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Methodology for geothermal exploration: comprehensive approach for advanced geophysical investigations.

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Summary

Comprehensive geophysical investigations are fundamental for the exploration and development of geothermal resources, providing high-resolution, non-invasive characterization of the subsurface. Geothermal reservoirs are frequently situated in geologically complex settings, such as volcanic terrains or faulted regions, where heat and fluid distribution exhibit significant spatial variability. Conventional, limited exploration approaches risk overlooking subtle but critical features, potentially leading to unsuccessful drilling and economic loss. Integrating multiple geophysical techniques allows for detailed assessment of reservoir geometry, depth, permeability, and thermal potential, enabling optimized drilling strategies and efficient energy extraction.

Electrical and electromagnetic methods, including magnetotellurics (MT) and electrical resistivity tomography (ERT), are particularly effective in delineating zones of high conductivity associated with hydrothermal fluids, impermeable sealing layers, and shallow geological structures. MT surveys provide deep resistivity profiles, whereas ERT resolves near-surface variations. Seismic approaches, such as reflection profiling and the horizontal-to-vertical (H/V) spectral ratio method, reveal stratigraphy, fault networks, and fracture systems, critical for understanding fluid migration and reservoir compartmentalization. Gravity and magnetic surveys identify density and magnetization contrasts related to magmatic intrusions and hydrothermal alteration. Very Low Frequency (VLF) measurements complement these methods by mapping conductive faults and lithological boundaries. Collectively, these integrated geophysical datasets enhance subsurface models, reduce exploration uncertainty, and support sustainable, targeted development of geothermal energy resources.

Introduction

The primary advantage of conducting a comprehensive geophysical investigation for geothermal exploration is the acquisition of detailed and accurate subsurface information through non-invasive methods. Geothermal reservoirs are often located in geologically complex regions, such as volcanic areas or regions with active faulting, where heat and fluid distribution are highly variable. Limited exploratory methods may overlook subtle but significant features, leading to unsuccessful drilling and wasted investment. Comprehensive geophysical studies reduce uncertainty by providing a multidimensional understanding of reservoir size, depth, permeability, and thermal potential. This information enables engineers to design optimal drilling strategies, minimizing costs while maximizing energy extraction efficiency.

Electrical and electromagnetic methods, such as magnetotellurics (MT) and electrical resistivity tomography (ERT), are particularly effective in identifying zones of elevated temperature and fluid content. MT surveys exploit natural variations in the Earth's electromagnetic field to image resistivity structures at depths exceeding several kilometers. High-conductivity anomalies often indicate the presence of hydrothermal fluids, while resistive zones may correspond to impermeable lithologies. Shallow ERT surveys provide complementary high-resolution data for mapping near-surface features, such as clay caps, fault zones, and shallow aquifers, which influence reservoir recharge and heat transport.

Seismic methods are essential for characterizing subsurface stratigraphy and structural features. Seismic reflection data enable the identification of layering, faults, and fracture networks, which are crucial for understanding fluid pathways and reservoir compartmentalization. Additionally, passive seismic monitoring can detect microseismicity associated with fluid movement, providing valuable insights for both reservoir evaluation and operational safety.

Gravity and magnetic surveys provide further constraints on the subsurface structure. Gravity anomalies reveal density contrasts associated with intrusive bodies, or sedimentary basins, all of which affect the distribution of geothermal heat. Magnetic surveys detect variations in rock magnetization, which can indicate hydrothermal

alteration zones or volcanic intrusions, providing indirect evidence of thermal anomalies. Integration of these potential field data with seismic and electromagnetic results enhances the reliability of subsurface models, before the most expensive direct drilling methods.

Methods

- Magnetotelluric method (MT) – for deep scanning of electrical conductivity.
- Ground magnetic mapping – measurement of the magnitude of the total intensity of the magnetic field along profiles to separate anomalous zones.
- VLF measurements - measure the secondary electromagnetic field induced by VLF radio transmitters and provide additional information about the electrical conductivity of underground structures.
- Electrical methods (ERT) – for identifying electrical resistivity parameters in the upper part of the section.
- Seismic methods (reflected waves, refracted waves, H/V method) – for determining layers and faults;
- Gravimetry – for identifying anomalies associated with hydrothermal systems.
- Radiometry (gamma-spectrometry) – for tracking elevated areas of the gamma background caused by underground fluids.
- Measurement of magnetic susceptibility – application of field and laboratory analyses.

Magnetotellurics

The magnetotelluric (MT) method is a passive geophysical method for studying the electrical conductivity of the Earth's crust and upper mantle. It uses natural variations in the Earth's electric (E) and magnetic (H) fields, which are induced in the Earth's crust and mantle by external sources (Chave and Jones, 2012).
Magnetotelluric measurements use the relationship between the electric and magnetic fields, expressed by the impedance tensor Z:

$$E = ZH. \qquad (1)$$

The impedance is a complex value that contains information about the phase and amplitude relationships between the fields. For two-dimensional media, the impedance tensor is represented as:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix}. \qquad (2)$$

This tensor is used to determine the anisotropy and structural orientation of geological bodies.
Frequencies used in magnetotellurics, for depths up to 50 km, are in the range of 0.001 – 1 Hz
The magnetotelluric method is used to identify and map geothermal anomalies, allowing:

- Localization of geothermal reservoirs and thermal zones.
- Determination of the depth and distribution of low-resistivity zones that may be associated with geothermal fluids.
- Differentiation of zones of ascending thermal fluids and deeper zones of hot rocks.
- Identification of sealing layers that limit the migration of hot fluids to the surface.

Ground magnetic mapping and VLF

Ground magnetic mapping is a key geophysical method used in geothermal exploration. This technique involves measuring variations in the Earth's magnetic field caused by differences in the magnetic properties of underground rock formations. When applied systematically along linear profiles, it enables the creation of a detailed model of subsurface structures and helps identify areas with higher geothermal potential (Dimitrov and Stavrev, 1986).
The purpose of geomagnetic profiling in the context of geothermal exploration is to detect structural and lithological anomalies that may indicate the presence of hot fluids, fractures, faults, or magmatic bodies – all of which play a crucial role in the development of geothermal systems. Magmatic bodies, for example, often serve as a heat source, while faults provide pathways for the movement of thermal waters to the surface.
The fundamental physical principle of magnetic methods is that different geological materials have different magnetic properties that can be measured. These properties are expressed in magnetic susceptibility (χ), which determines a material's ability to become magnetized under the influence of an external magnetic field. Magnetic susceptibility is a dimensionless parameter that shows the ratio between magnetic induction (B) and external magnetic field (H):

$$B = \mu_0(1 + \chi)\mathrm{H}, \qquad (3)$$

where:
B is the magnetic induction (in Tesla), H is the magnetic field (in Amperes per meter), μ_0 is the magnetic constant ($4\pi\times10^{-7}$ H/m),
χ is the magnetic susceptibility of the material.
Differences in χ of geological materials lead to variations in magnetic induction, which are measured using magnetometers.
Magnetic anomalies occur when local variations in the magnetic susceptibility of different geological materials cause changes in the magnetic field. They can be divided into two main types:

- Positive anomalies, which are observed in areas with a high concentration of magnetic minerals, such as magnetite, or in geological structures such as magmatic bodies.
- Negative anomalies, which are observed in areas with a lower concentration of magnetic minerals or in areas with significant alternation of minerals that have low magnetic susceptibility.

Ground magnetic technique is used for profile measurements or to create magnetic maps of a given area. The obtained data helps in:

- Mapping magnetite-bearing rocks, which often serve as indicators of magmatic intrusions, potential heat sources of geothermal systems;
- Detecting hydrothermally altered zones – thermal fluids destroy magnetite, creating low-intensity magnetic anomalies;
- Identifying structural faults that function as conduits for the movement of hot water and gases.

Combining the magnetometer with a VLF sensor (which measures the secondary electromagnetic field induced by VLF radio transmitters) provides additional information about the electrical conductivity of underground structures. The Very Low Frequency Electromagnetic (VLF-EM) technique relies on the propagation of naturally transmitted radio waves (15–30 kHz) from distant naval communication stations. Subsurface conductive structures distort these fields, inducing secondary electromagnetic responses. Measuring the amplitude and tilt of the resulting magnetic field enables the mapping of faults, fractures, and fluid pathways, making VLF-EM an effective tool for shallow geological and geothermal investigations.
Combining the GSM-19W with a VLF sensor (which measures the secondary electromagnetic field induced by VLF radio transmitters) provides additional information on the electrical conductivity of subsurface structures.
The VLF-EM method is particularly sensitive to:

- Conductive fault zones – filled with mineralized or fluid-saturated rocks;
- Contacts between lithologies with different electrical properties;
- Hydrothermal zones – with the presence of clays, sulfides and other conductive minerals associated with geothermal activity.

Electrical methods (ERT)
Several electrical resistivity methods are employed in geothermal research because temperature influences the electrical properties of rocks. However, temperature is not the only factor affecting rock conductivity; increasing water content or the total dissolved solids (mineralization) can also significantly raise electrical conductivity (Kisyov, 2020).
In addition to the direct mapping of highly conductive zones caused by geothermal sources, electrical resistivity methods can also be used to locate and map fault zones, along which the transfer of hot water to the surface most often occurs, as well as to separate the various geological structures and their underlying rock foundation.
One of the primary physical and geological prerequisites determining the effectiveness of most electrical methods is the differentiation of rocks and minerals based on their specific electrical resistivity, ρ [Ωm], or their electrical conductivity, γ, measured in [S/m]. The parameters of polarizability, dielectric permittivity, and magnetic permeability, among others, are also important for electrical methods in applied geophysics.
Electrotomography is a modern approach to geoelectrical surveying that focuses on mapping in two-dimensional space. Such surveys are typically conducted using a large number of electrodes, often exceeding 25, connected to a multi-core cable. It provides the ability to obtain data from continuous sequences for certain intervals or volumes in space or in certain periods. The information obtained is about natural conditions of rock placement and provides a two-dimensional (2D) and three-dimensional (3D) study of the geological structure.

Seismic methods (H/V)

The amplification of seismic waves caused by local effects of the earth's layers is responsible for much of the material damage and human casualties in strong earthquakes. Studying the response of the support (earth environment) is important and is done using the spectral ratio method of the horizontal to vertical components of the seismogram (H/V). The method is usually used in microzoning studies and in examining the local response of specific sites, but in recent years, more studies have also used it to determine the velocity structure to greater depths (about 1 km).

The horizontal-to-vertical spectral ratio (HVSR) method (Nogoshi and Igarashi, 1971) is a passive seismic technique that utilizes ambient seismic noise, which is present everywhere in nature, including anthropogenic sources. These microtremors are detected using a three-component seismograph, and analyzing the seismic record (seismogram) helps determine the fundamental resonant frequency (f_0) of the layer beneath the seismic station close to the Earth's surface. This parameter is crucial in earthquake engineering for evaluating the local site effects. The method is entirely non-invasive and can be used anywhere without drilling or requiring external seismic sources.

Gravimetry

Gravimetry is a geophysical method used to measure variations in the Earth's gravitational field (Telford et al.,1990). These variations are due to the uneven distribution of mass in the Earth's crust and mantle, which can result from geological structures such as faults, fissures, hydrothermal reservoirs, and other geothermal anomalies. Gravimetry is widely used in exploration geophysics to assess geothermal resources, as geothermal reservoirs are typically located in areas with distinct geological structures that result in variations in the density of the Earth's layers.

Geothermal zones, typically located in regions with active faults or hydrothermal basins, are areas where underground temperatures are higher, resulting in changes to the physical properties of underground materials. In high-temperature geothermal zones, the density of rocks can be lower compared to the surrounding areas, resulting in negative gravity anomalies. Gravimetric measurements can detect these anomalies, which can then be used to identify geothermal resources.

Density changes can be associated with the following geothermal features:

- The presence of low-density geothermal aquifers;
- Faults and fissures that may contain hot fluids;
- The presence of magmatic bodies or deep geothermal reservoirs.

The proposed methodology for advanced geophysical investigations in geothermal exploration will be assessed through real fieldwork and optimized to achieve technology readiness level 7 (TRL 7).

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