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GEOLOGY OF GEOTHERMAL WELLS AND THE GEOLOGIST’S WORK

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ABSTRACT

Building geothermal wells represents high costs; however, they provide invaluable geoscientific information. Process dynamics demands the active participation of the expert geologist in charge of the drilling; as part of his/her work, he/she has to make the correct decision in the appropriate time in order to meet the objectives proposed. To successfully complete a geothermal drilling, the work of the geologist of the well can be divided into three phases. The first takes place before starting the drilling and consists in compiling data and information that he/she integrates and interprets to make the geoscientific projection of the well to be built; the second phase is carried out during boring when the cuttings, rock cores, and drilling parameters to obtain information on the geological context of the area are described and analyzed in detail; and the third phase is carried out after the well is completed to synthesize and integrate lithological, mineralogical, hydrogeological, thermal and structural information. The three of them are highly important to properly control the geological data in order to guarantee the quality of the information to be used for decision making purposes. Thus, the objective of this article is to describe the work of the geologist during the process of drilling geothermal wells, and the theoretical foundation in which the activities and decisions are supported, based in the experiences developed in geothermal fields of Costa Rica.

1. INTRODUCTION

Costa Rica is located in Central America, southeast of Nicaragua and northwest of Panama. The most important tectonic event that has influenced in the geological evolution of the region is the interaction of the Coco and Caribbean plates. According to Minster & Jordan (1978), subduction velocity reached by the Coco plate when moving under the Caribbean plate, in front of the Pacific Cost of Costa Rica, ranges between 8-9 cm/year. This phenomenon results in tectonic (Montero, 1986; Montero, 2000) and volcanic (Nyström et al., 1988; Montero, 2000) activity in the region.

In the continent, the internal magmatic arch or volcanic arch of Costa Rica runs parallel to the Mesoamerican trench, due to de magma generated by the subduction process in the asthenospheric mantle zone, when the subducted Coco plate is at a depth higher than 80 km. Its northeast segment is known as the Guanacaste Volcanic Mountain Chain (Figure 1).

The above mentioned geotectonic frame, places Costa Rica in a geological environment with high geothermal potential. This is due to the combination of the different elements needed to develop geothermal systems in active volcanic areas. Magma induces to thermal anomalies (Norton, 1984) caused by the emplacement of dikes or plutons (Noorollahi et al., 2007) resulting in a source of heat. Rocks with high fracturing density associated with tectonic activity (Curewitz & Karson, 1997) and cooling decompression (Norton, 1984) are ideal to storage fluids which is the energy transportation means; this fluid can be water of marine (Mottl, 1983), meteoric (Giggenbach, 1992; Curewitz & Karson, 1997), or juvenile origin or a mixtures of two or more of them.

During the last four decades, the Costa Rican Institute of Electricity (ICE) has carried out a series of studies to use geothermal energy from the Guanacaste Volcanic Mountain Chain; to date, a total of 70 geothermal wells have been built. This has generated the experience needed to facilitate the organization and implementation of drilling activities. The process has been divided into three phases known as: Geoscientific Projection of the Well, Geological Control of the Well, and Final Geological Report of the Well.

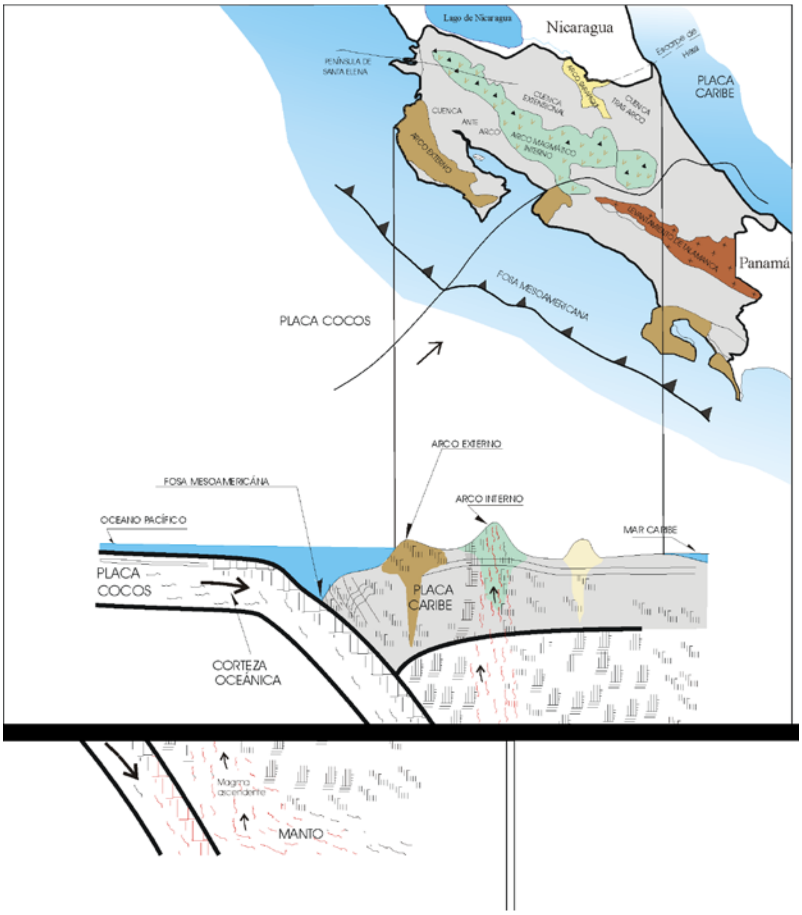

FIGURE 1: Location map of Costa Rica and a schematic cross-section showing the subduction process of the Coco Plate under the Caribbean Plate.

2. GEOSCIENTIFIC PROJECTION OF THE WELL

Before elaborating the report on the "geoscientific projection of the well", it is necessary to clearly state the purpose of the boring. In this phase, the main activities of the geologist are to compile, analyze, synthesize and integrate geological, geophysical and geochemical existing data and information. According to Christopher et al., (1989), this projection is intended to build a tridimensional model of the geological environment of the site where the drilling will take place.

Geological information is made up mainly of reports and maps which describe and represent spatial distribution of lithological units outcropping, as well as of the main structures that affect the area. These are correlated by means of profiles with the geological units described in gradient and deep wells (if existing), they project themselves to facilitate the calculation of unit thickness, and identify the depths at which alteration zones and aquifers can be found in the new boring. In this phase, it is advisable that the geologist carries out field work in the areas surrounding the drilling site to verify the existing information and search new outcrops that could be exposed during the preparation of access ways and the platform.

Geochemical information is initially obtained from the study of thermal manifestations. According to Molina (2009), it is necessary to analyze their spatial distribution, chemistry, temperature and origin, since several processes that change the chemical composition and physical parameters of the fluid and the rock take place during the way of the fluids in the subsoil; this information is transported up to the surface and exposed by means of the thermal manifestations. In drilled wells, hydrogeological, thermal and chemical data on the aquifers must be gathered and analyzed. Thermal manifestations and aquifers identified during the borings are sources of data that help to elucidate hydrogeological processes that are carried out in vast areas where the fluids circulate. Through these manifestations, temperature and geochemical composition of the fluid that constitutes the geothermal reservoir are determined; additionally, proximity and kind of heat source that generates the thermal anomaly and the structural pattern through which they move are also estimated.

Geophysical information is obtained through magnetometry, gravimetry, electric and magnetotelluric studies. These are indirect methods intended to obtain some physical parameters from the geological formations in the depths, as well as the form, size and other characteristics of the geological structures that could constitute the geothermal reservoir (Noorollahi, 2005). Magnetometry is based on detecting the magnetic field induced by rocky bodies; it is used to delimit volcanic rocks and emplaced intrusives at short depths that contrast with the rocks that have a lower magnetic effect. Gravimetry is based in detecting changes in density generated by different lithologies and/or alteration degrees; it is used to identify basements, landfills, intrusive bodies and geological structures, among others. Magnetotelluric and electric methods give an idea of rock resistivity that can be related with the lithology and/or alteration. Additionally, these methods help to better define the existence of geothermal fluid in the geological structures, since they are more sensitive to the presence of fluids and to temperature variation.

Geothermal gradient is another geophysical method. It represents change relationship between temperature and depth. It is determined through temperature measures that are taken at the drilling site. It provides a profile of temperature with respect to depth, from which the distribution of the thermal anomaly and flow direction are deduced. With these data, a distribution map of the thermal gradient and temperature is generated.

When integrating the information, the geologist designs or updates the geological model, where are detailing the lithological, mineralogical and structural conditions, as well as temperature expected of the drilling site. This work allows to deduce thickness of lithological units, as well as their physical mechanic properties, zones of hydrothermal alteration, especially clays of the smectites family, that can trap the drilling tool (due to its high index of compressibility), aquifers that need to be cemented, or on the contrary be protected for its geothermal potential.

This information is highly important to plan the drilling, that is, depth of the target points and of the well itself; if it is directional, azimuth, inclination degree, horizontal distance of the drilling targets, etc.; and also some activities that the geologist develops since he/she can estimate the amount of samples of cuttings, thin sections and X-rays diffractometry that have to be analyzed. It is additionally used to plan depths for core extraction, prepare bit program and completion design of well (casing program).

3. GEOLOGICAL CONTROL OF THE WELL DURING DRILLING

Knowing that job is done in environments dominated by hydrothermal alteration and thermal anomalies, since, the geothermal fluids react with the rock in its search for a chemical and thermal equilibrium; the geologist, in order to obtain a good interpretation must keep in mind that there are different factors that influence the degree and intensity of the hydrothermal alteration; these vary in importance from one place to another, depending on the geological frame.

According to Browne (1978), these factors are: temperature, pressure, kind of rock, permeability, composition of the fluid and length of the activity. According to Reyes (2000), temperature plays an important role in hydrothermal alteration since it controls the relationship and velocity of the alteration processes, as well as the degree and composition of the association of secondary minerals. Alteration velocity presents an exponential behavior with respect to temperature; this is due to the fact that temperature acts as a catalyst agent of chemical reactions. Arnórsson (2000) indicates that for each 10ºC reaction relationships increases 2 to 3 times, which implies that at 100ºC the increase ranges between 2^{10} and 3^{10} (1024 to 59049) times.

In areas dominated by geothermal anomalies, thermal gradient is of the conductive type, increasing continuously according to depth until an aquifer is reached, where it turns into the connective type. Thus, in this phase, the main activities are focused in implementing an adequate geological control of the rocks being drilled. The geologist describes rock cuttings every three meters, and thin sections every nine meters; however, these intervals can vary according to his/her criterion or need. Additionally, he/she selects samples to carry out X-ray diffractometry and crystal for microthermometry analyses.

The above mentioned activities are carried out with the aim of identifying the kind of rock, and studying the petrophysical characteristics emphasizing in mineralogical alterations which are the result of physical-chemical processes that are carried in the hydrothermal systems. Therefore, they are valued as unique source of information to be interpreted. According to González et al. (1992), this determination and quantification provide information on the existing conditions at the moment of precipitation and consequently, of the evolution of the system. The purpose of interpreting mineralogical associations is to obtain information on the degree and kind of hydrothermal alteration, temperature and permeability, and on the reducing or oxidant character of the system at the moment of mineral precipitation.

X-ray diffractometry analyses search to differentiate clayish minerals that due to their characteristics are used as geothermometers, considering that in some cases alteration minerals represent geological conditions that occurred in the past (fossils). In consequence, it is very important to base the interpretation in minerals that are more susceptible to thermal changes (geothermometers), such as the phyllosilicates (clays) that change their reticular structure to obtain their equilibrium with the actual temperature. These studies are complemented with the analysis of fluid inclusions in newly formed minerals to determine homogenization temperature, from which the existing temperature during the formation of the mineral is deduced. This allows inferring thermal history of the area. In the same way, salinity of the brine (that originated the mineral) can be deduced from fusion temperature.

Daily, the geologist analyzes drilling parameters, since these are closely linked to the physical-mechanical characteristics of the rock. For a better comprehension, they are included in the drilling graphic, together with the lithological column, mineralogy of alteration (with its corresponding descriptions), and zones of circulation loss. This helps to identify: lithological contacts, fracturing associated to structures or permeable horizons and clayish levels that could lead to serious problems of entrapment of the drill string.

Due to the high cost implied, and the risk that sometimes represent for the future of the drilling, core extraction activities must be fully justified. Considering the information that the geologist uses and interprets every day, he/she is the key professional to request the implementation of this activity.
In general, the request for core extraction is proposed when, according to the geological model, it is necessary to obtain information at a given depth, there is a permeable zone or there is one close (where the study of mineralogical associations can generate invaluable information), boring has taken place without recuperation and there exist changes in drilling and/or thermal and hydraulic parameters of the well, boring has taken place without recuperation for more than 200 m, or at the end of the well.
Since the geologist is the expert that constantly integrates geological information with drilling parameters, generating a scenery that closely represents the geological environment of the site, his/her daily presence in the drilling rig is indispensable to keep direct contact with the engineer in charge of site, the driller and the personnel in charge of fluid circulation system, to exchange information that allows to continue with the drilling with the lowest possible amount of setbacks (Browne, 1984). He/she also actively participates with the different groups in decision making on: casing anchorage and testing design. The geologist is also the liaison between the Drilling and Geosciences groups when carrying out an intervention in the well to evaluate thermal, hydraulic and/or chemical conditions.

In those cases in which geological conditions indicate low promising sceneries from a geothermal perspective such as thermal inversions, acid fluids, unstable lithological horizons, etc., the geologist is in the position of proposing to cancel the boring before reaching the final depth projected. On the other way, if geological conditions are positive, the geologist can propose a deeper drilling.

4. FINAL GEOLOGICAL REPORT OF THE WELL

To prepare the “final geological report of the well” lithological, mineralogical, hydrogeological, structural and thermal information is analyzed, synthesized and integrated in such a way that this document becomes a reliable consultation source to update the geological model of the geothermal field; this would facilitate work and decision making processes in future drilling. This report is made up mainly by the following sections:

Lithostratigraphy: the limits of the lithostratigraphic units are defined, including in a summarized fashion the descriptions of the different lithological units. For this purpose, the geologist must clearly understand the volcanic-sedimentary processes that were carried out during deposit of materials.
Mineralogy of alteration: identification and quantification of secondary minerals is used to determine alteration degree and intensity, as well as, the most representative mineralogical associations, according to temperature and permeability conditions of the milieu with respect to depth. Furthermore, with the information from the clays, alteration zones are identified, which helps to define the cap rock and the geothermal reservoir. Together with the microthermometry data, thermal history is obtained and current system conditions are defined.

Hydrogeology: this section is mainly based on the analysis and interpretation of the zones of circulation loss (total or partial) of drilling fluids, with the corresponding lithology, alteration mineralogy, as well as hydrogeological, thermal and chemical conditions. The aim is to identify and characterize the different aquifers from a petrophysical perspective.

Structural: lithologies and alteration mineralogy are correlated through profiles with other existing wells, with the purpose of identifying relative displacements. In addition, lithologies at depths where circulation loss is present are analyzed to define their origin (per contact or fracture) and identify structures. Finally, the initial structural scenery (proposed in the geoscientific projection of the well) is corroborated and the zones of loss are correlated with failure traces in the surface. To do this, they are projected using dips congruent with efforts systems of the area. If necessary, the structural model is updated according the new information.

5. CONCLUSIONS

The work of the geologist of the well begins before doing the drilling, by creating or updating the geological model of the site of interest. This allows to conceptualize the geological environment and, consequently, to plan the activities to be developed in the following phases.

During drilling, daily presence of the geologist in the site is needed since he/she is a trained professional who studying the cuttings and rock cores obtained at different depths together with drilling parameters determines petrophysical and thermal conditions of the site, leading to decision making in the correct moment during the development of this phase.

The geologist with expertise in geothermal drilling must be proactive and capable of observing, analyzing, synthesizing and integrating data; communication and team work skills are also required to interact and exchange ideas with the different groups involved in the process to meet the proposed objective, that is, a geothermal well built with the lowest possible amount of setbacks and from which the highest possible amount of geoscientific information is obtained. All of this is translated into safe of time and money, important factors to consider the process as successful.

The work of the geologist of the well must result in three products: well projection, drilling graphics and final report of the well. These three documents are a source of reliable information to be used in decision making in future phases.

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