Introduction

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The Role of Geophysics in Geothermal Energy

Geothermal energy represents one of the most promising paths to a more sustainable energy future. It offers a reliable, renewable source of heat and power while significantly contributing to global decarbonization efforts. However, harnessing geothermal energy is anything but straightforward. Geological uncertainties, high exploration and drilling costs, and regulatory hurdles create significant risks that can limit project development. This is where geophysics becomes indispensable, acting as the "eyes and ears" of engineers in the subsurface world.

This book explores the critical role of geophysics throughout the lifecycle of geothermal projects – from initial exploration and feasibility studies to reservoir management and long-term monitoring. By employing advanced geophysical techniques, project developers can reduce uncertainties, identify optimal drilling locations, and minimize costly mistakes. The objective of geophysicists is to transform measurements of the subsurface into actionable insights, enabling engineers to unlock the Earth's geothermal potential with greater confidence and precision.

We invite the geophysical community to take on the challenge of innovating and collaborating to advance geothermal energy. Developing new technologies, refining multi-physics approaches, and monitoring are essential steps toward mitigating risks and optimizing resource extraction. Yet, progress in geophysics alone is not enough. The responsibility for advancing geothermal energy must be shared.

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Project developers, institutional stakeholders, and policymakers also have a critical role to play in enabling the success of geothermal projects. Investment in the acquisition and interpretation of geophysical data is vital for de-risking exploration and maximizing project efficiency. Without sufficient geophysical data, engineers and decision-makers are effectively navigating in the dark, increasing the likelihood of costly errors and missed opportunities. By prioritizing geophysical studies and integrating their findings into project planning, stakeholders can significantly enhance the success rate of geothermal developments.

Glossary of Geothermal Energy

Definition and Sources

Geothermal energy leverages the Earth's internal heat, originating from radioactive decay and residual heat from planetary formation. This heat transfers through conduction, convection, and radiation, creating a geothermal gradient where temperature increases with depth. Variations in the geothermal gradient arise due to subsurface geological differences.

Harnessing Geothermal Energy

Despite geothermal heat at the surface being minimal (0.06 W/m^2), subsurface temperatures stabilize below 10–20 meters, enabling surface applications like geothermal heat pumps. Deeper geothermal energy is tapped for direct heating (50 °C and above) or power generation (150 °C and above), with temperature-dependent applications ranging from district heating to electricity production.

Applications and Impact

Geothermal systems provide sustainable, year-round heat, contributing to electricity generation and industrial processes with minimal emissions. As heating accounts for 50% of global energy consumption, geothermal energy supports decarbonization efforts and reduces greenhouse gases. Installed capacity has grown globally, reaching over 16 GW for power and expanding direct-use heating applications.

Technological Advancements and Challenges

Advances in geophysics and drilling have expanded geothermal capabilities, but challenges like regulatory barriers, high drilling costs, and geological risks hinder growth. Enhanced Geothermal Systems (EGS) and closed-loop systems offer solutions in regions lacking natural hydrothermal resources, unlocking untapped geothermal potential.

Geothermal Systems

Geothermal resources manifest naturally (e.g., hot springs, geysers) or via engineered systems:

- **Direct Use**: Low-temperature fluids (30–80 °C) for heating and agriculture.
- **Electricity Generation**: High-temperature reservoirs (150 °C and above).

- **Heat Pumps**: Stable subsurface temperatures (10–16 °C) for efficient building heating and cooling.

Geothermal Resources

- Conventional Hydrothermal Systems: These systems involve naturally occurring hot water or steam reservoirs. They are typically used in volcanic or high-geothermal-gradient areas and are well-suited for electricity generation.
- Non-Conventional Systems (Enhanced Geothermal Systems and Closed Loop). In regions lacking natural hydrothermal reservoirs, EGS can artificially create or enhance pathways in hot dry rock/low permeability rocks for water to circulate, picking up heat for use at the surface. Closed-loop systems involve circulating a working fluid through pipes underground without any interaction with natural groundwater, making them potentially viable and after a complete economic assessment in a broad range of geological environments.

Hydrothermal Play

Conventional hydrothermal systems exploration requires four key elements: a heat source (e.g., magmatic activity or geothermal gradients), a porous and permeable reservoir for fluid storage, a circulating fluid to transfer heat, and a caprock to trap fluids. Geophysical methods can contribute to the assessment of these components.

Derisking subsurface elements

- **Identifying subsurface structures**: For instance, faults, fractures, and geological boundaries between different geological formations are important to characterize.
- **Mapping temperature distribution**: Mapping the temperature distribution underground and monitoring its variation over time allows engineers to target regions with sufficient heat for effective geothermal energy production.
- **Characterizing reservoirs**: It is important to have insights into rock types and properties away from the wellbore to estimate the size, depth, porosity, permeability and productive thickness of the geothermal reservoir.
- **Characterizing geothermal fluids**: Identifying fluid pathways, assessing fluid properties, tracking thermal and cold fronts in the reservoir are important to address success.
- **Fault activity assessment**: Avoiding active faults minimizes the risk of induced seismicity and other drilling complications, enhancing operational safety.
- **Real-time well steering**: Need reassurance on optimal drilling trajectories by guiding wells toward the targeted zones.

Geothermal Energy in France

Here's a summary of the geothermal energy landscape in France from the 2023 report from the AFPG (2023), including upcoming projects, current operations, and both deep and shallow geothermal energy contributions:

- Upcoming Projects:
  - 22 geothermal research permits granted for mainland France,
  - 7 research permits were issued for geothermal exploration in French overseas territories.
- Heat Production:
  - 79 deep geothermal operations are currently active in France,
  - 1 million people benefit from geothermal heating in the country,
  - deep geothermal operations generate 2.05 TWh of heat energy annually.
- Geothermal lithium extraction: several projects in Upper Rhine Graben are underway.
- Power Generation: Two geothermal power plants are operational:
  - Bouillante, Guadeloupe: 15.5 MW capacity,
  - Soultz-sous-Forêts, Alsace: 1.7 MW capacity.
- Shallow Geothermal Energy:
  - over 205, 300 shallow geothermal installations provide heating and cooling,
  - shallow geothermal systems contribute 4.58 TWh of heating and cooling energy annually from near-surface resources.

This range of geothermal initiatives highlights France's commitment to leveraging both deep and shallow geothermal energy for sustainable heating, cooling, and power generation.

Book content

After an introduction on geothermal energy and an overview of the different geothermal systems (chapter 1), the book focuses on geophysical methods. Chapters 2 and 3 give the current state of knowledge respectively in surface methods (gravity, magnetic, electrical – EM and seismic methods) and borehole methods (conventional logging, hydrogeological measurements, full waveform acoustics, VSP). Fundamentals of each method are described in basic words and illustrated with field examples, notably geothermal examples. The reader is invited to refer to the selected papers or books listed in the references for detailed information on each method.

Chapter 4 describes the integrated approach that led to the establishment of the geothermal model in the Upper Rhine Graben. It shows how the occurrence of fractured reservoirs characterized by natural brine circulations with fractured zones obliged developers to adapt geophysical exploration methods, geophysical well logging strategies as well as technical well design for reaching geothermal targets.

Chapters 5 to 10 illustrate the use of geophysical methods for geothermal exploration and monitoring, with the following topics:

- ERT-IP for geothermal exploration and de-risking,
- The use of passive seismic methods for geothermal exploration and monitoring,
- Seismic inversion and characterization applied to geothermal energy,
- Seismic anisotropy applied to geothermal prospection,
- Feasibility of monitoring cold fronts of geothermal doublets using 4D active electromagnetic techniques – a field trial in the Dogger play in the Paris Basin,
- Defining high enthalpy geothermal drilling target with multi-physics integrated exploration program. Mayotte's Petite-Terre Island case study.

This book serves as both a guide and a call to action. It highlights the value of geophysical methods in building a sustainable energy future and emphasizes the need for collaboration across disciplines and sectors. Geophysics is not just a tool; it is the bridge between the subsurface's hidden secrets and the engineers striving to harness them. Together, by investing in and advancing geophysical science, we can overcome the challenges of geothermal energy and unlock its full potential.

Reference

AFPG (2023) *La géothermie en France*, Étude de filière 2023, 6^{e} édition.