



Conventional Methods of Geothermal Exploration

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Abstract

Geothermal energy, as a reliable and sustainable source of renewable energy, makes use of the Earth's natural heat that is largely continuous under the surface, as opposed to solar or wind energy, which are intermittent and reliant on the weather. In recent times, this source of energy has served as the mainstay of some nations' energy industry. However, the biggest risk in developing geothermal energy is resource overestimation, especially in the exploration phase when a deep well has not constructed yet. The problem of overestimation of geothermal energy can be solved by using conventional methods that provide accurate data about the resource. Therefore, geothermal exploration must be undertaken using a reliable method. This paper presents a study on the conventional methods of geothermal exploration. The study aimed to identify and analyze the conventional methods used for exploring geothermal energy. Secondary data were used for the study and were collected from textbooks, journals, reviews, bulletins, and reports on geothermal exploration. The findings of the study revealed that the conventional methods of geothermal exploration include geothermal exploration surveys (geological survey, geochemical survey, and geophysical survey), deep exploration drilling, and estimation methods. The study also revealed that the choice of a conventional method of geothermal exploration is based on the type of resource and application, and available funds. It was urged that the stakeholders of geothermal energy projects should understand the conventional methods in order to choose the best method for their geothermal exploration and avoid overestimation of resources.

Keywords Geothermal Energy; Geothermal Exploration; Resource Overestimation; Conventional Methods

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Introduction

Geothermal energy is one of the energy sources currently being used globally for heating (geothermal heating) and cooling and the generation of electricity. Countries such as Indonesia, U.S.A, Turkey, Italy, Philippines, New Zealand Japan and Kenya derive a substantial part of their electricity from geothermal energy sources (Richter, 2026). Geothermal energy is the thermal energy of the earth. It originated from the formation of the earth; coming together of planetisema (National Geographic Society, 2025). The thermal energy is retained in the core of the earth and some rocks within the earth interior (U.S. Energy Information Administration, 2022a). The fluids within the earth (especially water) conducts this heat and presents it as hydrothermal resources or geothermal reservoirs. Radioactivity and thermal activities (volcanism) also play important role in supplementing the geothermal energy (Turcotte & Schubert, 2002).

The earth thermal energy is distributed between the constituent host rock and the natural fluids that are contained in its fractures and pore at temperatures above ambient levels (National Geographic Society, 2025). These fluids are mostly water with varying amounts of dissolved salts, typically, in their natural in situ state, they are present as a liquid phase but sometimes may consist of a saturated liquid-vapor mixture or superheated steam vapor phase mixture. The amounts of hot rock and contained fluids are widely distributed within the earth. Thus, geothermal energy is a source of clean, reliable, stable base load power used to provide direct heat for a number of purposes, including district heating, greenhouses, electricity generation and industrial purposes (Richter, 2020). Unlike other power sources, geothermal energy is dispatchable (available whenever needed, and can quickly adjust output to match demand).

Local and regional geologic and tectonic phenomena play a major role in determining the location (depth and position) and quality (fluid temperature and chemistry) of a particular resource (Tester et al., 2021). For example, regions of higher than-normal heat flow are associated with tectonic plate boundaries and areas of geologically recent igneous activity or volcanic events (U.S. Energy Information Administration, 2022b). In prospecting for geothermal resources, people usually consider places where the above conditions are found. Moreover, the best suitable site for commercial production of geothermal energy are high temperature (>150°C) hydrothermal systems associated with recent volcanic activity and located near active plate tectonic boundaries (U.S. Energy Information Administration, 2022b) or at crustal and mantle hot spot anomalies (Lay et al., 2008). On the other hand, regions with high radioactive isotope decay are potential sites to harness geothermal energy. However, some areas of the earth called “geothermal fields” are well favored in terms of the availability of both high temperature and subsurface fluid at relatively shallow depths. In the past, only these areas have been targets for geothermal development.

Furthermore, the biggest risk in developing geothermal energy is resources overestimation, especially in an exploration phase when a deep well is not constructed yet. The greatest effort at the beginning of a geothermal project is always focused on understanding the resource through effective exploration methods in conjunction with adequate capital allocation (Purba et al., 2021). The result of resource exploration or assessment can determine the sustainability of a geothermal project. Therefore, geothermal exploration must be undertaken using a reliable method.

The aim of this study is to identify and analyze the conventional methods used for exploring geothermal energy.

Geothermal Resources

The geothermal resources or systems can be broadly classified into three systems: hydrothermal, geopressed and hot dry rock (HDR) systems. Geothermal energy is generated in form of hydrothermal energy via heating of nearby rocks and underground aquifers by magma (U.S. Energy Information Administration, 2022b). The heated or hot water can be released through geysers, hot springs, steam vents, underwater hydrothermal vents, and mud pots. The hydrothermal systems can be categorized into liquid dominated and vapor dominated (or dry steam) systems depending upon whether water or vapor is present as the continuous and pressure controlling phase (Ganguly & Kumar, 2012). However, in vapor dominated systems, water and vapor coexist together. The geopressed system

is a type of static system in which water gets trapped inside permeable sedimentary rock within low permeable rock strata. The trapped water is subjected to high pressure and temperature. On the other hand, the hot dry rock system is an artificial reservoir system in which boreholes are drilled and water is injected into hot igneous rock (Richter, 2020; Syed, 2024). The injected water extracts heat from the rock body moving through the fractures and the hot water and steam is extracted by another borehole.

Geothermal resources that have sufficient natural permeability to produce enough water at a suitable temperature for commercial power or heat production are called hydrothermal reservoirs (National Geographic Society, 2025). Geothermal reservoirs can be classified based on the energy content of utilization. The reservoirs are divided into: shallow (<200–400m, <25 °C, used for heat pumps), middle-deep (200 – 3000m, moderate temperatures), and deep (>3000m, 300 – 500 °C, used for power/district heating) based on depth and temperature (World Energy Council, 2013; Zhang et al., 2025). These reservoirs or systems tap into Earth's internal heat, ranging from low-temperature heating applications to high-enthalpy volcanic sources.

Geothermal reservoirs can also be classified based on the equilibrium state of the reservoir which depends mainly on the circulation of the reservoir fluid and the mechanism of heat transfer (Ganguly & Kumar, 2012). The first is the dynamic category, in which the reservoir is continuously recharged by water and discharged into the surface or through the permeable formations. According to the temperature regimes, this category may include high temperature systems ($T > 150$ °C) and or low temperature system ($T < 150$ °C). The heat transfer is achieved through the convective or circulating movement of water through the system. The second category is the static one that includes normal low-temperature systems and or geopressured systems, which may be found in large sedimentary basins. Static systems have little to no fluid recharge, with heat transfer primarily via conduction.

Conventional Methods of Geothermal Exploration

Geothermal exploration is the exploration of the subsurface in search of viable active geothermal regions (Manzella, 2009). The exploration is aimed at finding or discovering a geothermal field and particularly geothermal resources using a number of geophysical and geological methods. Geophysical exploration deals with measurement of the physical properties of the earth. The main focus of exploration is on parameters that are sensitive to the subsurface temperature and fluid content of the rocks. Thus, geothermal exploration involves identification of subsurface heat, fluid, and permeability using geological mapping, geochemistry, and geophysics (electrical resistivity, gravity, seismic) to locate reservoirs for power generation or direct use (Dobson, 2016). The objective of the exploration is to get the maximum amount of information about the properties of the geothermal system (Georgsson, 2009). In addition, conventional, or hydrothermal exploration focuses on locating natural, high-temperature, shallow reservoirs, often identified by surface manifestations like hot springs (Dobson, 2016). The important physical parameters/properties of a geothermal system are temperature, porosity, permeability, chemical composition of fluid, pore pressure, flow rate and water saturation. Other parameters such as electrical resistivity, seismic velocity, thermal conductivity and streaming potential can be measured and linked with the parameters mentioned above and may give important information related to geothermal system (Ochieng, 2013). The benefit of a successful surface exploration is reduction in the cost of later stages in the development phase. Geothermal exploration methods are divided into two groups: the direct and indirect methods. The methods can further be categorized into survey, deep exploration drilling and estimation methods.

Direct geothermal exploration methods

The direct methods give detailed information on different parameters that are very much influenced by the geothermal activities. The direct methods involve identifying heat, fluid, and permeability through surface and subsurface techniques, including geology, geochemistry, and geophysics (Shah et al., 2015). These methods pinpoint reservoir targets to reduce drilling risk and optimize production for conventional, naturally occurring hydrothermal systems. Direct exploratory stages include: geological field surveys (basic geology and structural geology); in situ measurements of geothermal properties (temperature, pH and flow); geophysical surveys (gravity, magnetic and magnetotellurics); hydrochemistry of naturally heated waters; and numerical modeling. These approaches usually require deep well data to constrain the models that are often limited in availability and extremely costly to acquire.

However, direct investigation gives insight about the genesis of geothermal phenomena. Precambrian basement rocks and volcanic rocks of Pleistocene-Recent age may act as a heat source, while the presence of fractures and faults creates fluid pathways. Despite the influence of basement rock lithology, the presence of intensive zones of rock fracturing and faulting is the main control on the activity of geothermal fluids. These faults are mostly associated with recent tectonic events. The methods are chosen based on the local geologic conditions and the presence of surface manifestations.

Indirect Geothermal Exploration Methods

The indirect methods give the detailed information about subsurface structures or geological bodies that are very important for the understanding of a geothermal system. The indirect exploration methods use geophysical techniques to infer subsurface structures, lithology, and heat potential without direct sampling. Indirect methods therefore, map the host rock's physical parameters to provide structural context. The common methods include magnetic, gravity (potential), and seismic surveys, which identify geological faults, rock density, and heat-carrying structures, often integrated into a conceptual model to guide drilling (Purba et al., 2021). The indirect methods involve the utilization of a Geographic Information System (GIS)-based approach in geothermal investigation by integrating constraints from different datasets such as the distribution of geothermal manifestation, rock types, tectonics, and geophysical data (Cariaga, 2025). These datasets are combined into several Thematic Layers of evidence (TL) utilizing a GIS environment, which is used to map the geothermal potential of an area, showing the priority zones for possible geothermal exploitation. The input evidence layer in the GIS model are rock types, faults, surface manifestations, seismic activity, and heat flow map derived from the aeromagnetic map. Hence, the geothermal potential map of an area can be generated by analysis of a number of TL that include geological and structural map of the area, volcanic and geothermal surface manifestations TL, seismic activity TL and heat flow TL calculated from magnetic data.

Geothermal Exploration Survey

Geothermal exploration aims at identifying the geothermal resources in terms of surface extent, volume, rock and fluid properties. Geothermal exploration include surveys such as geological survey, geochemical survey and geophysical survey.

Geological survey

In geological methods, a preliminary mapping of the selected prospects (major geological units, tectonics and volcanism) is performed. Thermal manifestations like hot springs and fumaroles and alteration (U.S. Energy Information Administration, 2022b) are also mapped and the physical properties of surface manifestations like temperature, flow rate, conductivity are measured in geological methods (Shah et al., 2015). The geological survey includes study of surface rocks in terms of mineral content, fluid inclusions and the hydrology of the area. The survey is aimed at:

1. Mapping surface geology and major fault zones.
2. Identifying the age of rocks.
3. Establishing local stratigraphy and possible permeable deep zones for geothermal exploration.
4. Identifying volcanic formations of recent geological age, which indicate the presence of hot magma chambers close to the surface.
5. Identifying hydrothermally altered rocks, which are a product of a fossil or active hydrothermal system.

Geological survey can provide valuable insight into the behavior and evolution of active fracture controlled geothermal system. The geological methods can also be used for evaluating permeability distribution, fluid flow patterns and distribution of fractures in the area (Wangie, 2012). Three dimensional (3D) geological models are the foundations of geothermal exploration, majorly helping in the interpretation of geochemical and geophysical signatures of geothermal systems.

Geochemical Survey

Geochemical methods are extensively used in preliminary prospecting of geothermal resources and during exploration and exploitation of geothermal resources. The main objective of geochemical exploration is to obtain the subsurface composition of the fluids in a geothermal system. The different composition from the fluids gives the detailed information about hot spring temperature, origin of the hot spring and flow direction (Mwangi, 2013). The survey involves analysis of gas and liquid samples from springs to estimate reservoir temperatures and fluid composition via geothermometry (Dobson, 2016). This geothermal exploration survey includes sampling of surface and near surface water, chemical analysis and application of geothermometers (Gupta & Roy, 2007). The latter assumes that the chemical equilibrium of dissolve species remains unaltered during their rise from depth towards the surface, and as chemical equilibrium is a function of temperature, the deep temperature of the fluids can be derived. Geological survey and geochemical survey or mapping are usually limited to direct observations on the surface and conclusions and extrapolation that can be drawn about the system and possible underlying structures (Sæmundsson & Sigurgeirsson, 2022). In addition, geochemical surveys are relatively inexpensive when compared to geophysical surveys and subsurface investigations by drilling.

Geophysical Survey

Geophysical surveys are surveys that are used to develop images of rock units below the shallow subsurface and to determine deeper structure that might represent permeability in a geothermal system (Shah et al., 2015). Heat sources, permeability structures, fluid flow and drilling targets are identified by an integration of geophysical techniques. Geophysical surveys include gravity, geo-electrical survey, seismic and magnetic methods.

(a) Gravity Survey

Gravity survey or gravimetry studies use changes in densities to characterize subsurface properties (Burger et al., 2006). Gravity surveys are used during geothermal exploration to define lateral density variation related to deep magmatic body (dense subsurface anomalies), which may represent the heat source (Manzella, 2009). The gravity method is a passive geophysical exploration method that involves measurement of the acceleration due to the Earth's gravitational field using a gravimeter (Sahajpal et al., 2015). The variations in gravity are due to density lateral changes of the subsurface rocks (Shah et al., 2015). Thus, the gravity method involves measuring rock density variations to delineate subsurface geological formations, such as detecting low-density zones that might indicate hydrothermal alteration.

In volcanic environments where there is a large difference in the density between the upper volcanic formations and the deeper basement of metamorphic rocks, the gravity survey provides useful information concerning the thickness of the volcanic formations. Subsurface fault lines are also identified with the gravitational methods. The densities of these faults lines are much less than surrounding material and therefore, are often identified as prime drilling locations. Changes in groundwater levels may also be measured and identified with gravitational methods (Gupta & Roy, 2007). In gravity survey, elevation, latitude and weather conditions must be carefully observed and taken into account in the survey (Burger et al., 2006).

(b) Reflection Seismic

A seismic survey is a geophysical technique that is used to develop images of the rock layers below ground. Seismic surveys record acoustic echoes from sedimentary rock layers beneath the surface. The survey is used in characterizing a potential site for storage of hydrocarbon and geothermal energy (Shah et al., 2015). The various components used in seismic surveys are energy sources, receiver, cables, recording device, and batteries. Active seismology and passive seismology are the two sub categories that are relevant to the source of the seismic signal (Burger et al., 2006). While active seismology relies on using induced/man-made vibrations at or near the surface, passive seismology uses earthquakes, volcanic eruptions or other tectonic activity as sources.

Active seismic method is of two types; refracted and reflected seismic. Reflection seismic methods are more commonly used in geothermal exploration, as they give high lateral resolution compared to refraction seismic and require much shorter profiles. The reflection seismic method is of high cost, but with credible penetration to depth

down to 3km. The method includes the reaction of an artificial seismic event and monitoring of the seismic waves as they are reflected back to the surface. Seismic methods rely on elastic waves that have different velocities when travelling through different rock types, and are refracted or reflected at discontinuities in or between formations (Zhang et al., 2021). Moreover, seismic reflection surveys can be carried out either by exploding dynamite in shot holes as an energy source or by using some non-explosive source such as the Vibroseis (Manzella, 2009). Active seismic measurements give information on the density of the formations, the porosity and texture, boundaries and discontinuities and fluid-filled zones and even temperature. In addition, processed seismic data can give information about subsurface geology, including rock types and fault structures (Young et al., 2012). The fault structures are always associated with high permeability, and are targets of geothermal production wells. Seismic data can also be correlated with gravity surveys to define more accurate velocity models (Jennejohn, 2009).

(c) Geo-electrical Survey

Electrical survey or methods (DC resistivity, magnetotelluric, and self-potential surveys) are the most common and successful tools for identifying geothermal systems throughout the world prior to deep drilling (Anderson et al., 2000; Ussher et al., 2000). The parameter of interest in the DC resistivity and magnetotelluric (MT) techniques map is the electrical resistivity of the rocks which correlates both with the temperature and alteration of the rocks (key parameters for the understanding of the geothermal systems). The DC resistivity and MT techniques map out the subsurface distribution of low resistivity cap rocks that form as a result of argillic alteration thereby defining the top and margins of the geothermal reservoir. On the other hand, the self-potential surveys can identify zones of enhanced permeability (Garg et al., 2010). The rock electric conductivity depends on the rock types, the minerals present, the fluid temperature and the fluid salinity. So, these surveys can provide excellent imaging of subsurface by delineating rock types, locating deep fault zones, and mapping subsurface hydrothermal zones which are characterized by extremely low electric conductivity.

(d) Magnetic surveys

Identifying the depth of Curie (critical) point or Curie temperature is the most common application magnetism in geothermal exploration. Magnetite is the most common ferromagnetic mineral and in most cases, the magnetic permeability is controlled by the presence of varying amounts of magnetite and related minerals in the rock (Manzella, 2009). The magnetic method is used for identifying and locating masses of igneous rocks that have relatively high concentrations of magnetite. Rocks such as basalt and gabbro are strong magnetic rocks while rocks such as granite, granodiorite and rhyolite have only moderately high magnetic susceptibilities. Ferromagnetic materials exhibit a phenomenon characterized by a loss of nearly all magnetic susceptibility at Curie temperature; changing from ferromagnetic to paramagnetic. Various ferromagnetic minerals have differing Curie temperatures, but the Curie temperature of titanomagnetite, the most common magnetic mineral in igneous rocks, is in the range of 200 to 570°C (Manzella, 2009). Although the magnetic method is useful in mapping near-surface volcanic rocks that are often of interest in geothermal exploration, its greatest potential for the method lies in its ability to detect the depth at which the Curie temperature is reached.

Deep Exploration Drilling

Drilling provides the resource and most accurate information in the geothermal exploration process, but is also the most costly method. It provides useful information on subsurface geology; rock properties, mineral present, fluid inclusion, as well as distribution of key reservoir parameters such as temperature, pressure, porosity and permeability that are necessary to access the geothermal resources. Exploration wells (slim holes), thermal gradient holes (TGH) and full-scale production wells (wildcats) created through drilling provide the most reliable information on the subsurface (Jennejohn, 2009). Geothermal characteristics such as temperature gradients and thermal pockets can be measured directly after drilling, providing valuable information. Geothermal exploration wells rarely exceed 4 km in depth. Subsurface materials associated with geothermal fields include limestone, shale, volcanic rocks and granite (Manzella, 2009). Moreover, most drilled geothermal exploration wells, up to the production well, are still considered to be within the exploration phase (Jennejohn, 2009). Drilling provides the resource for estimation methods of geothermal exploration.

Estimations

Estimation methods of geothermal exploration include geothermal gradient, temperature changes, thermal conductivity, natural heat flow, radiogenic heat production, recoverable geothermal potential, geothermometer and isothermal maps.

Geothermal Gradient

The geothermal gradient (the rate at which the subsurface temperature increases with depth) is a very important parameter in any geothermal study. The overall heat flow of the earth's surface is generally constant within any particular area; in so doing, the heat flux through the various formations with depth is in equilibrium. The rate of change of temperature across a formation with a low thermal conductivity (due mainly to high porosity) will be high. Conversely, a low geothermal gradient is indicative of the high thermal conductivity formations with much lower porosity (Hughes, 1999). For a given area, the geothermal gradient is usually assume to be constant and it can be calculated using the following equation;

$$G.G = \frac{\Delta T}{\Delta Z} = \frac{(T_2 - T_1)}{(Z_2 - Z_1)} \times 100 \quad (1)$$

Where $G.G$ is the geothermal gradient in °C/km

ΔT is the temperature change with a depth interval in °C

ΔZ is the depth interval in m

Calculation of Temperature Changes

The temperature changes in area or formation where borehole has no continuous temperature logs can be determined using equation 2 (Husson et al., 2008).

$$\Delta T = T_{bht} - T_{dt} \quad (2)$$

Where ΔT is the temperature change in °C

T_{bht} is the bottom hole temperature in °C

T_{dt} is the discharged temperature in °C

Isothermal Maps

Isothermal maps help in identifying high-potential areas for geothermal energy exploitation by showing the spatial distribution of hot rocks at shallow, accessible depths (Chambers et al., 2024). Isothermal surface of 175°C is considered to be the major important temperature for generation of electricity. Isothermal maps, specifically those calculating depth to a specific temperature, are created by rearranging the geothermal gradient formula as shown in equation 3.

$$H = \frac{(T - T_a)}{G} \quad (3)$$

Where H is the depth in m

T is the temperature on the particular depth in °C

T_a is the mean annual air temperature at the ground level in °C

G is the geothermal gradient in °C/m

Areas with high heat flow or thin crust (high G) show shallower depths for specific, high temperatures like 120°C isotherm (Chambers et al., 2024). However, the isothermal maps require accurate subsurface temperature measurements, borehole data, thermal conductivity, and sometimes radiogenic heat production data. In addition, mapping assumes steady-state heat conduction, and accuracy relies heavily on data density, which can be uneven.

Thermal Conductivity and Heat Capacity

Thermal conductivity (λ) is a basic physical property of rocks and fluids that changes with rock composition and is inversely proportional to thermal gradient (Pichugin et al., 2022). This important petrophysical parameter can be either measured in laboratory using crushed samples and well cuttings or from well logs (Demongodin et al. 1991). Based on the compressive compendia of thermal conductivity data by Clark (1966) and Roy et al. (1981), the in situ thermal conductivity of most sedimentary rocks is in the range of about 1.0 - 4.5W/m°C, although some lithologies fall outside of this range. In general, the thermal conductivity of most clastic sedimentary rocks is inversely correlated to their clay content (Deming 1996). Different types of mixing models have been proposed to relate the thermal conductivity of an aggregate to its individual components. One of the most widely used models for calculating the bulk thermal conductivity of a reservoir rock is the weighted geometric mean model, sometimes called "logarithmic mixing rule" or Lichtenecker model and is given as:

$$\lambda = \lambda_{ma}^{(1-\phi)} \cdot \lambda_w \tag{4}$$

Where, λ is the bulk thermal conductivity in W/mK

λ_{ma} is the thermal conductivity of the matrix in W/mK

λ_w is the thermal conductivity of the pore fluid (water) in W/mK, and

ϕ is the fractional porosity

The geometric mean model determines the effective thermal conductivity of aggregate/porous materials. The model shows good agreement between the calculated and experimental data for crystalline, low-porous rocks (Chopra et al., 2018), and other two-phase media, especially with low contrast (less than 20) of the thermal conductivity of the components. The difficulties in preparing the core surface for measurements of thermal properties of reservoir rocks results in 15–50% underestimation in bulk thermal conductivity (especially for highly porous and fractured samples), ignoring the influence of anisotropy and heterogeneity (Popov et al., 2013). Nevertheless, studies (Fuchs et al., 2013; Selley & Sonnenberg, 2015) have demonstrated confidence in the reliability of application of the model for reservoir rocks has been demonstrated.

Specific Heat Capacity

In order to calculate the specific heat capacity of water-saturated rocks (C_{ws}) in geothermal fields, the porosity and degree of saturation of the rocks must be known. The water content of a rock has a dominating influence on the total specific heat capacity because the specific heat capacity of water is about four to five times higher than that of the rock matrix (Scharli & Rybach, 2001). The specific heat capacity of water-saturated rock is calculated using equation 5.

$$C_{ws} = \frac{C_m \times \rho_m (1 - \phi) + (C_w \times \rho_w \times \phi)}{\rho_{ws}} \tag{5}$$

Where, C_{ws} is the specific heat capacity of water-saturated rock in J/KgK

(C_w) is the specific heat capacity of rock matrix J/KgK

C_m is the specific heat capacity of rock matrix J/KgK

ρ_{ws} is the density of water-saturated rock in kg/m³

ρ_m is the density of rock in kg/m³

ρ_w is the density of water in kg/m³

Estimation of Natural Heat Flow

The method for the estimation of natural heat flow involves estimating both conductive and convective heat components of natural heat flow from the earth to the surface (Hochstein & Bromley, 2005). The conductive heat flow is calculated by multiplying the thermal conductivity of near surface with the geothermal gradient. The thermal conductivity is estimated by core sampling and laboratory measurements while the geothermal gradient is estimated by drilling shallow bores and measuring bottom hole temperature. The conductive heat flow component is calculated using equation 6.

$$H = \iint \lambda \frac{dT}{dZ} dA \quad (6)$$

Where $\frac{dT}{dZ}$ is the geothermal gradient in °C/m
 H is the conductive heat flow in W
 A is the surface area in m²
 λ is the rock thermal conductivity in W/m°C
 T_b is the bottom hole temperature in °C
 T_a is the mean ambient temperature in °C
 Z is the depth in m

The convective heat flow component is calculated using equation 7.

$$F = \sum M.C (T_f - T_a) \quad (7)$$

Where, F is the convective heat flow in kW
 M is the mass flow rate of thermal fluid in kg/s
 C is the heat capacity of fluid is kJ/kg °C
 T_f is the fluid discharge temperature °C
 T_a is the mean ambient temperature °C

The total heat flow (F_T) is calculated using equation 8.

$$F_T = H + F \quad (8)$$

This method estimates the natural heat flow from geothermal area that has occurred for thousands of years and will continue to occur in the future, corresponding to the minimum amount of geothermal resources that can be utilized in the area.

The Radiogenic Heat Production

The abundance of the naturally occurring radioactive elements in the earth's crust constitutes a large source of heat supply to the surface heat flow. Therefore, quantifying the vertical and lateral distribution of these elements is of prime interest in any geothermal study. All natural radioactive isotopes generate heat to a certain extent, but only contributions of the decay series of ²³⁸U, ²³⁵U, ²³²Th, and ⁴⁰K are geologically significant. About 40% of the measured heat flux at the earth's surface on continents comes from the thermal decay of these radioactive elements (Leyton et al., 2017). In studying the geothermal potential of a certain area, the concentration of these radioactive elements can be determined analytically when rock samples, either hand specimens or crushed, are available or indirectly using the suitable subsurface logging suites. The radiogenic heat production can be determined from the integrated gamma ray spectrum or from the natural gamma spectrometry log.

Gamma Ray Method: The empirical relationship introduced by Buecker and Rybach (1996) can be used to derive the heat production from gamma ray reading (API). The general form of this equation is;

$$A = a(GR[API] \pm b) \quad (9)$$

Where, A is the rate of radiogenic heat production in μW/m³
 a and b are empirical constants

Natural Gamma Ray Spectroscopy: The radiogenic heat production rate (A) is a scalar and isotopic petrophysical property independent of the in-situ temperature and pressure. The radiogenic heat production rate can be determined using equation 10 if the concentration of uranium (U), thorium (Th) and potassium (k) elements, and the density (ρ) of the rock are known (Abubakar et al., 2023).

$$A = 10^{-5} \rho (9.52C_U + 2.56C_{Th} + 3.48C_k) \quad (10)$$

Where, A is the radiogenic heat production rate in μW/m³
 C_U is the concentration of uranium in ppm

C_{Th} is the concentration of thorium in ppm
 C_k is concentration of potassium in ppm, and
 ρ is the rock density in kg/m^3

Geothermometry

The principal purpose of geochemical surveys is to predict the subsurface temperatures to obtain information on the origin of the geothermal fluid and to understand the subsurface flow directions. Geothermometer is a chemical substance or isotope in water that may be used to predict the subsurface temperature in geothermal systems. The basic assumption behind using the geothermometers is the chemical equilibrium between the substance (minerals and isotope) in the reservoir (Nilgün, 2003). While using these geothermometers, an approximation is made that chemical and isotopic reactions do not significantly modify the composition of the fluid as it ascends from the source aquifer to the point of sampling, whether it is at well head, thermal spring, or fumaroles. Theoretically, any cation ratio and any aqueous species concentration can be used as a geothermometer as long as equilibrium prevails. The most important geothermometers are the silica (SiO_2), Na/K, and Na-K-Ca geothermometers. The important form of silica geothermometer used in this study is quartz and its temperature equation by (Fournier, 1977) is:

$$T = \frac{1.309}{5.19 - \log C} - 273.15 \quad (11)$$

Where T is the temperature in °C
C is SiO_2 concentration in mg/l

Quartz geothermometers estimate subsurface temperatures in geothermal systems (usually greater than 150 - 200°) based on silica solubility in water (Nilgün, 2003). They assume that hot water in the reservoir is in equilibrium with quartz. One of the limitations of geothermometer is that silica may precipitate during ascent to the surface, causing underestimation of temperatures.

Recoverable Geothermal Potential

Recoverable geothermal potential is the subset of total subsurface thermal energy that can be technically and economically extracted over time, typically estimated using recovery factors and numerical modeling of reservoirs (Fan et al., 2022). The concept of recoverable geothermal potential varies with respect to the type of rock formation and its peculiarity characteristics and provenance. These may include but not limited to Deep Saline Aquifer, Hot Dry Rock Formation and Geopressured Reservoirs amongst others. Key methods for determining recoverable geothermal potential are assessment metrics (total heat in place, recovery factors, reservoir temperature ranging from 50 to 250°C+ and wellbore heat loss) and estimation methods (numerical thermo-hydraulic coupled modeling). Geopressured reservoirs or geopressured gas reserves can be estimated using Quantitative Geopressured Gas Reserves (QGGR) method.

Determination of QGGR requires accounting for high rock compressibility, water expansion, and shale water influx. The common methods include modified material balance equations (MBEs), binomial regression for pressure-production data, and volumetric calculations based on reservoir geometry and high-pressure fluid properties (Zhu, et al., 2024). The MBE is the primary method, incorporating complex drive mechanisms, such as rock compressibility, water influx, and abnormal pressure, tailored for unconventional reservoirs like shale gas or condensate systems (Abdel et al, 2023).

The production term is expressed as;

$$Production = Fluid\ Expansion + Rock\ Compression + Water\ Influx + Desorption$$

The production term has many models, and it assumes that gas is stored as free, absorbed, and dissolved gas. The volume of dissolved gas in formation water is insignificant compared to the volume of free and absorbed gas, so it can be ignored (Zeng et al., 2021). It is also assumed that the production process is isothermal, natural fractures serve as pathways rather than storage spaces. So, when the pressure falls below the critical desorption pressure, gas

is subsequently released (desorbed) from organic matter and the shale is deformed due to the combined effects of stress changes and matrix shrinkage.

Conclusion

This study has revealed that the conventional methods of geothermal exploration include geothermal exploration surveys (geological survey, geochemical survey and geophysical survey), deep exploration drilling and estimation methods. The study has also revealed that the choice of a conventional method of geothermal exploration is based on the type of resource and application and available fund.

Finally, it is necessary that the stakeholders of geothermal energy projects should study and understand the conventional methods in order to choose the best method for their geothermal exploration and avoid overestimation of resources.

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