Synthesis

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A range of geothermal systems

The first deliberate attempt to generate power from geothermal energy was made in 1904 in Larderello, Italy, where the French engineer François Jacques de Larderel used steam from a geothermal well to generate electricity. Since then, geothermal technology has evolved significantly, with modern techniques now allowing us to drill deep into the Earth and access high-temperature geothermal reservoirs.

However, it's essential to recognize that geothermal energy is not a one-size-fits-all resource. We can classify geothermal systems based on the intended usage, the fluid or geological context involved, and even the energy production design.

Classifying by usage:

- Direct Use of Hot Water: This is one of the oldest and most straightforward uses of geothermal energy, in which naturally heated water (30–80 °C) from geothermal springs or wells is used for heating buildings, agricultural greenhouses, aquaculture ponds, and industrial processes.
- Electricity Generation: Higher temperatures, typically above 150°C, are required to produce electricity. In these systems, steam from geothermal reservoirs drives turbines connected to generators. These are commonly used in areas with high geothermal activity, like volcanic regions.

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- Geothermal Heat Pumps (GHPs): GHPs leverage stable ground temperatures (10–16 °C) found a few meters below the surface to provide efficient heating and cooling for buildings. This technology is widely applicable and doesn't require high temperatures.

Classifying by geological settings:

- Shallow Geothermal Systems: This involves tapping into the moderate temperatures found at shallow depths, typically up to a few hundred meters, to power geothermal heat pumps.
- Sedimentary Basin Systems: In regions with porous/fractured/karstified sedimentary layers, geothermal reservoirs of hot water can be found at moderate depths, often used for direct heating or low-temperature electricity production.
- Volcanic Systems: High-temperature geothermal reservoirs in volcanic regions are ideal for electricity generation. Countries like Indonesia and New Zealand are renowned for tapping volcanic geothermal resources for power.
- Rift and Fault Zones: In areas where tectonic plates pull apart or fracture, crust is thinner, and heat flow is higher than usual promoting geothermal reservoir development in conjunction with volcanic activity.
- Fractured Granite and Crystalline Rock: Some geothermal resources are found in fractured hard rock, where engineered geothermal systems (EGS) create or enhance pathways for water to circulate and absorb heat.

Conventional and non-conventional 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.

These advancements allow us to make use of geothermal energy far beyond natural manifestations, making it a sustainable and reliable source of heat and power. The need to characterize subsurface is critical and require the use of geophysical techniques.

A range of geophysical techniques

Historically, geophysical methods have played a pivotal role in the exploration of oil, gas, and minerals, serving as the backbone of resource discovery for decades. There are various geophysical methods, each based on distinct theoretical principles, that provide valuable data about subsurface materials. By acquiring and analyzing this data through specific geophysical surveys, we can better understand the subsurface properties and characteristics, offering important insights for exploring and managing subsurface resources and developing geotechnical engineering.

Geophysical methods encompass various techniques, each designed to characterize specific properties.

- Gravity and gravity-gradiometry are sensitive to density variations.
- Magnetic methods respond to rock magnetization properties, including magnetic susceptibility and remanence.
- Electrical and electromagnetic (EM) methods capture resistivity variations.
- Seismic methods are influenced by both velocity and density variations.

By measuring variations in the subsurface's physical properties, geophysical surveys can provide valuable insights into geological features, helping to identify critical characteristics of geothermal systems before the costly process of drilling.

Generally, no single geophysical method can characterize all the elements of a geothermal play. Each technique has unique strengths and limitations, responding to specific subsurface properties and functioning at different scales, depths, and spatial resolutions. Instead, multi-physics approaches combine several geophysical techniques, allowing experts to construct a more reliable picture of the subsurface.

Geophysics for geothermal systems

This book further illustrates the techniques and strategies that can be employed to investigate geothermal systems via geophysical methods.

Surface geophysical methods enable the construction of a 2D or 3D geophysical model of the subsurface link to one or more physical parameters. Borehole methods help to investigate the nearby well and calibrate the models derived from the surface geophysical methods. As in any geophysical study, multi-physics approaches facilitate interpretation.

By providing insights into the subsurface's physical properties, geophysical methods help better understand, assess, and monitor geothermal resources. The goal is to enable engineers to optimize production, mitigate risks, and ensure the sustainability of the reservoir. Here is a selected list of the key information that geophysicists can contribute.

- Identifying subsurface structures.
- Mapping temperature distribution.
- Characterizing rock types and reservoir properties.
- Differentiating geothermal fluids.
- Assessing fault activity.
- Real-Time well steering during drilling.

Geophysical methods contribute to the understanding of geothermal systems.

Electrical and electromagnetic methods are one of the geophysical techniques potentially sensitive to water content and temperature. Surface-to-borehole Controlled Source Electromagnetic Method (CSEM) can be used to establish an initial geo-electric state of a geothermal doublet and determine whether a cold front could be detected. Active and passive seismic methods help to better understand the geological structure of the subsurface, locating fractured zones and geological formation interfaces and potentially identify hydrothermal fluids presence and circulation pathways. Passive methods, being less invasive and cost-effective, are valuable tools. When combined, passive seismic, MT, and gradiometry can yield a shear velocity model, resistivity distribution with depth, and insights into bedrock location and fault structures. Seismic inversion and characterization are disciplines that aim at converting seismic amplitude into key reservoir properties, leading to valuable information between wells to lower the risk while planning exploration or development of geothermal production, either with low or high depth objectives. Furthermore, anisotropy magnitude and orientation, extracted by both VVAZ (Velocity versus Azimuth) and AVAZ (Amplitude versus Azimuth) analysis, can be linked to fracture intensity and orientation. The fracture characterization plays a crucial role in identifying zones with secondary porosity and enhanced permeability, increasing the prospectivity. The fracture connectivity must be evaluated to derisk the development of a geothermal project.

As an example for a geothermal volcanic system, various geophysical methods were used to confirm the existence and location of deeper geothermal resources in Mayotte's Petite-Terre volcanic Island and to define the geothermal drilling targets. Geophysical data allowed for the placement of a reservoir, a heat source, the base of the volcanic substratum, as well as several areas with higher vertical permeability (chimneys) connecting the reservoir to surface material ejection zones. MT measurements enabled the construction of a well-constrained 3D image of a potential geothermal target, Electrical profiles crossing the island detected the presence of faults, Gravity measurements were inverted to obtain a density model and confirm the presence of faults. The inversion is performed jointly with the inversion of MT data, using a global correlation of resistivity and density structures as a constraint.

As an example of a geothermal rift and fault zones system, a multi-physics image of deep fractured geothermal reservoirs is essential to reduce the risks of deep geothermal resource, as shown by the establishment of the geothermal model In the Upper Rhine Graben. The example 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.

The objective is always to select and combine the most appropriate geophysical methods to build the most comprehensive geological models for the specific geothermal system.

From resource exploration to drilling project de-risking and asset monitoring

Whatever the geothermal systems, it is important to make an inventory of existing geophysical data at the basin (exploration) or project scale (drilling de-risking). For instance, micro seismic recordings are useful to assess the seismicity of the site. For geothermal projects in sedimentary basins, it is important to make an inventory of the seismic lines that have been recorded for oil and gas exploration. The objective is to reprocess these legacy seismic lines using customized processing sequences that make it possible to obtain both an accurate high resolution structural model with distribution of faults and fractures, and a reservoir model with distribution of physical (acoustic impedance) and petrophysical parameters (porosity, permeability). Conventional processing sequences can be adapted to evaluate the potential of geothermal reservoirs, but innovative sequences are being developed. Among these innovative techniques we can mention the use of full-waveform inversion to directly infer temperature, the use of ambient seismic noise for fluid detection or the use of fiber optic for permanent monitoring.

Overall, the integration of multiple geophysical methods enhances subsurface imaging and offers more reliable insights, enabling more informed decision-making in resource exploration and drilling project de-risking of geothermal sites. Ultimately, geophysical surveys aim to optimize the success of exploration and minimize risks when planning a new well at the project scale. However, more like others, the subsurface industries now face challenges related to the energy transition, which extend beyond merely identifying sustainable energy sources like geothermal energy. It also involves adapting surveillance technologies for new purposes, such as asset and resource monitoring during production, while addressing economic constraints, and environmental concerns.