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From Industry Standard to State-of-the-Art

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Workflows, Data and Modelling Technologies for Geothermal Heat Exploration: From Industry Standard to State-of-the-Art

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Summary

High technical and economic risks stemming from the lack of detailed knowledge of the subsurface hold back large-scale investments in geothermal energy. In a survey conducted on nine use cases from diverse geological settings across Europe and with different purposes (electricity/heating and cooling) and project objectives (scientific/commercial), we identify the “common practice” and the aspiration for the “state of the art” in geothermal exploration. For each use case, the survey investigates what workflows have been adopted and what data acquired by which methods at different stages of exploration. This provided a benchmark for exploration in a range geothermal play types. The survey shows that this industry-standard base-case can be adapted to improve exploration success and efficiency by (1) applying numerical modelling in early stages of exploration to guide strategic data collection, (2) novel application of innovative technologies and (3) closer integration of software tools for static geological interpretation and dynamic heat flow simulation.

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Introduction

The growth of geothermal energy usage lags behind EU targets, because geothermal projects have comparatively high technical and economic risks that negatively impact public uptake and hold back investment. The fundamental challenge when exploring a geothermal resource is a lack of knowledge of the subsurface: geothermal fluids are produced from rocks located deep underground (up to 5 km) where limited information is available. During the exploration phase it is, therefore, desirable to acquire additional geological and geophysical data, but this takes time and often comes at a cost that is too high. However, as the price for a well failing to meet the target temperatures and flow rates is an order of magnitude greater, investment in adequate exploration is worthwhile.

We use a survey of nine use cases (Table 1) for geothermal energy across Europe to identify the industry standard and state-of-the-art for data, technologies and workflows for geothermal exploration. The use cases exploit three different types of geothermal resource: (1) Low-enthalpy resources have temperatures below 100ºC, which are hosted in (shallow) sedimentary aquifers or fractured crystalline basement; the geothermal fluid remains in the liquid phase and is used for district heating and/or seasonal storage of thermal energy. (2) Medium-enthalpy resources have temperatures of ~150ºC or more, and include deep aquifers in sedimentary strata and fault-hosted, convective geothermal fluids; the geothermal fluid remains in the liquid phase but contains sufficient energy for power production; residual heat after power production can be used for heating. (3) High-enthalpy resources are in volcanic areas and typically have temperatures of ~250ºC such that a significant amount of steam containing sufficient enthalpy can be used for power production; residual heat after power production can be used for heating or agriculture.

Test Site	Type	Use	Stage	Geology / Geological Play
Litoměřice, Czech Republic	low enthalpy	heat, cool, storage	appraisal	(Fractured) schists, (fractured) rhyolite ignimbrites, Cretaceous and Carboniferous clastic sediments
Delft, Netherlands	low enthalpy	heat	development	Early Cretaceous fluvial sandstones
UKGEOS Cheshire Observatory, UK	low enthalpy	heat, cool, storage	appraisal	Permian and Triassic fluvial sandstones (partially fractured)
London, UK	low enthalpy	heat, cool, storage	appraisal	Cretaceous fine-grained fractured carbonates (Chalk)
Rittershoffen, France	medium enthalpy	power & heat	production	Tertiary grabens with fractured Triassic sediments and Carboniferous granites
Soultz-sous-Forêts, France	medium enthalpy	power & heat	production	Tertiary grabens with fractured Triassic sediments and Carboniferous granites
Reykjavik & Mosfellsbaer, Iceland	low & medium enthalpy	heat	production	Tertiary & Quaternary basalts with abundant fractures
Hengill, Iceland	high enthalpy	power & heat	production	Magmatic
Canary Islands, Spain	high enthalpy	power	exploration	Magmatic

Table 1. *Overview of the surveyed geothermal plays and use cases.*

Test Sites

Four of the nine use cases (Table 1) are commercial projects (Rittershoffen, Hengill, Reykjavik & Mosfellsbaer, Canary Islands), five are designed to demonstrate technical feasibility and for scientific research (Soultz-sous-Forêts, Litoměřice, Delft, UKGEOS, London). Delft use case is partly commercial and partly scientific.

Workflows

Exploration strategies in the oil and gas industry follow a hierarchical, conceptual model-based exploration workflow (play-based exploration; e.g. Fraser 2010; Figure 1), which is not ubiquitous in geothermal energy. For most of the surveyed use cases (Table 1), a review of regional geological context based on previous work and legacy data formed a starting point for exploration (Figure 2). Most use cases (including all commercial projects) then utilised this review to compile an inventory of prospective geothermal systems in the region, and to generate a 'play-scale' risk assessment of these prospective geothermal systems (Figure 2). Exceptions are use cases that focus on demonstrating the technical feasibility of a particular geothermal play and/or that repurpose legacy boreholes. For most use cases, new data were collected to reduce risk in the prospective geothermal system(s). Numerical modelling of the prospective geothermal system(s) was conducted to assess the impact of geological uncertainty and to estimate possible ranges of flow rates and breakthrough times, but detailed mapping of 'sweet spots' or 'prospects' was not considered necessary in most cases (Figure 2). Conceptual geological understanding gained through these workflow steps was sufficient to estimate the geothermal resource that can be exploited (Figure 2). Collection of new data to constrain resource estimates was required before deciding to exploit the geothermal resource in Rittershoffen, Litoměřice and Delft. In addition, revision of the conceptual geological model for the geothermal play in Soultz-sous-Forêts after the start of production required additional data. Numerical modelling, probabilistic methods and/or statistical analysis, including of analogous geothermal systems, supported estimation of geothermal resources in some use cases. 1.5 to 24 person months of technical work was typically required to support the exploration workflows outlined above, although more technical work has been carried out in long-running use cases that have acted as a test bed for different technologies.

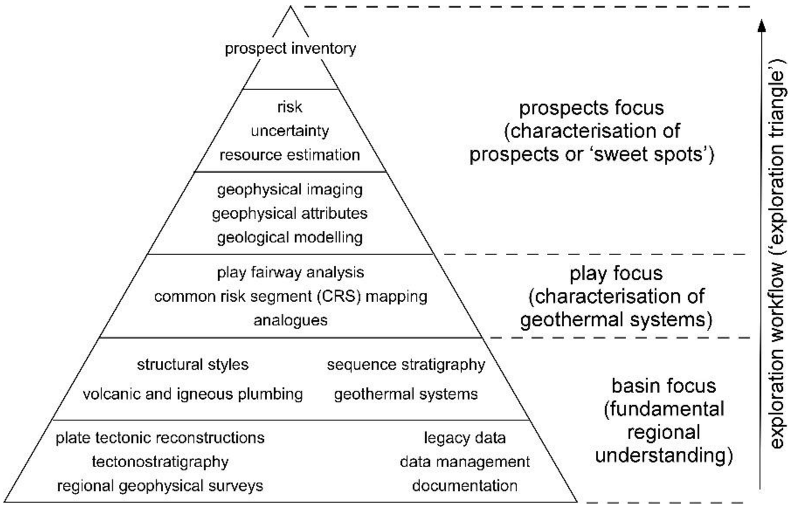

__Figure 1.__ Play-based exploration for geothermal resources, adapted from oil and gas exploration.

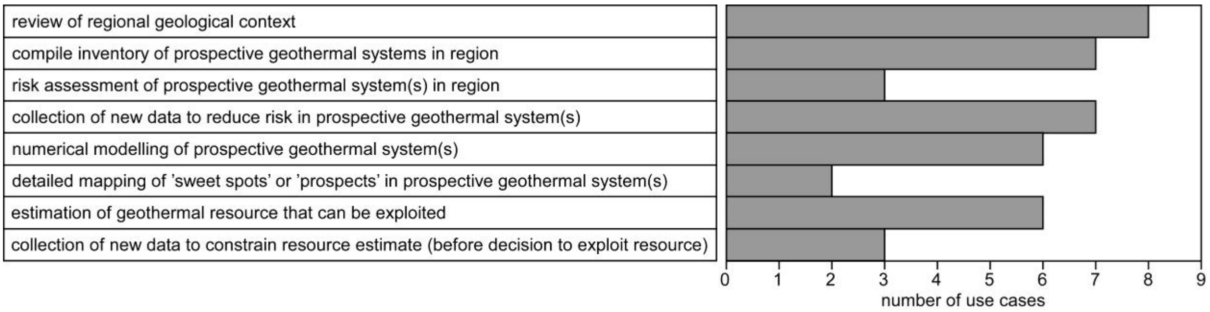

__Figure 2.__ Steps in exploration workflow used in the surveyed use cases (Table 1).

Data

A wide variety of geophysical exploration (Figure 3), borehole (Figure 4) and monitoring and remote sensing data (Figure 5) have been utilized in the surveyed use cases (Table 1), with data collection strategies aligned to the exploration workflows summarised above. For low- and medium-enthalpy geothermal systems in sedimentary basins, some data are the legacy of previous oil and gas exploration (e.g. 2D/3D reflection seismic surveys, boreholes with well logs, core, and/or cuttings). Acquiring new such data for geothermal exploration is challenging due to budget constraints, access rights, time-consuming permitting, and disruption of local communities. Alternative geophysical exploration methods exist that are cheap to acquire and/or non-invasive, for example passive seismic, controlled-source electromagnetic, resistivity, and gravity surveys. Some methods were applied to specific types of geothermal systems, such as magnetotelluric surveys of medium- and high-enthalpy geothermal systems in volcanic areas. Most use cases also use bespoke data from multiple boreholes (e.g. advanced well logs, pressure transient tests, tracer tests, core) and monitoring methods such as distributed temperature sensing along wells, seismicity, and global navigation satellite system. 2D or 3D reflection seismic and vertical (along-borehole) seismic profiles, which are both common in the oil and gas industry, were collected to support revision of the conceptual geological models at Soultz-sous-Forêts and Litoměřice. Additional data types have also been adopted for specific use cases, for example short-wave infrared spectroscopy well logs to detect hydrothermal alteration in permeable zones at Rittershoffen and Soultz-sous-Forêts (Glaas et al. 2019).

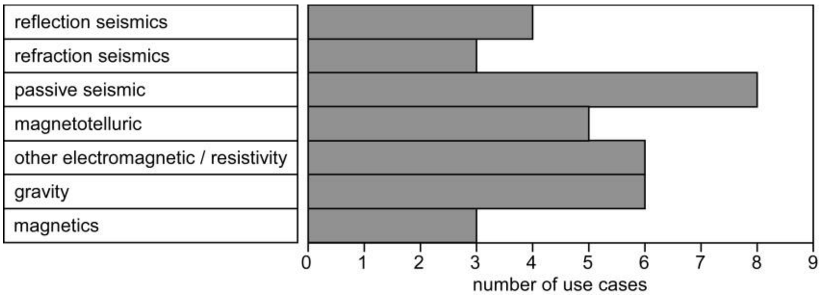

Figure 3. *Geophysical exploration data used in the surveyed use cases (Table 1).*

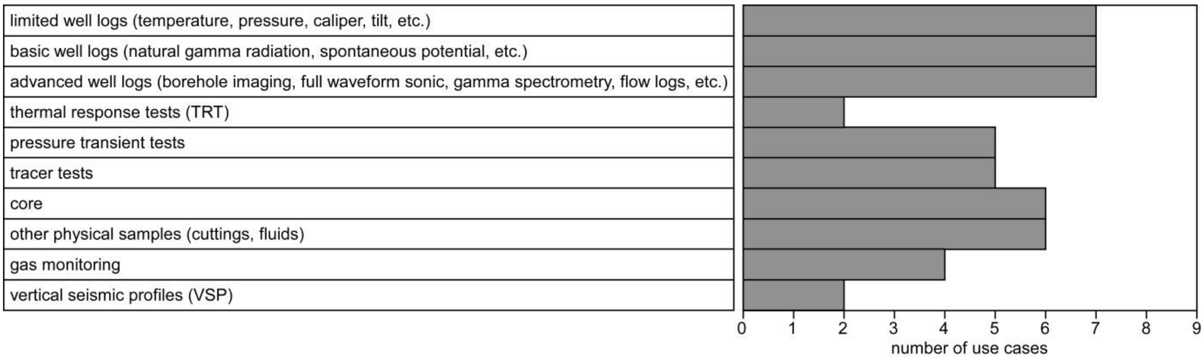

Figure 4. *Borehole data used in the surveyed use cases (Table 1).*

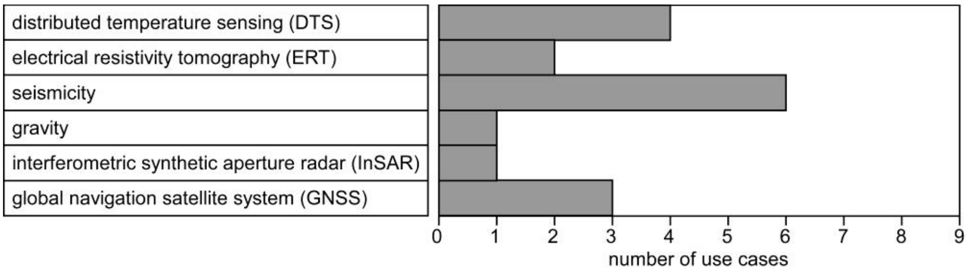

Figure 5. *Geophysical monitoring and remote sensing data used in the surveyed use cases (Table 1).*

Modelling Technologies

In addition to technologies for data acquisition and processing, a wide range of specialist software tools are used to interpret specific data types (e.g. seismic, magnetotelluric, well-log), to integrate the resulting interpretations into a 'static' geological model, and to simulate fluid flow and heat transport in a 'dynamic' model. Multiple software tools are employed for each use case, reflecting the range of data types and vintages, geological setting of the geothermal play, and availability of appropriate commercial, proprietary and/or open-source software tools. The use of multiple software tools that are difficult to integrate does not facilitate implementation of exploration workflows. In addition, the software tools and resulting modelling approaches are limited in their capacity to generate rapidly and flexibly models of multiple geological scenarios from the sparse available data, in capturing fracture properties that are an essential component of many geothermal systems, and in incorporating accurate equations of state into simulations of geothermal resources.

Future Directions: Towards State-of-the-Art in Geothermal Heat Exploration

The use-case survey provides an industry-standard benchmark for exploration in low-, medium- and high-enthalpy geothermal systems. It also highlights several ways in which this industry-standard base-case can be adapted to improve exploration success and efficiency:

(1) Multiple geological conceptual models and scenarios can be developed for most geothermal plays, based on the sparse data available during exploration and appraisal. Numerical modelling and simulation of these scenarios early in the exploration phase has the potential to inform later exploration workflows, reduce geological uncertainty and exploration risk, and guide strategic data collection.

(2) Cross-fertilisation of knowledge, data and innovative technologies (e.g. inversion of legacy seismic data, electromagnetic tomography, short-wave infrared spectroscopy well logs; Glaas et al. 2019; Gonzalez et al. 2022; Samrock et al. 2023) between operators in different types of geothermal play will help in formulating best-practice exploration workflows.

(3) Specific gaps and inefficiencies in exploration workflows can be addressed via: closer integration between software tools; incorporation of geologically constrained effective fracture properties in geological models; rapid iteration between 'static' geological models and 'dynamic' heat flow simulations; and application of open-source research software tools that simulate fluid flow and heat transport efficiently and accurately based on fundamental physical processes.

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