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Characterization of Geothermal Reservoirs

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ABSTRACT

Characterization of geothermal reservoirs is crucial for efficient heat recovery and representative numerical reservoir simulation. The applicable reservoir characterization techniques are pressure transient tests, stratigraphic maps, tracer tests, reservoir surveillance, seismic interpretation, outcrop analysis, well logs, and drilling mud loss data. These techniques provide crucial information about natural fractures in the reservoirs from millimeters to kilometers in length. The accuracy and detection limits of the characterization methods are critical for their applicability in geothermal reservoirs. Some are limited with wellbore diameters, while others might provide large-scale information about fractures. We present the theories, implementation, advantages, and drawbacks of the geothermal reservoir characterization techniques. This study aims to serve as guidance for geoscientists interested in reservoir characterization. Field applications and the latest approaches are provided to increase the understanding of the subject.

1. INTRODUCTION

Natural fractures, vugular shape pore spaces, and artificially created fractures are the main fluid conduit paths in the geothermal reservoirs. The fracture systems usually show anisotropic behavior, which is critical for developing geothermal reservoirs. The primary target of the geothermal producers is to successfully place geothermal wells into productive and high-temperature zones called sweet spots. Target zones can be identified by characterizing pressure, temperature, and fractures in geothermal fields. Numerous characterization methods are applied to decrease uncertainty in heterogeneous reservoirs. The important characterization techniques are well testing, tracer test, seismic, outcrop analysis, drilling data, production monitoring, well logging, and modeling approaches.

Typical preliminary works conducted in a geothermal field are formation identification, outcrop analyses of reservoir rocks and faults, geochemical analyses of spring water, and natural geothermal discharges. As the result of the geological studies, the prospect area is determined for seismic measurements. High-quality 2D-seismic and 3D seismic measurements are interpreted to understand the distribution of horizons and faults' dip and angle. Thus, a 3D structural and geological model of the field is constructed as a basement for the geothermal project's exploration, production, and appraisal phases. After a long evaluation of the aforementioned studies, drilling activities are successfully completed, and well completion tests are performed to understand wells' deliverability. Pressure transient tests are then performed to understand important reservoir parameters and wells' connectivity, which will be used for the field injection and production strategies, and field development. The characterization studies conducted during the production phase of the field are production monitoring of pressure, temperature, and non-condensable gases. Besides, a tracer test is essential to understand the connectivity between injection and production wells during long-term production. Numerical reservoir simulation is the most comprehensive study that includes all the aforementioned studies.

This study aims to provide a comprehensive review of reservoir characterization techniques applied in geothermal fields. The working principles, latest advances, advantages, drawbacks, and field applications of these methods are presented to give good insights for geoscientists. We categorized geothermal reservoir characterization techniques during exploration and production phases (figure 1).

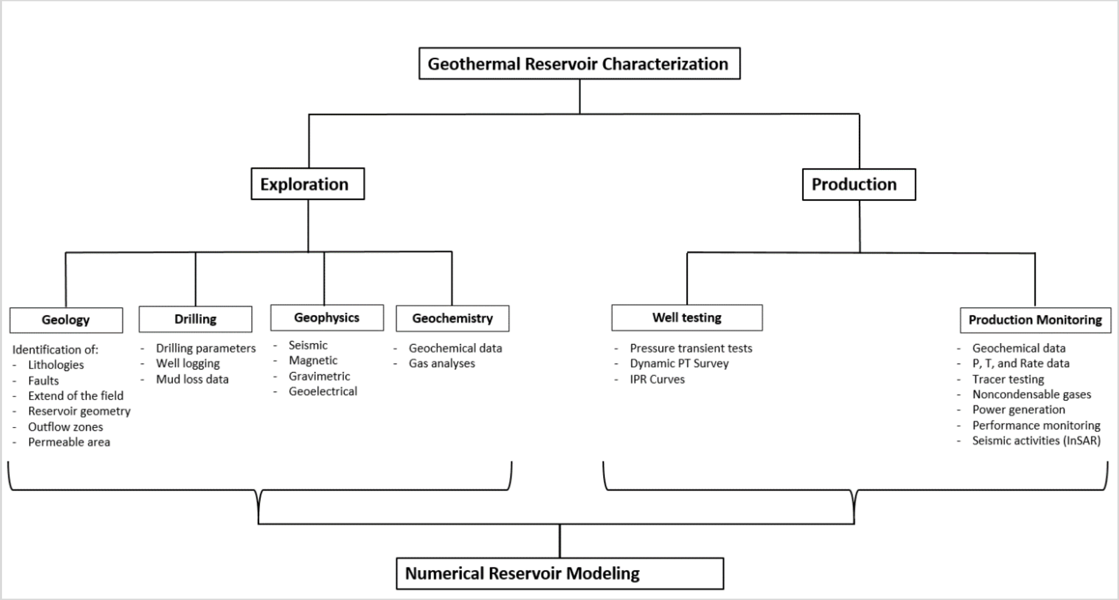

Figure 1: Geothermal characterization techniques

2. CHARACTERIZATION TECHNIQUES DURING EXPLORATION

Exploration of geothermal resources in a wildcat field requires extensive study that involves geophysical, geological, and geochemical studies. A collaboration work of these disciplines help to understand the geometry of the reservoir, heat source, lithologies, hydrological system and evaluation of tectonic activities in the field (Ochieng, 2013).

Geological study starts with understanding surface geology and identifying lithologies by analyzing rock minerals. Rock outcrops are analyzed in the Scanning Electron Microscope (SEM), XR- Diffraction (XRD), and XRF measurements. The rocks' mineral content and alteration types are identified to evaluate the geothermal prospect area. The fault traces on the surface are identified with their dip angles and directions. The geological formation map and structural geological map of the field are constructed. Well-site geologists play an important role during drilling. Cutting analysis is critical for the drilling casing program and proximity to the fracture zones. Well-site geologists typically look for diagnostic features of the cuttings such as alterations, rock hardness, brittleness, rounding, color, and sorting. Bignall et al. (2010) defined lithologies and extending the geological formations in the western Wairakei-Tauhara system by using alterations. Mijnlieff (2020) highlighted the geothermal potential of Cenozoic, Upper Jurassic-Lower Cretaceous, and Triassic oil reservoirs in the Netherlands. A conceptual model of geothermal fields is constructed mainly based on the distribution of geological formations. Fragoso-Silva et al. (2021) integrated geologic observations with MT and gravity data to update the conceptual model of the Domuyo geothermal area, northern Patagonia, Argentina. Tut Haklidir et al. (2021) updated the conceptual model of the Kızıldere geothermal field, Turkey, by using new findings with deep wells (figure 2).

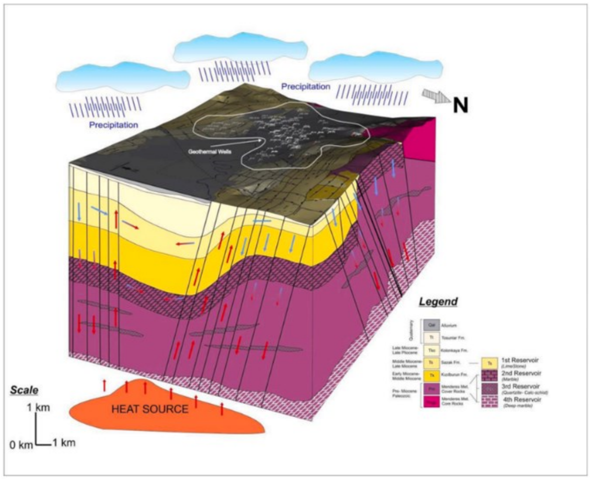

Figure 2: Geological conceptual model of Kızıldere geothermal field (Tut Haklidir et al. 2021)

Geophysical methods implemented in geothermal exploration have been developed originally for oil and gas reservoirs. This technology was transferred to the geothermal industry by adopting measurements to high temperature, steam, and brine. Geophysical exploration methods typically measure the physical properties of rocks. The measurements are focused on the temperature, salinity, permeability, and porosity of the geothermal reservoirs. The widely applied geophysical methods in geothermal exploration are seismic, electromagnetic, radiometric and electrical methods. Well location of a new drilling well and the target depth of the well is determined by evaluation of geophysical data.

Seismic is one of the indirect geophysical methods that measure sound velocity distribution and anomalies in the earth. The source of a sound wave is generally hammering devices and explosions (figure 3). This is called active seismic. In the passive seismic, the seismic activity in the earth is monitored to obtain information about the geothermal system. Passive seismic relies on natural seismic activity to understand the active faults and permeable zones in the field. The seismic working principle relies on the velocity of two types of elastic body waves, which are P-waves and S-waves. P-waves movement is in the travel direction while S-waves materials movement is perpendicular to the wave direction (Kana et al., 2015). S-waves penetrate only through solid rocks, not fluids. Active measurements provide information about the density of the formations, texture, porosity, boundaries, and discontinuities. Fadel et al. (2021) used three seismic attributes to create a 3D facies model of the German Molasse Basin. Aravena et al. (2021) used 13 horizontal/vertical ratios of seismic noise to delineate geothermal potential in the Puyuhuapi, Southern Patagonia, Chile. Gonzalez (2021) characterized fault networks in geothermal exploration with seismic attributes. The study proposed an automatic workflow to characterize the fault plane instead of manual effort in tracing faults. Austria et al. (2021) investigated the effects of fracture permeability and saturation on the seismic attributes in a Philippine geothermal field. They showed that P/S wave velocities were reduced significantly after fracture development.

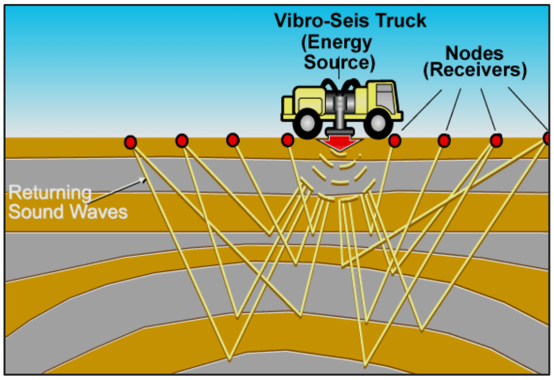

Figure 3: Seismic Reflection Survey (Geosiam, 2021)

The magnetic method is typically used to complement gravity and seismic measurements in mapping geothermal structures. The two main magnetization of rocks are induced magnetization and permanent magnetization. The properties of igneous rocks predominate the permanent magnetization. Induced magnetization is in the same direction as the earth's field. A common practice of magnetic measurement in geothermal fields is about 100 m above ground and 100 m spacing between profile lines, influenced by topography at the down. Parallel profile measurements are done for local structures like particular faults. Magnetic anomalies are attributed to alteration zones or igneous rocks. Magnetic method is widely applied in the exploration of geothermal resources. Mohammadzadeh-Moghaddam (2012) presented a magnetic survey over 250 square kilometers of the ground surface in Mahallat, Iran, for geothermal exploration. Zaher et al. (2018) estimated the Curie Point Depth (CPD) and geothermal gradient at Siwa Oasis, Western Desert, Egypt, by using airborne gravity and magnetic survey. Ismail et al. (2019) used magnetotelluric data acquired at ten stations to understand the subsurface structures of Suelawah Agam geothermal field in Indonesia. Maryanto et al. (2019) acquired magnetic data from 80 magnetic stations at geothermal area of Mount Pundan, East Java, Indonesia. Zhao et al. (2020) used magnetic data with gravity data for the delineation of EGS in Gonghe town, China. The study reported that lithology, stress, and hydrothermal alteration affected the density models. Therefore, seismic and microgravity would be needed for more precise interpretation. Zhang et al. (2021) investigated the geothermal structure of the Sulawesi in the western Pacific by using gravity and magnetic method. They calculated the curie depth of this region as 14.3 km.

The density contrast between formations creates the gravitational force that can be measured to delineate subsurface structures. The gravimetric method determines the density of subsurface rocks, governed by the mineral contents and porosity. Several corrections are needed to determine the subsurface density. Bougar anomaly correction is the most widely used one.

The geoelectrical method uses the electrical resistivity of the subsurface formations for stratigraphic and structural information about geothermal reservoirs. Electrical methods are categorized based on the type of power source. Active method uses electric source from alternative current or direct current to the ground in vertical electrical sounding called Schlumberger. The passive method uses natural electromagnetic fields as power sources energizing the ground.

Drilling activities start after the evaluation of geophysical and geological interpretations. The important data sources used for formation characterization are penetration rate, torque, drilling mud loss data, and well logging during drilling. The penetration and mud loss rate generally increases in unconsolidated formations and fractured zones. Therefore, the lost circulation of mud loss can be attributed to permeable zones if the drilled formation is consolidated. Mud loss data is used to characterize natural fractures in geothermal wells by using cubic law, overpressure ratio, and radial flow relations. Machine learning methods like neural networks are useful to characterize formations using drilling data.

Brine geochemistry and reservoir gas analysis provides tremendous information such as flow direction, the origin of the water and gases, and the temperature of the resource. Generally, geothermal brine is originated from meteoric water, oceanic water, and magmatic water. Geothermal brine is classified according to its anion and cation contents. The most widely used descriptions are bicarbonate water, acid sulfate-chloride, acid-sulfate water, and alkali-chloride water (Mwangi, 2013). Conservative components like stable isotopes (^{2}H and ^{18}O) are used as complementary to B and CI to trace the origin of water and flow direction in the reservoir. Important geochemical data used for subsurface temperature estimations are Na, K, Ca, Mg, SiO_2, CO_2, and H_2.

3. CHARACTERIZATION TECHNIQUES DURING PRODUCTION

Pressure transient tests are conducted to obtain crucial information about reservoir characteristics such as permeability, porosity, thickness, boundaries, skin factor, etc. Well test applications gained popularity with the development of permanent downhole gauges and resistance of test tools in harsh conditions. Modern well test analysis using computer software is the other revolutionary step in well testing. The most widely applied pressure transient tests in geothermal reservoirs are pressure buildup, drawdown test, interference test, and injection fall-off test. The theory of all kind of pressure transient tests works in similar way that a pressure disturbance is created in the reservoir by either changes in production or injection rates. The pressure variation in the reservoir is observed with time. The pressure recording data is then interpreted in the special well testing analysis plots such as semi-log, log-log, Horner plot, etc., to obtain important information about reservoir rock.

Dynamic PT survey is conducted periodically in production wells to understand dynamic reservoir parameters such as temperature and pressure variations. The dynamic PT profile of the well is used as calibration data for the wellbore flow simulators. The calibrated flow simulation can then be used to understand flow behavior at different flow rates. Inflow Performance Relation (IPR) curves can be constructed using wellhead flowing pressure and flow rates. The IPR curves should be periodically updated.

The typical flow rate of geothermal wells varies between 100 ton/hour and 500 ton/hour, which are very large rates compared to oil wells. This is because of high reservoir conductivity and low fluid viscosity. Therefore, well-interference is high in geothermal reservoirs. Monitoring of production data is essential for evaluating connectivity and performance estimation of the reservoir. In practice, wellhead data is recorded and stored via SCADA and DCS systems. Downhole data is generally gathered only when PT survey is conducted. Geochemical data are used to understand the hydraulic connection between injection and production wells. Chloride and NCG are the most widely monitored parameters indicating the contribution of reinjection in production wells. Silicate is a temperature-sensitive mineral typically used to estimate temperature variation in the production wells. Aydin et al. (2018) monitored Alaşehir geothermal reservoir in Turkey by evaluating changes in production wells' Cl and SiO2 concentrations. Strong hydraulic connectivity was reported between injection and production wells, causing the thermal effect.

Tracer testing is a strong method used to characterize geothermal reservoirs. Typical tracers used in geothermal reservoirs are fluorescein, naphthalene sulfonates, salts, and radioactive elements. A quantitative tracer test analysis provides detail information about geothermal reservoirs such as swept pore volume, fluid mean traveling time, Peclet number, and flow paths. Analytical models are used to simulate tracer concentration data. Multi-fracture and Double Porosity models are the two most representative models for geothermal reservoirs. Aydin and Akin (2021) simulated tracer return curves with a multi-fracture model in Alaşehir geothermal reservoir, Turkey. Aydin et al. (2022) matched tracer breakthrough curves of Salihli geothermal reservoir, Turkey, with double fracture-matrix and multi-fracture models.

Due to high fluid is withdrawn from limited reservoir volume, surface deformation is observed as ground subsidence in the geothermal areas. Senturk et al. (2020) reported a significant pressure decline in the Kızıldere geothermal field after production from wells at the capacity of 165 MWe. Interferometric Synthetic Aperture Radar (InSAR) is an advanced technique measuring ground deformation from radar images of orbiting satellites. Seismic is also used to monitor induced seismicity created by reinjection fluid into geothermal reservoirs. Evans et al. (2012) documented 42 European case histories describing the seismogenic response to fluid injection into sedimentary rocks.

4. NUMERICAL RESERVOIR SIMULATION

Numerical reservoir simulation is the most comprehensive characterization technique that is populated with different data sources such as geology, geophysics, well testing, production data, and tracer tests. A 3D numerical model starts with the construction of the conceptual model. In the conceptual model, geological data and fault planes are created based on field observations and drilling data. Existing wells are also created on the conceptual model with their orientation and inclination. The grid process is performed to subdivide the large reservoir volume into small pieces that are used for the finite-difference fluid flow process. Model boundaries such as heat source and no flow boundaries are defined in the model. The natural state of the model is calibrated with the static PT profile of the wells. The steady-state model is then tested under a transient flow regime. In the transient phase of the model, the model is calibrated with the pressure and temperature data of the wells. The tuning parameters for model calibration are permeability and porosity. A calibrated numerical model can be used for production forecasts under a different scenario. Numerous reservoir simulators are available to model geothermal reservoirs. The most widely used numerical model code group is TOUGH2. Aydin and Akin (2020) and (2021) estimated upcoming problems in Alaşehir field, Turkey by using a numerical reservoir model. They highlighted NCG decline and temperature reduction of the wells as the most significant risk in the near future of the field. They also created a DFN model of the field using FracMan software.

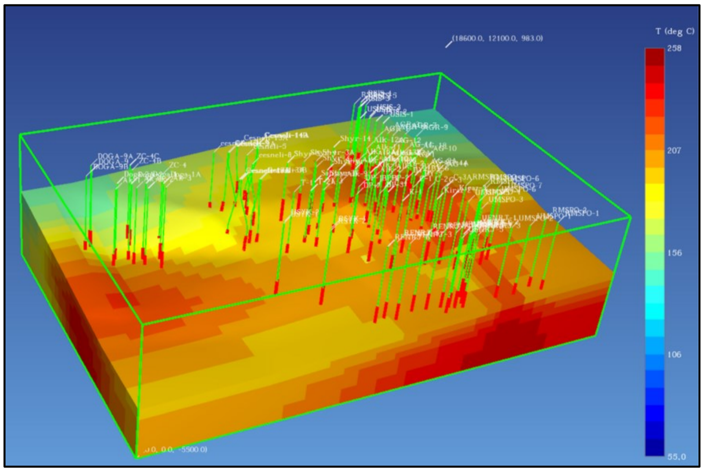

Figure 4: Numerical reservoir simulation of Alaşehir field (Aydin and Akin, 2021)

5. CONCLUSION

Geothermal reservoirs are highly heterogeneous systems requiring advanced methods to understand their behavior. We divided geothermal characterization methods into two phases: the first group is categorized under exploration, and the second group was reviewed under the production phase of the geothermal projects.

The exploration phase of the geothermal characterization, geology, geophysics, geochemistry, and drilling are studied with their theories and field applications. These methods can be complementary to each other for a better understanding of the heterogeneous system. Despite various advantages, they have some drawbacks. To illustrate, seismic can cover a large field area; however, it cannot describe small fractures. The outcrop is a reservoir rock sample, which is not under confining pressure. Deformation and erosion of outcrop might lead to wrong interpretation about reservoir rock. Therefore, it is critical to decide on the most reliable data source during characterization.

The production phase of the reservoir is a dynamic process in which data changes with time and well-interferences. Pressure transient tests are crucial in the characterization of geothermal reservoirs because most critical information is gathered through PTA. Dynamic PT surveys should be periodically performed in a producing well to monitor temperature and pressure variation in the reservoir. Tracer test is an advanced method to understand the connectivity between injection and production wells. Quantitative analysis of tracer tests can provide important information about flow paths in the reservoir. Seismic methods are implemented to monitor seismicity and surface deformation created by production and injection in geothermal reservoirs.

Numerical reservoir simulation is the most comprehensive characterization method describing the geothermal system by involving all other characterization methods. Model calibration is critical in the modeling study. A representative numerical model can be used to forecast production under different scenarios.

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