GEOTECHNICAL METHODS IN GEOTHERMAL RESERVOIR EXPLORATION

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INTRODUCTION

The purpose of this brief presentation is to discuss a number of commonly employed geochemical and geophysical methods in geothermal reservoir identification, both their assets and shortcomings. The latter must be discussed explicitly, because lack of appreciation of the pitfalls of each of the employed methods may lead to unwarranted conclusions regarding the existence of a geothermal reservoir, and its expected temperature and volume.

The term reservoir in itself must be cautiously employed. A geothermal reservoir, especially a liquid-dominated reservoir, cannot be likened to a petroleum reservoir, where the resource itself has a definite mass and fairly well-defined boundaries. Petroleum cannot be replenished at a rate that has any meaning in terms of a life of a power plant. On the other hand, a geothermal reservoir may receive very significant contributions of both heated fluid, colder water and heat during the life span of a power plant (one-third of a century). Hence, the definition of reservoir must be made more explicit and must state whether the dynamics of the system (i.e., recharge region of heat and water, and recharge rate) are included in the area defined as a reservoir.

GEOCHEMICAL METHODS

Surface geochemical methods provide important clues as to the nature of the geothermal system in a region, whether liquid-dominated or dry steam (vapor) dominated, whether saline or brackish, whether single reservoir system or a mix of two systems or a dry steam system leaking into a liquid-dominated system. However, assertions based upon geochemical data are fraught with pitfalls due to unfulfilled conditions.

Sampling of hot springs at the surface provides means for determining the base temperature of liquid-dominated reservoirs, and for identifying the presence of vapor-dominated reservoirs. A geothermal reservoir at any given temperature will dissolve a known amount of silica at that temperature. As the reservoir fluid cools from its original temperature to a much lower temperature as it travels towards the surface, it may retain most of the dissolved silica in solution. Thus, the dissolved silica in solution becomes a fossil thermometer, indicating the minimum reservoir temperatures.

One problem with silica thermometry, which may tend to cause an overestimation of reservoir temperature, is that of assuming quartz solubility vs temperature as the calibration curve. If other types of silica, such as opal, cristoballite or amorphous silica are present in an abundant amount in the host rock, the quartz solubility geothermometry would provide an unduly optimistic reservoir temperature estimate.

An unduly pessimistic estimate of reservoir temperature, based upon silica thermometry, may be arrived at when there has been dilution of the original reservoir liquid with shallower, colder ground water; when the actual reservoir temperature is above 180°C (356°F); when the rate of movement of the geothermal liquid to the surface has been very slow, and when a high-solubility of silica (e.g., amorphus silica solubility) has been assumed while quartz solubility would have been more appropriate.

The solubility ratio of Na/K is another often-employed geochemical thermometer. The Na/K ratio in geothermal water is inversely proportional to temperature, for the temperature range of geothermal water. The advantage of the Na/K ratio is that, like any other ratio, it is not affected by dilution by pure water. Yet, many problems may occur in the use of the Na/K geothermometer. The solubility of Na and K in cold ground water is quite different from that in the geothermal range, or alternatively, no equilibrium with temperature is normally attained at normal surface water temperature. However, advance knowledge of equilibrium conditions in the source rock is not known. Hence, other verification approaches are required. Another possible thermometer is the Ca/K thermometer, inasmuch as Ca solubility is inversely related to temperature. Some workers (Fournier and Truesdell) have recommended combining Na-K-Ca into one single thermometer, by using certain empirically derived relationships.

Discrepancy between different geothermometers may serve as a warning that the simplest rules of chemical thermometry are not necessarily fulfilled. Furthermore, an agreement between independent geothermometers in themselves does not provide assurance against fortuitous coincidence.

GEOPHYSICAL METHODS

Electrical resistivity methods, both active and passive, may provide important information on the location of reservoirs and their dimensions, or the occurrence of a heat source nearby and its geometry. Under especially favorable conditions, resistivity data may be employed to provide semiquantitative data on relative salinities, relative temperatures, and relative porosity. Without exception, all known liquid-dominated reservoirs anywhere in the world are characterized by electrical resistivities that are lower than those of the surrounding rocks. Most liquid-dominated geothermal reservoirs are characterized by resistivities less than 5 ohm-meters, no matter how high the resistivity of the surrounding country rock.

Electrical resistivity is affected by five different factors:

(1) Temperature. At temperature ranges of 20-300°C (68-572°F), the electrical conductivity of the electrolyte, the water, provides the main conductive component of the system. Electrical conductivity of electrolytes increases by about 2.5% per degree centigrade. At temperatures near melting (500-1000°C [932-1832°F]), matrix conductivity becomes important. The resistivity of some silicate rocks at melting is 1-2 ohm-meters.

(2) Salinity. Electrical conductivity varies almost linearly with salinity of the pore-fluid.

(3) Porosity. Electrical conductivity increases approximately with the square of porosity.

(4) Formation Factors. Tortuosity of the pore space decreases its electrical conductivity (increasing the 'formation factor').

(5) Clay Content. The higher the clay content, the higher the matrix conductivity of the rock.

Were these five factors totally independent of each other, resistivity studies would be useless in geothermal exploration. In reality, many of these factors vary together, amplifying the effect of temperature very significantly. Thus, as temperature increases, salinity increases, because of the higher dissolving power of warmer water. Porosity may increase because of the higher solubility of rocks at elevated temperature, and hydrothermal alteration may increase the clay-like mineral content of the rocks.

Yet, undue reliance on electrical resistivity alone may result in drilling expensive holes into cold brine pools or large clay bodies. Resistivity must be corroborated by other geological, geophysical, or geochemical data before commitments for deep drilling are made.

Gravimetry has often been employed for mapping of the geological structure in the given area. Gravity lows have been assigned to the effect of melting on density (The Geysers, California), collapsed caldera effects (Mono Lake, California) and increase in sedimentary column thickness. Gravity highs have been related on rare occasions to densification of sediments by hydrothermal fluids and to cold magmatic intrusions. Gravimetry has been employed primarily as an auxiliary structural tool, rather than a direct exploration tool. On one occasion (East Mesa, California, field), gravity data was employed for estimating convective heat flow rates, by ascribing the densification of the rocks to depositioned effects from a cooling convective plume (1). In another case (Wairakei, New Zealand), changes in gravitational attraction over the producing field were converted into a mass-loss estimate and compared to the actual mass loss due to production of geothermal fluids (2). That comparison showed that the gravimetrically-determined mass loss is about one-third lower than the actual mass loss, indicating that significant recharge is taking place. A similar use of gravimetry is being presently made of gravity in The Geysers by the U.S. Geological Survey (USGS).

Microearthquake seismology has enjoyed an increasing utilization as a geothermal exploration tool. Westphal and Lange have observed the empirical correlation between higher microseismicity in The Geysers area and the area of dry steam occurrence (3). Similar reports have been made by investigators in Iceland, Kenya, El Salvador, and elsewhere (see, for example, 4). However, it is important to note that microseismicity can occur extensively in non-thermal areas. Thus, microseismicity is a necessary but not a sufficient condition for geothermal reservoirs.

An even less definite statement may be made with regard to ground noise, the continuous vibration of ground at any point. While some correlation has been shown to exist between ground noise and some productive geothermal areas, the number of high-amplitude ground noise areas has been so large that any statement relating ground noise to geothermal reservoir occurrence must be treated with the greatest caution.

Temperature gradient measurements can be most valuable in delineating promising structures. Yet, the utilization of thermometric data must be treated with the greatest of caution, if any extrapolation is attempted. No extrapolation is ever safe, as data from Marysville, Montana, Dunes, California, San Miguel, Azores, would show. In the first two mentioned examples, a very steep shallow gradient changes into a flat or even negative gradient at depth. In the last case, a very flat gradient changes into a very steep one at a depth of about 100 meters (330 ft). In drilling in highly pervious strata, it is most important to drill to a depth below the zone of desaturation or extensive downward ground water flow. Temperature gradient data in itself is reliable only to the depth that the hole has been drilled and no more. Extrapolations must be always supported by other data.

Integration of a number of techniques, such as resistivity-plus-geochemistry-plus-thermometry will always lead to results that are superior to those from the application of a single method. Judgment and regional experience will determine the degree of success in finding economically viable geothermal reservoirs.

REFERENCES

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