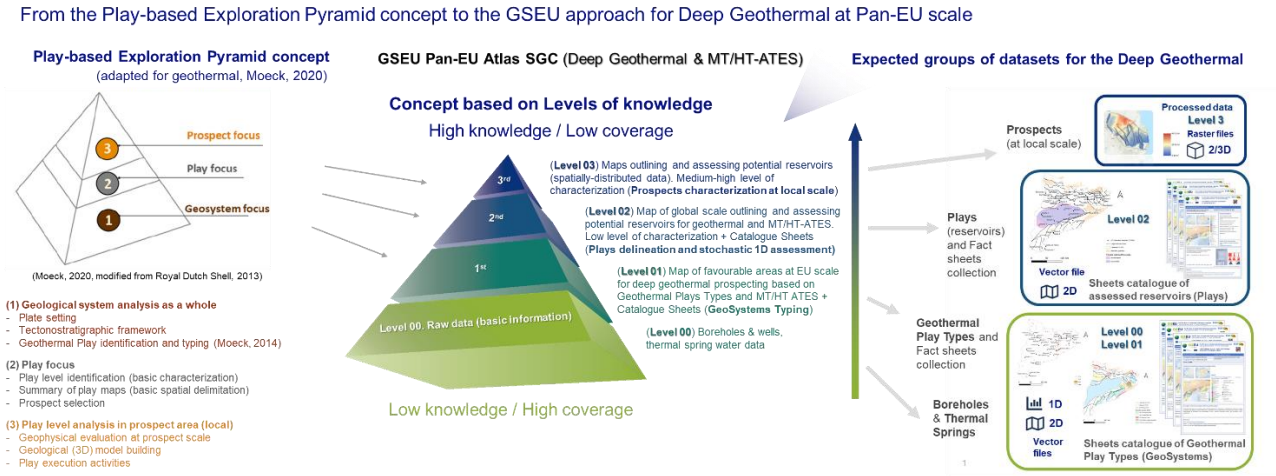

Figure 2: From the Play-based Exploration Pyramid concept (Moeck, et al. 2019, 2020) to the GSEU approach for Deep Geothermal at Pan-EU scale.

In this context, the GSEU Pan-EU Atlas deep geothermal scheme is organized into four levels:

- **Level 00,** included in the version 1.0 published in Spring 2025 (Fig. 03, 04 and 05) provides two datasets (point vector layers) corresponding to base information, including a dataset of inventory of boreholes & wells (41899 points), with its attribute table containing collected information of depth, year of drill, purpose, Bottom Hole Temperature, etc; and thermal springs (6621 points,), including an attribute table with data related to temperature, flow rate, among other data. As of the date of this paper, additional offshore boreholes are still pending to be incorporated (e.g. western part of the North Sea area).

- **Level 01** included in version 1.0 to be published in Spring 2025 (Fig. 03 and 06), provides a harmonized and generalized vector polygon dataset representing a map of favorable prospecting areas for deep geothermal energy across the EU. Almost 400 geosystems, classified according to the geothermal play type catalogue (Moeck, 2014; Moeck & Beardsmore, 2014), have been identified. As of the completion date of this paper, additional areas are still under development, including Greece, Romania, and the identification of further offshore zones with geothermal potential for power generation along certain coastlines, in addition to those already compiled. Each geosystem polygon on the map includes a downloadable fact sheet in PDF format (Fig. 03, 06 and 07), which provides the name, code, and type of geothermal play. The spatial delimitation of each polygon is referenced using the IGME 5000 database (Asch & Tschopp, 2005). The fact sheet also includes a geological description, identifies the potential reservoirs (which will later be included in the Level 2 dataset), specifies the range of depth and temperatures, and references.

- **Level 02** will provide a vector polygon dataset as a map focusing on a harmonized, continental-scale assessment of potential deep geothermal reservoirs and Medium- to High-Temperature Aquifer Thermal Energy Storage (M/HT-ATES). This will include a 1D lumped stochastic calculation for the whole reservoir of the Heat-in-Place (HIP) method according to Muffler and Cataldi, (1978) and Heat Storage Potential (HSP), according to Frick et al. (2022), to estimate base resources and total capacities for MT/HT-ATES in suitable reservoirs. To perform the 1D lumped stochastic simulations of the HIP and HSP, a re-adapted open-access python-based tool with a graphical user interface has been prepared, which will then make available for external users through the knowledge hub of GSEU.

- **Level 03** will represent the highest level of characterization and lays the foundations for future extensions. It offers a more detailed evaluation through spatially distributed (2D/3D) reservoir data, including both qualitative and quantitative attributes that describe the appraisal status and expected performance of the geothermal systems. Within the framework of the GSEU project, Level 03 will primarily compile existing datasets from previous cross-border or national projects available to the partners, especially those that do not currently have a dedicated online publication and need to be preserved into the EGDI geological repository for the whole community. This level will also be progressively expanded with contributions with datasets and 3D models developed in successive projects, some of which are already underway, such as the Horizon Europe Go-Forward project (2024-2028) led by Fraunhofer IEG and in which several geological survey organizations participate such TNO; ICGC, GEUS, GeoSphere, BGS.

2.2 The Deep geothermal content with the version 1.0 of the Pan-EU Atlas of SGC.

The first version (1.0) of the Atlas was published in Spring 2025 (Fig. 3). This initial release focuses on the first's datasets related to deep geothermal energy and CO_2 storage potential. It includes three CO_2 storage datasets (storage formations, storage units, and storage traps), as well as the first versions of Deep Geothermal topics with the Level 00 and Level 01.

- **Boreholes and wells (Level 00)** serve as a cross-cutting layer for both CO_2 storage and geothermal energy, providing foundational data for the assessment of these two key topics. Threshold of temperature (min 30 ºC) and depth (800 m) were considered, unless geological relevant information let to include the point.

- **Deep Geothermal** includes two layers: **Level 00** as vector data point for **Thermal springs**. **Level 01** as polygon data referring to **geothermal play types across the EU**, plus a catalogue of 392 downloadable sheets including descriptions and references.

It's expected that version 2.0 of the Pan EU will be compiled and completed by December 2025, with publication in Q1 of 2026. It will include Level 02—a map assessing potential deep geothermal reservoirs and medium- to high-temperature ATES for deep geothermal, as well as storage capacity calculations for CO_2 storage.

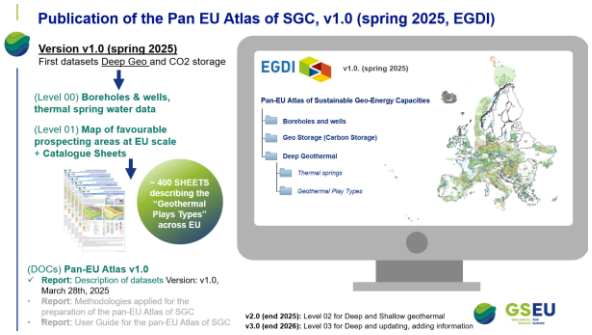

Figure 3: Publication version 1.0 Pan-EU Atlas of SGC, Spring 2025.

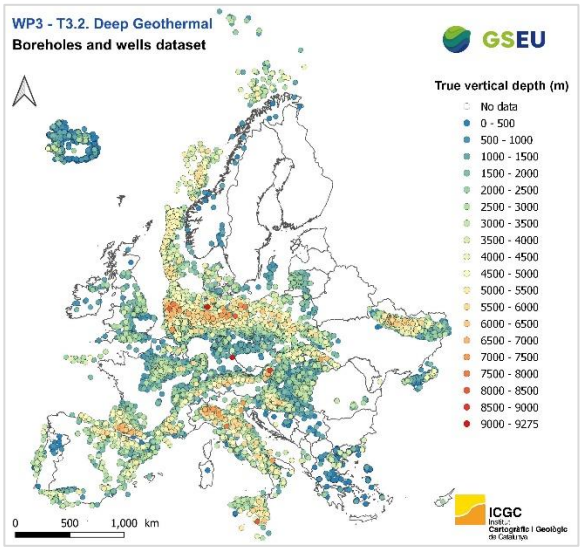

Figure 4: GSEU Project (2025). Map of Geo-Energy Boreholes and Wells. Version 1.0. (41899 points) classified according to the vertical length (m).

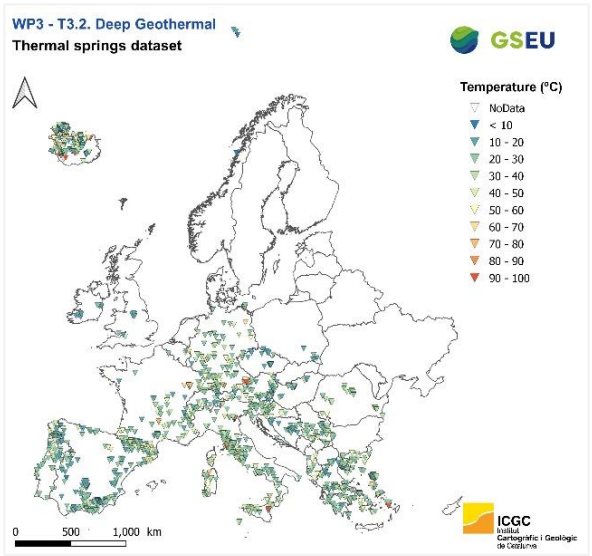

Figure 5: GSEU Project (2025). Map of natural Thermal Water Springs. Version 1.0.

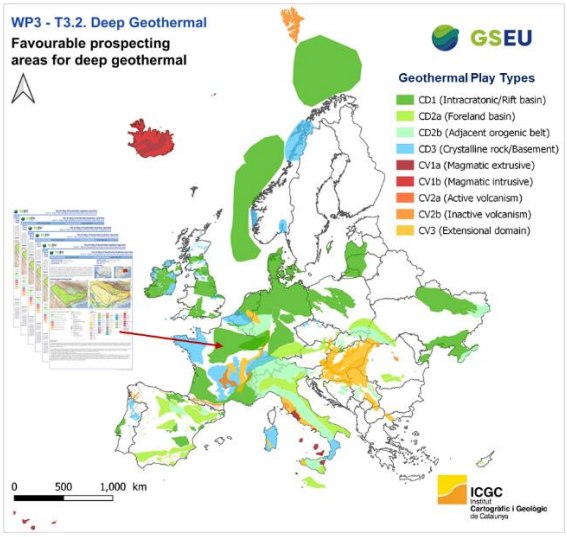

Figure 6: Level 01 map of favourable prospecting areas for deep geothermal across the EU classified according to the geothermal play catalogue (Moeck, 2014).

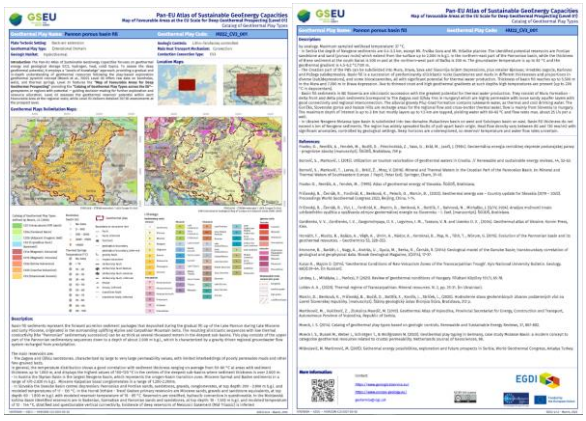

Figure 7: Example of the two pages-based fact sheets for one geosystem (geothermal play type). The image corresponds to the Pannonian basin geothermal play (code HU22_CV3_001).

The process of developing the layers followed four steps: 1) the preparation of specifications for defining the product and guidelines on how to prepare and collect information from the partners (the European Geological Surveys); 2) the data preparation and collection phase; 3) the harmonization, standardization, and compilation of the information to generate a single dataset in GeoPackage format (*.gpkg) with a unified legend and 4) the preparation of metadata and publication on EGDI.

Additionally, with the version 1.0 publication, a report downloadable in PDF format provides a description of the datasets, including all the attributes of the layers, how to cite this product, and the terms of Use / License which is Creative Commons Attribution 4.0 International License (CC BY 4.0). Furthermore, all

layers are accompanied by metadata, which can be accessed through the EGDI metadata catalogue.

3. FIRST RESULTS

Based on the collected information for the whole dataset of Level 01, a preliminary statistical treatment has been conducted to characterize the identified potential geothermal reservoirs associated with each play type in terms of temperature and depth ranges (Figure 08). The results are expressed in terms of the 10th (P10)—as minimum—and 90th (P90)—as maximum—percentiles of their distribution. These first values provide a preliminary understanding of the typical and extreme conditions expected across Europe within each geothermal play category.

For conduction-dominated geosystems, including CD1, CD2a, and CDb—typically deep hot sedimentary aquifers in passive tectonic settings—temperature values range from 50 °C (P10) to 180 °C (P90), and depths range from 1,500 m (P10) to 5,300 m (P90).

For CD3-type systems, associated with fractured crystalline rocks that exhibit low permeability but high radiogenic heat production, temperatures range from 100 °C (P10) to 150 °C (P90), and depths from 2,500 m (P10) to 5,100 m (P90).

In convection-dominated settings, types CV1a and CV1b, linked to volcanic reservoirs with shallow magma chambers and high heat flow, show temperature ranges of 200 °C (P10) to 340 °C (P90), and depths from 990 m (P10) to 2,000 m (P90).

For CV2a and CV2b, related to plutonic-associated systems, temperature ranges lie between 130 °C (P10) and 260 °C (P90), with depth values between 700 m (P10) and 3,300 m (P90).

Lastly, CV3-type geosystems, associated with areas of crustal thinning that allow for the deep circulation of heated meteoric water through permeable faults or layers, show temperature values from 50 °C (P10) to 176 °C (P90) and depths between 2,000 m (P10) and 5,000 m (P90)

This percentile-based analysis provides a clearer view of the upper limits of reservoir conditions across different geothermal play types, supporting further exploration and resource assessment strategies.

Then, Level 02 will assess these identified reservoirs by stochastically estimating the Heat in Place (HIP) and Heat Storage Potential (HSP) densities in terms of PJ/km^2.

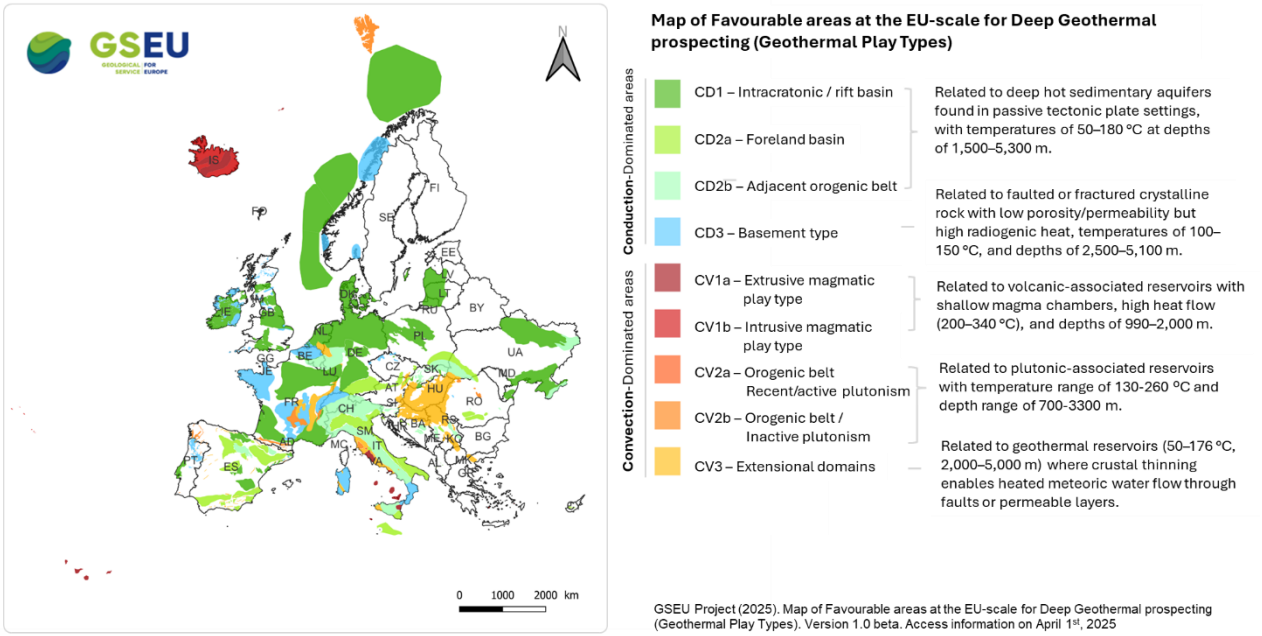

Figure 8: Temperature and depth ranges (P10–P90) of potential geothermal reservoirs identified for each geothermal play type, based on preliminary statistical analysis from the EU-scale Map of Favourable Areas for Deep Geothermal Prospecting (version 1.0, spring 2025)

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