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Mapping deep geothermal resources in Europe by European geological surveys using an adapted play-based exploration pyramid within the Horizon Europe co-founded GSEU Project

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INTRODUCTION

The GSEU is a Horizon Europe co-funded project (Coordination and Support Action) running from 2022 to 2027 with a total budget of 24 M€. It is led by EuroGeoSurveys (EGS), a non-profit membership organisation representing the Geological Survey Organisations of Europe. EGS brings together more than 10,000 experts who collaborate through scientific expert groups, task forces and EU-funded projects, including its flagship initiative, the Geological Service for Europe (GSEU) project https://www.geologicalservice.eu/. Building upon the outcomes of previous European initiatives - notably the GeoERA Programme (Horizon 2020 ERA-NET, 2018 - 2021), which supported 14 projects in the fields of Raw Materials, GeoEnergy and Groundwater, as well as a dedicated Information Management project that advanced the European Geological Data Infrastructure (EGDI) - the GSEU project aims to establish the foundations of a the future Geological Service for Europe. This service is grounded in the pan-European integration and harmonisation of national subsurface data and in collaborative research carried out by national and regional geological survey organisations (NGSOs).

The GSEU consortium brings together 49 NGSOs from 36 countries. Its overarching goal is to develop and ensure the long-term availability of reliable, harmonised and up-to-date geological data across five main thematic areas: Critical Raw Materials, Geo-Energy, Groundwater Resources, Geological Modelling and Mapping, and Coastal and Offshore, as well as to support the continued development and deployment of the European Geological Data Infrastructure (EGDI).

1 THE PAN-EU ATLAS OF SUSTAINABLE GEOENERGY CAPACITIES

The activities related to Geo-Energy resources are organised under the WP3, whose overarching objective is to develop and consolidate pan-European inventories, characterisations and knowledge related to sustainable geo-energy capacities covering geothermal resources (deep and shallow) and subsurface storage capacities for CO_2 and sustainable energy carriers (hydrogen, heat and cold).

The main output is the development of the bases of the so-called “Pan-European Atlas of Sustainable GeoEnergy Capacities (Pan-EU Atlas of SGC)” (Herms et al., 2023; Canteli et al., 2024). It is being collaboratively developed by the 34 national and regional geological surveys participating in the GSEU consortium. The Atlas will provide harmonised and generalised maps and databases, serving as a central reference for subsurface geological carbon information across Europe.

By continuously integrating, enhancing and harmonising historical spatial and scientific datasets, the Pan-EU Atlas of SGC aims to create a robust, evidence-based resource to support policymakers, investors and other stakeholders in designing sustainable strategies for Europe’s decarbonisation. This process includes synthesising information from previous European projects and national data repositories, as well as

incorporating new national assessments. It also helps identify data gaps and future needs, ensuring that the resulting products are consistent, comparable and aligned across all participating countries. In addition, standards, vocabularies, and data models have been reviewed and applied, strengthening long-term data interoperability and consistency.

Importantly, the GSEU project establishes the foundations and produces the first core datasets of the Pan-EU Atlas, but this is not conceived as a product ending in 2027. Instead, it has been designed as a long-term, scalable knowledge-based GIS product that will continue to expand and evolve within the framework of the future Geological Service for Europe (GSEU). This ensures continuity, progressive enrichment of data, and sustained integration of new scientific knowledge beyond the duration of the GSEU project. All resulting datasets and products will adhere to the FAIR principles, ensuring that data are findable, accessible, interoperable and reusable. They will be fully accessible through a single open-access gateway provided by the European Geological Data Infrastructure (EGDI). The EGDI platform includes a powerful and user-friendly online GIS viewer and a dedicated search engine (https://www.europe-geology.eu/) for visualising and querying spatial information. It serves as a key component of the GSEU, enabling long-term access, consistent data integration at national and European levels, and improved subsurface management and decision-making. Partial deliveries and their updates are already being progressively incorporated into it as thematic datasets are completed.

This extended abstract presents the approach agreed upon by the GSEU project partners in December 2023 to structure and mapping the deep geothermal component of the future Pan-EU Atlas of SGC, which will be published through the EGDI platform. As new versions are produced, they will be released mainly between mid-2025 (already published) to provide early information for future geothermal actions and strategies that may be undertaken by the European Commission until the mid-2027 at the end of the project.

1.1 Deep Geothermal Energy thematic working group within the Pan-EU Atlas of SGC

As mentioned, the Pan-EU Atlas of SGC is structured by themes and, to organise the work, different thematic working groups have been created. These groups, under the coordination of the IGME-CSIC, ICGC and LNEG geological surveys, collaborate and are responsible for establishing the methods as well as collecting, compiling, harmonising, and delivering the datasets. The defined Deep Geothermal thematic working group is nurtured by the cooperation, collaboration and knowledge of the experts from 34 NGSOs across 30 European countries, and responsible among different issues, to stablish the assessing and mapping methods.

1.1.1 The play-based exploration pyramid approach

In relation to the mapping of deep geothermal resources at the EU scale - including medium and high temperature aquifer thermal energy storage (M/HT-ATES) - 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. (2020, 2021) and applied by Weydt et a. (2025) for geothermal applications (Figure 1).

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). At the end, this customized methodology and terminology, adds a new 00 level referring boreholes and wells and thermal springs data with a final structure of four main levels of knowledge (Level 00-Level 03) (Figure 1). From bottom (Level 00) to top (Level 03) in the pyramid concept, the reliability and understanding increase, as well as the amount of data; and the coverage of the territory decreases.

GSEU builds upon data and information from national databases and previous European projects - reusing, updating, expanding, and complementing them - to produce new harmonised datasets. The play-based concept applied, together with the currently planned datasets, is designed to identify favourable areas for geothermal prospecting, delineate potential reservoirs, and provide more detailed project-scale information. This approach is intended primarily for conventional geothermal technologies, that is, those relying on geological formations that naturally provide sufficient temperature, fluid, and permeability. Consequently, the mapping of geothermal resources associated with reservoir-independent schemes (i.e., unconventional or next-generation technologies such as AGS or EGS, where heat is present but natural permeability and/or fluid are lacking) is not explicitly included in the current GSEU approach. Instead, efforts focus on integrating into the EGDI legacy outputs from earlier transnational and Pan EU projects, such as the GeoElec project (2011-2013) (Kölbel et al., 2013), - which produced relevant raster maps but currently lacks a dissemination platform - as these still provide

highly valuable baseline information for such reservoir-independent schemes. This legacy information is being complemented with the new datasets generated within GSEU, until future dedicated developments enable new updates.

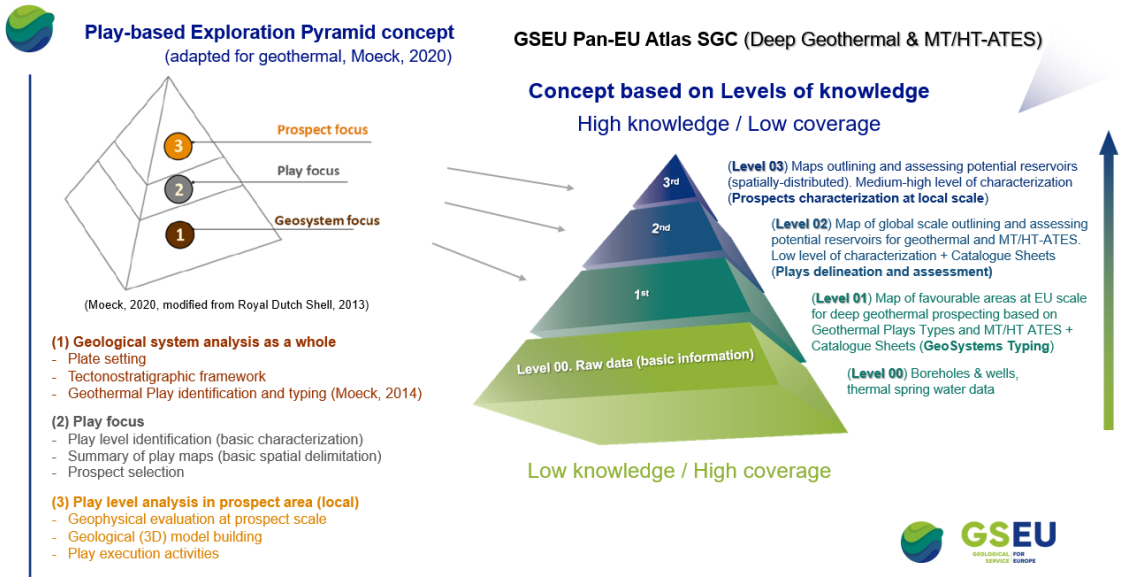


Figure 1. Play-based exploration pyramid methodology as an approach to gather, manage and construct the data to the Pan-European Atlas SGC by the Deep Geothermal thematic working group.

1.1.2 Level 00

As the foundational tier in the hierarchical structure, Level 00 offers the broadest territorial coverage but restricted geological insights within the geospatial distribution of 6982 thermal springs and 54768 geo-energy boreholes and wells as vector point datasets (in its version 1.0). All the thermal springs have a temperature of the outflowing water of at least 5 ºC over the mean air temperature of the spring point, and all the boreholes and wells at least 30 ºC and/or 800 m of true vertical depth. Based on the expert judgment of the contributing researchers and from the petrophysical perspective, some exceptions for the boreholes have been accepted. All points included in those datasets are accompanied by an attribute table populated with key attributes relevant to geothermal and/or CO_2 storage purposes, such as temperature, depth, chemical hydrofacies, among others, and which can be interactively explored through the Atlas. All thermal springs have been provided from onshore, while boreholes and wells from both, onshore and offshore positions.

1.1.3 Level 01 (Geosystem)

The following hierarchical step still offers a broad territorial coverage and includes the geological insights from the general perspective of the geological setting. Level 01, constructed as polygon vector layer from the spatial delimitation of the IGME 1:5M database (Asch, k. & Tschopp, H., 2005), is directly related to the baseload level of the pyramid structure methodology proposed and focuses on the geosystem configuration. The identification, description and classification of the geosystems across the European territory, for the GSEU project, have been performed according to the scheme from the catalogue of Geothermal Play Types proposed by Moeck (2014), and following the results obtained in Germany (Moeck et al., 2020) from the application of this catalogue. It mainly refers to the dominant heat transfer mechanisms of either conduction or convection, and the geological constraints such the plate tectonic setting, among others.

The results for this level have required the collaboration and coordination to provide a continuum map of polygons across the whole territory. From gathering, revising and discussing the available data from historic EU projects (such as the GeoEra projects, the Atlas of geothermal resources in Europe (Hurter, S., & Schellschmidt, R., 2003, among others), almost 400 polygons (Figure 2) have been provided to the Pan-European Atlas SGC conforming the areas where the future exploration in deep geothermal energy is more favourable to be performed. Each of those polygons is supported by a downloadable factsheet (Figure 2) which includes all the information gathered. In the description section, all the potential geothermal reservoirs have been highlighted including temperature and depth range, when this data is available, and the references supporting its inclusion. Note that offshore polygons have also been included, as offshore geothermal energy for power generation may become applicable soon.

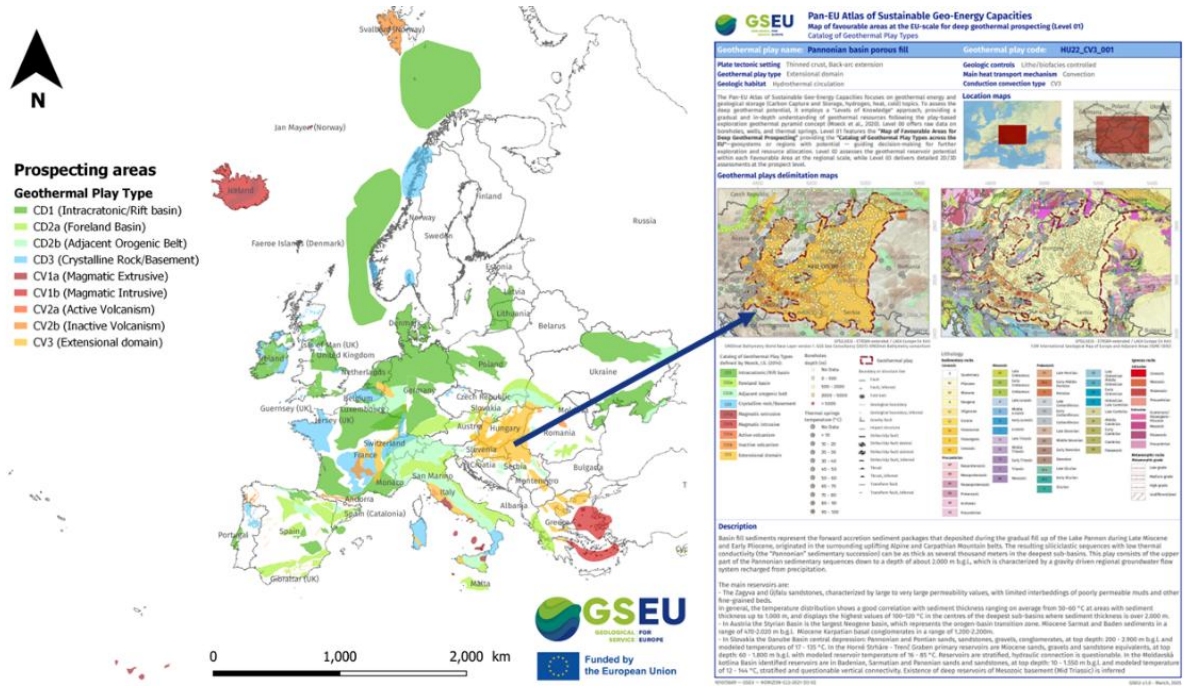


Figure 2. Polygons from favourable areas for Deep Geothermal exploration across Europe, and the factsheet from the Pannonian Basin polygon.

1.1.4 Level 02 (Play)

In this level the territorial coverage is focused on the extension of potential geothermal reservoirs and the current geothermal fields, also known as plays in the scheme from Moeck et al. (2019, 2020, 2021). The objective of reservoir delimitation is to identify reservoirs ranging from those with inferred potential in early exploratory stages to those with well-established, measured potential, for: 1) geothermal use and and/or 2) the medium to high temperature aquifer thermal energy storage (MT/HT-ATES). Both purposes have been assessed by applying a repurposed python-based tool that performs a 1D lumped stochastic calculation, following the procedure of Muffler, L.J.P. & Cataldi, R. (1978) for the Heat in Place (HIP) purpose, and the procedure of Frick, M., et al. (2022) for the Heat Storage Potential (HSP) topic. To address parameter uncertainty in the HIP and HSP equations, probabilistic distribution functions were assigned to the various parameters of for each case, using the knowledge compiled by the NGSOs. The reference temperature to assess the HIP is 30 ºC, the minimum threshold temperature of the reservoirs. For the HSP two different scenarios have been considered: 1) 60 ºC and 2) 90 ºC, which means that the natural temperature of the reservoir must be lower than these values. Following the procedure as in Level 01, each polygon in the Atlas is accompanied by a downloadable factsheet, which includes a specific description of the reservoirs and all the parameters used in the calculations.

1.1.5 Level 03 (Prospect)

In the highest level of reservoir characterisation, the extension coverage will be the lowest, focused on the exploitable area from the highly assessed reservoirs. Local evaluations based on spatial distributed data should fit in Level 03 accounting for both, qualitative and quantitative data, from the prospect perspective. It will conform the target for a specific project of geothermal energy exploitation. The aim is to gather existing datasets from previous projects, or latest results, related to deep geothermal energy, and which do not have current dedicated platforms where to be published, even in 2D and/or 3D. Indeed, is intended to include the contribution of current in-development projects, such as the Horizon Europe Go-Forward project (2024-2028) led by Fraunhofer IEG, directly involved in the assessment of fractured reservoirs of any rock source for deep geothermal energy purposes. Data published under Level 03 should follow the established hierarchy and correspond to geological formations acting as reservoirs that were previously delineated at Level 02, and that were already referenced within the geothermal play contexts defined at Level 01.

2 THE ATLAS AS A SUPPORTING TOOL

The Pan-EU Atlas of SGC is a cornerstone deliverable of the GSEU project, which includes an extended variety of reliable, harmonised, and standardised datasets from different topics related to sustainable resources. It perfectly aligns with the EU decarbonisation goals and is designed to provide policymakers a key tool for the

decision-making process, with the aim to accelerate the transition to low-carbon heating solutions and strengthen Europe's energy resilience. Regarding Deep Geothermal Energy, the Atlas serves as a tool in strategic areas such as 1) in the energy planning, by identifying of high-potential regions and suitable "go-to areas" for geothermal and UTES development, 2) helps position R&D projects in locations with the most favourable conditions, 3) In the risk reduction by providing specific and technical data from real potential reservoirs and preliminary assessments of its capacity. 4) In assisting in the cross-border coordination in between the EU and 5) by providing reliable and harmonised data that consolidates the confidence for the investor's purposes.

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