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GEOTHERMAL TRAINING PROGRAMME

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GEOTHERMAL EXPLORATION PHASE

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ABSTRACT

The geothermal surface exploration phase is the first large undertaking in a full-scale geothermal project, aiming to harness a geothermal resource. It is entirely a scientific operation, giving the developer a valuable input in the effort to meet the ultimate goal of the project; a geothermal resource harnessed for utilization. This paper outlines the most frequently used geoscientific methods during surface exploration. The selection of methods is greatly dependent on the characteristics of the field under investigation. The list of methods in this paper is not complete and those listed here are not applicable in all cases. A proper large-scale geothermal project needs to be carefully planned and managed by the developer's management team, which in co-operation with trusted geo-consultants selects the appropriate methods to be exercised in the surface exploration study.

1. INTRODUCTION

Harnessing geothermal resources requires co-operation between a number of professions, and specialized knowhow. Initially the work is dominated by geosciences, mainly geology, geochemistry and geophysics, but as the project progresses additional experts join in the programme, such as drilling engineers, reservoir engineers, financial specialists, power plant designers and operation experts. The design of a geothermal

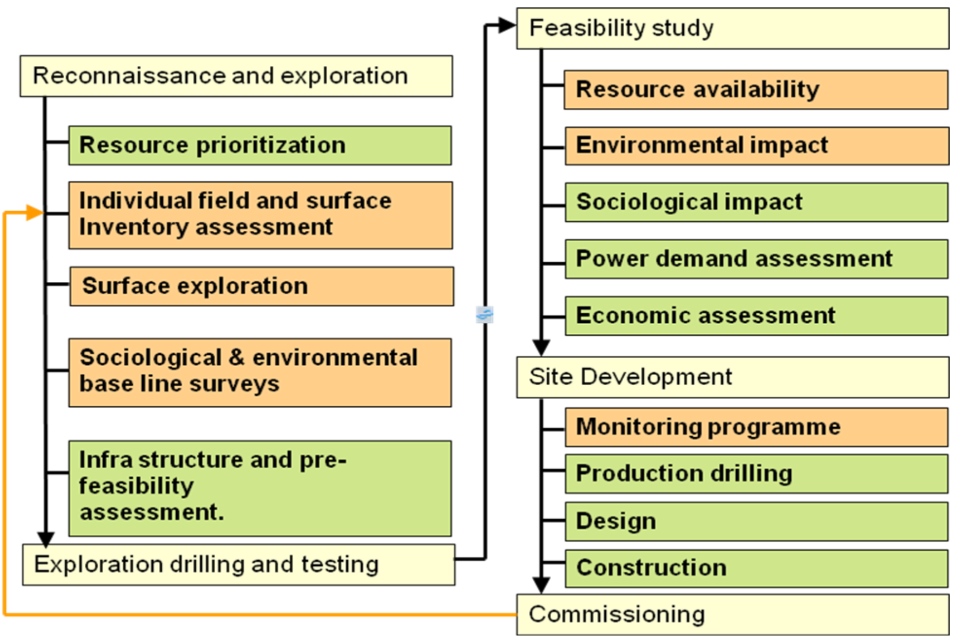

FIGURE 1: Best practice in geothermal development

programme can be visualized in many ways. Figure 1 is a graphic expression of the setup of a geothermal project, from the identification of a potential resource to an operational geothermal plant.

Large-scale utilization of a geothermal resource requires drilling of a borehole to tap the resource. Drilling is a relative costly operation, and the risk is high, especially during the exploration drilling phase, when the first boreholes are sunk in order to proof the existence of the predicted economically viable resource. In order to reduce the risk of failure and wasted funding, a geothermal exploration study is carried out prior to the drilling phase. The results of the surface exploration study forms the backbone of the pre-feasibility report where recommendations are given on the feasibility of the project, and whether or not it is safe to move on to the drilling phase .

2. SURFACE EXPLORATION

As the name implies surface exploration is carried out on the surface, above and outside the predicted geothermal resource. The methods used are geoscientific methods, modified and specialized towards the aim to identify and understand a geothermal reservoir. The collected data and the interpretation are used to produce the first conceptual model of the resource. If the resource is found likely to be of economic value, the scientists use the model to locate drillsites in order to directly explore the predicted resource by drilling

2.1 Geological exploration

The geologist is the first scientist to make investigations on new geothermal prospects, and he plays an important role in identifying a potential geothermal resource, making primary inventory assessment and prioritising the most promising targets (Figure 1). During the exploration phase the role of the geologist is to make a detailed geological map of the project area, with the primary aim to identify possible reservoir rocks and their geological setting, as well as the existence of a heat source. To achieve this, the geologist produces maps and records describing the bed rock, volcanology, tectonics, and ground water characteristics of the study area (Saemundsson, 1978). A detailed mapping is carried out of the extent and nature of geothermal surface manifestations, active or extinct. This data is not only necessary input for the making of a model of the geothermal resource, but also forms the basis for the sampling work of the project geochemist(s). A qualified geothermal geologist is usually an experienced hydrogeologist as well, because an understanding of groundwater movement is necessary to understand a geothermal reservoir.

2.2 Geochemical exploration

Geothermal geochemistry is a specialized subject, using chemical methods to predict underground temperatures, evaluate the origin of geothermal fluids, and evaluate scaling and/or corrosive potential of the geothermal fluid. During the exploration phase the main objective of the geochemist is to predict underground temperature and most likely flowpaths of the sub-surface water, including upflow zones from a geothermal reservoir. A detailed map of active surface manifestations, prepared by the geologists, will ease the fieldwork of the geochemists, and a close co-operation between these two is likely to improve the progress and success of the project.

Active surface manifestations vary greatly in appearance and character; from warm or hot springs, boiling pools, steaming ground or fumaroles to hot ground or de-gassing soil. Collection of representative samples of discharging water, steam or gas from the underground aquifers to complete a geochemical survey requires a large variety of sampling methods and a certain degree of flexibility and ingenuity of an experienced geothermal geochemist. The field work is not only concentrated on geothermal manifestations, samples of cold groundwater are essential for a complete set of samples from the study area.

With time groundwater (which has its origin in rainwater) reaches chemical equilibrium with the rocks of the reservoir where it resides. The composition of the water in equilibrium reflects the temperature of the reservoir rock and through intensive studies of these equilibria in a variety of rock environments, the geochemists are able to predict the original temperature at depth by sampling water, steam and gases from surface manifestations. The ratio of various isotopes in the water is also indicative of temperature and different water bodies in the sub-surface rocks. Figure 2 shows the correlation between silica (SiO_2) and temperature, the base of a so-called silica geothermometer, widely used in geothermometry. Furthermore, various "fingerprints" in chemical composition of the water can aid the chemist to track the flowpath of the water, such as recharge and discharge areas (Arnorsson et al., 2002).

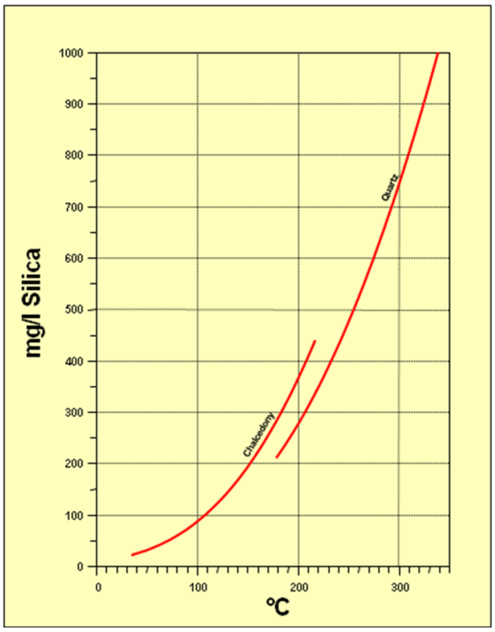

FIGURE 2: The correlation between reservoir temperature and silica concentration in reservoir fluid.

In a later phase of the project (i.e. exploration drilling and flow testing) the geochemistry adds intensive studies on the suitability of the geothermal fluid for exploitation, such as tendencies for precipitations of solids and/or corrosiveness of the water. These components will greatly influence the design and often economics of the project, and can be indicated already during the exploration phase by the geochemist.

2.3 Geophysical exploration

Although the exploration phase is a "surface exploration" all the methods used aimed to interpret the conditions at depth. The surface geology is a mean to predict geological structure at depth, which may control underground water movements, and to identify possible location of rock formations acting as heat source for the geothermal system. By carrying out geochemical exploration attempt is made to predict flow and temperatures of water in aquifers and reservoirs. Contrary to these methods, geophysical methods are designed to measure indirectly sub-surface characteristics and to measure lateral and horizontal extent of various anomalies, which may or may not relate to geothermal phenomenon. A variety of geophysical methods have been tried during the past decades, and by trial and error several methods have proven to be useful tools to probe for sub-surface geothermal anomalies. These include magnetic, gravity, resistivity and seismic measurements, each suitable for different geological environments, and like many geothermal studies, the success of the methods depends on the expertise of the team carrying out the field work and interpretation.

Different geological structures, often capable of influencing flow of geothermal water, may cause an anomalous behaviour of the magnetic pattern above geological formations, detected by magnetic measurement. A magnetic map of the area may aid to pinpoint the buried geological structures, which in turn becomes the drilling target.

During the gravity survey the strength of the Earth's gravity at a number of locations is measures in the study area, and buried bodies of rocks of different density than the host rock will cause a variation in the regional gravity picture. An elaborate interpretation of such data may identify the depth and the volume of such an alien body, aiding to fill in the puzzle of the underground stratigraphy and help to find possible intrusives which may be the heat source of a potential reservoir.

Apart from direct surface manifestations, the resistivity of subsurface rocks is often the most diagnostic parameter of geothermal activity that can be measured from the surface (Árnason et al., 2000). Rocks containing geothermal fluids have a different resistivity than cold rocks. Most commonly the geothermal water lowers the resistivity, but in some cases the resistivity increases again at very high temperatures (Figure 3). Several methods exist for measuring the resistivity of subsurface rocks. They can be divided into galvanic or direct-current (DC) methods and electromagnetic (EM) methods. Some decades ago, the DC methods (mainly Shlumberger soundings) were widely used. In recent times, the EM methods have gained more popularity, mainly the Transient Electro-Magnetic (TEM) method and the Magneto-Telluric (MT) method.

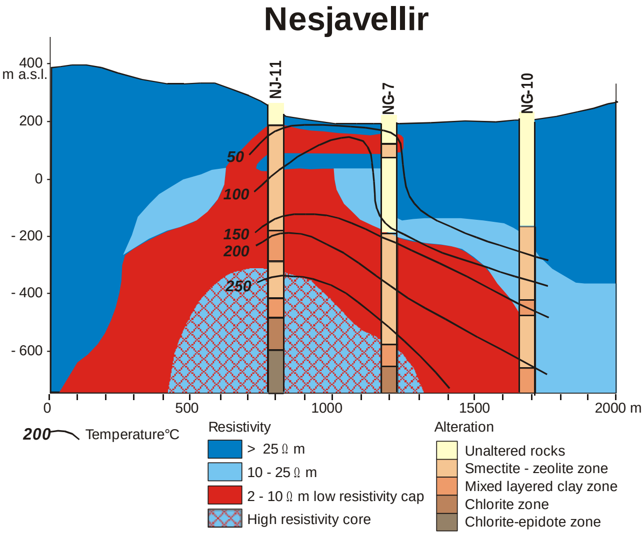

FIGURE 3: Resistivity cross section through an exploited geothermal field

The MT method is based on measuring currents induced in the ground by time variations in the Earth's magnetic field. In MT, the time dependent magnetic field and the electric field generated in the surface are measured simultaneously. The MT method has the greatest depth of exploration of the available EM methods (some tens or hundreds of kilometres) and is practically the only method for studying deep resistivity structures. It has, however, limited resolution at shallow depths (in the uppermost 1 km). The MT method also suffers from the so-called telluric shift problem, which is commonly resolved by applying the central-loop TEM method along with MT to resolve the resistivity in the uppermost kilometre.

Geothermal resources are frequently located in seismically active environments, especially the high-temperature resources related to volcanic fields. Measurements of natural seismic activity is a useful tool to map boundaries of rock units, and to locate bodies of rocks with anomalous sound velocity, which may reflect heat sources or major structural discontinuities.

The distinct physical properties of rocks exposed to different temperature environments offer a variety of physical measurements, which are continuously being developed for use in the geothermal industry. The above mentioned methods summarize the most frequently used methods at present, in addition to what carefully selected methods are applicable for each geological environment. These methods provide a valuable set of data to be interpreted for the construction of a conceptual model of the geothermal reservoir under study.

3. CONSEPTUAL GEOTHERMAL RESERVOIR MODEL

A geothermal exploration project is a multi-disciplinary undertaking, and a properly executed exploration should involve several or all of the above mentioned methods, plus any other which is deemed suitable to enhance further the understanding of the resource in study. The amalgamation of the geoscientific data into a conceptual model should be continuous as the project advances, and the exploration phase be closed when the project owner deems that his/her confidence in the model is high enough (i.e. the risk has been lowered enough) that it is timely to move the project into exploration drilling in the feasibility phase.

The conceptual model of the still unproven geothermal resource should reflect if possible all the data gathered under the surface exploration phase or be a reasonable arbitration of the available information. During the continuation of the surface exploration data collection the model should be constantly upgraded and improved. Towards the end of the surface exploration phase the geoscientist proposes a strategy to explore the findings by exploration drilling. The decision made on the continuation of the project based on the geoscientific consultation will depend heavily on the owner's decision, but environmental, logistic and geographical issues will also has an influence. Figure 4 shows one way of representing the geoscientific results and conclusions.

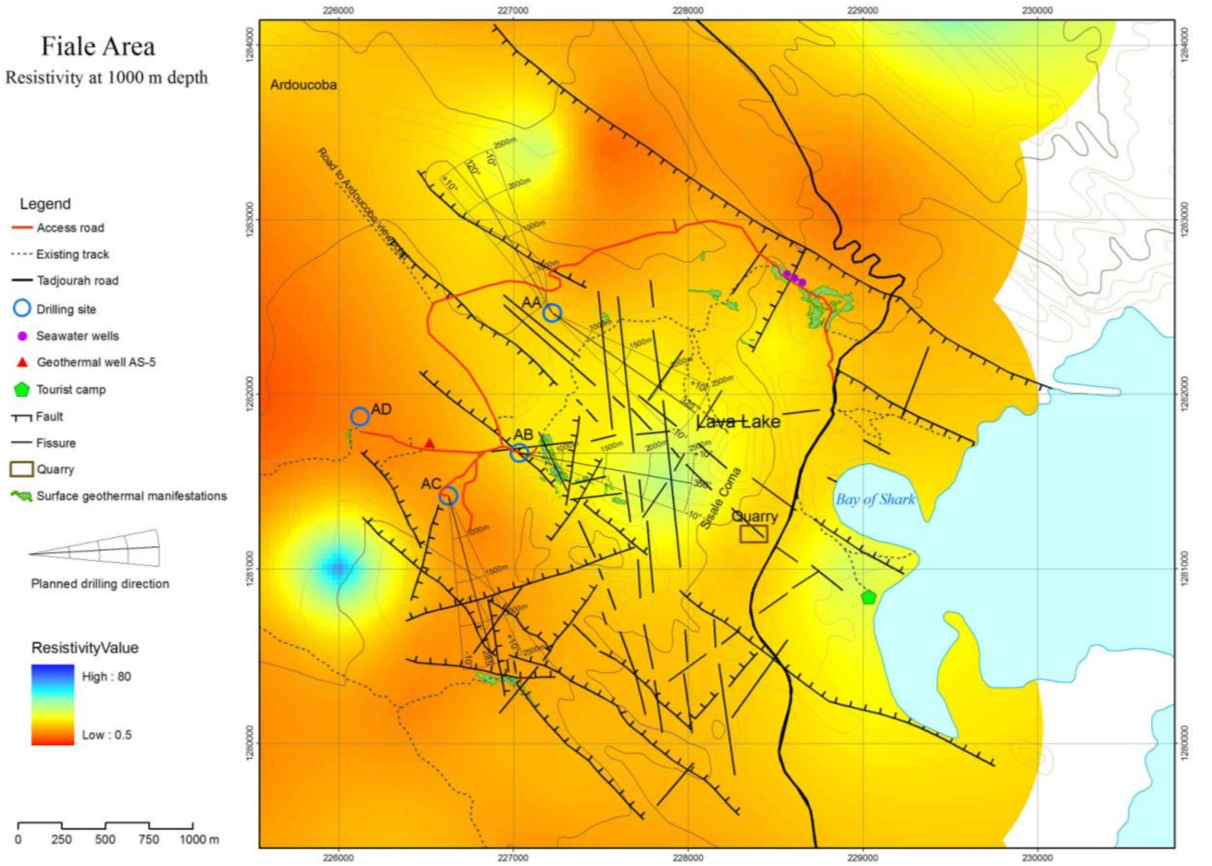

FIGURE 4: Assal Geothermal Prospect, Djibouti. Combined geological, geochemical and geophysical data, and proposed drillsites and direction of diviated drillholes

4. CONCLUSIONS

The geoscientific work carried out under the exploration phase of a geothermal project is of vital importance for the continuation of a geothermal project. It provides the first model of the geothermal resource, and reduces the risk in failed drilling. It is up to the project management to evaluate when the exploration work has provided sufficient data to complete the exploration phase, to let the project move into the exploration drilling phase, and to find decide if the project can be deemed feasible.

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