Presented at "Short Course on Surface Exploration for Geothermal Resources",
organized by UNU-GTP and LaGeo, in Ahuachapan and Santa Tecla, El Salvador, 17-30 October, 2009.

UNITED NATIONS UNIVERSITY
GEOTHERMAL TRAINING PROGRAMME

LaGeo S.A. de C.V.

GEOTHERMAL SURFACE EXPLORATION

Knútur Árnason[1] and Gestur Gíslason[2]
[1]ÍSOR - Iceland GeoSurvey
Grensásvegi 9, IS-107 Reykjavík
ICELAND
[2]Reykjavík Geothermal
Köllunarklettsvegi 1, IS-104 Reykjavík
ICELAND

ka@isor.is, gestur@reykjavikgeothermal.com

ABSTRACT

After decades of experience in geothermal surface exploration and geothermal development a sort of consensus on best practises has developed. This document summarises the main elements of surface exploration, up to the point of drilling the first exploration well(s). The main subjects of geological, geochemical and geophysical exploration are briefly described and the necessary human capacity and equipment is outlined.

1. BEST PRACTISES AND NECESSARY EQUIPMENT

Geothermal development for power production dates as far back as to 1904, when electricity was first produced from geothermal steam in Larderello, Italy. Geothermal power production has now become a big and steadily increasing industry in many countries. The process of harnessing geothermal energy has been developing for more than a century, largely by learning from mistakes. Even though details may be site dependent, a consensus on best practices in geothermal development has developed. This is well summarised on the World Bank Geothermal web page:

"With all projects of significant size, geothermal projects are developed through a series of logical stages, which may be summarised in the Geothermal Development Flow Chart (Figure 1). This diagram shows the various stages in a typical geothermal project. Decisions to proceed to the next stage are normally made progressively throughout the project.

Geothermal resources are usually located and defined by a progressively more intensive (and expensive) exploration programme that starts at a regional level and eventually results in a drilling program to positively delineate the resource.

Reconnaissance surveys will identify the most suitable prospect areas by recognition of favourable geological settings and locating any hot springs or other surface thermal discharge. Reconnaissance studies involve mapping any hot springs or other surface thermal features and the identification of favourable geological structures. The chemical composition of the discharging fluids reveals information about the deeper reservoir, including temperature and fluid characteristics. Geological studies provide information about the probable distribution and extent of aquifers, as well as the likely heat source and heat flow regime.

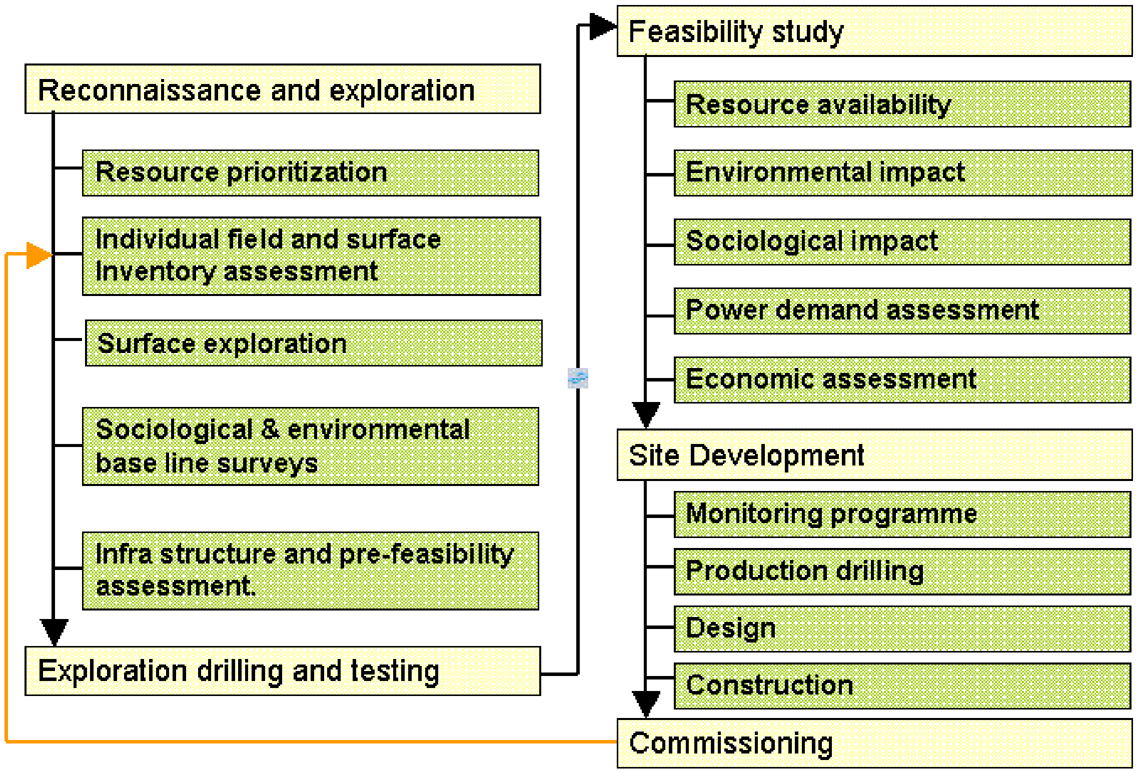

FIGURE 1: Geothermal development flow chart
(slightly modified from World Bank, 2009)

Areas identified as having high potential or that are favoured because of proximity to an energy use centre, will be explored by more comprehensive scientific survey methods.

In addition to more detailed geological and geochemical studies, a range of geophysical techniques may be used including gravity, magnetic and resistivity surveys. Resistivity surveys in particular can locate anomalies that are directly related to the presence of geothermal fluids. Interpretation of these integrated geoscientific studies leads to prioritisation of targets for exploration drilling programmes. The application of sound scientific method and analysis during these early phases increases the probability of success with subsequent drilling and development. If these surveys provide very good indications for the presence of a useful geothermal reservoir, the resource is tested by the drilling of exploration wells so that actual subsurface temperatures can be measured and reservoir productivity tested. The exploration programme should therefore be designed to suit the type of resource expected, the amount of energy expected to be produced from the project and the timeframe for the development."

It lies in the very nature of the resource, being underground and often modestly manifested on the surface, that the full potential is normally not know until it has been developed for some time. It is a costly and time consuming process to fully determine the capacity before a power plant is designed and implemented. Due to the high upfront costs of this method (mainly of drilling), it is nowadays considered more feasible to develop significant geothermal prospects in steps, in order to get revenues of the investments as soon as possible. This means that the process of geothermal development, as shown in the diagram above, often loops back to surface exploration and even individual filed inventory, and then onwards to commissioning of a new unit.

The present discussion focuses mainly on the geo-scientific aspects of geothermal development and in particular on what sort of equipment is needed. In the following paragraphs some of the development phases, mainly the ones prior to a feasibility study, will be discussed in more details in order to put the geo-scientific components and equipment need into place.

1.1 Resource prioritisation

In this phase, all possible geothermal prospects as inferred from general geological regime, surface manifestations and other indicators will be considered. They are ranked on the basis of geo-scientific indications as if likely resource is available, proximity to potential marked and likelihood of utilization within near future.

An exhaustive collection of existing information is performed. A thorough re-evaluation is performed both with respect to the likelihood of an exploitable resource being present, its accessibility and how the resource could be utilized.

The result of this phase is a ranking of possible prospects for further investigation (which in turn may change as further knowledge is gained)

1.2 Individual field and surface inventory assessment

This phase focuses on the further exploring the highest ranked prospects. If there are several prospects at hand, more than one (preferably three to four) should be chosen for inventory assessment so that they can be ranked for further work. The field and surface inventory assessment comprises:

1. **Geological investigations**: A preliminary mapping of the geology of the selected prospects is performed, such as main geological units, tectonics and volcanism, if present. Thermal manifestations and alteration are mapped and their relation to tectonics and/or volcanism is studied. The physical properties of surface manifestations are measured and recorded, including temperature, flow rate, conductivity etc.

   A skilled geologist makes this study. Good topographic maps, aerial photographs, compass and a handheld GPS are needed, as well as geological maps, if available. A portable combined temperature/pH/conductivity meter is required to measure geothermal manifestations. Rock units and alteration minerals are sampled. Thin sections are made and analysed for petrological investigations and surface alteration minerals are analysed by X-Ray diffraction (XRD). Some samples may be taken for isotope dating.

2. **Groundwater hydrology**: Main groundwater regimes are studied in order to determine likely recharge and off-flow regions and the water budget of the resources. The physical properties of the water from springs, lakes and boreholes are measured and recorded.

   The mapping geologist carries out this study. Topographic maps, aerial photographs, handheld GPS, a portable combined temperature/pH/conductivity meter and geological maps (if available) are needed. No sampling of groundwater is assumed at this stage.

3. **Geochemical investigations**: Geothermal water and/or stem is sampled at selected places in each prospect for chemical analysis and geothermometry.

   This task is carried out by a geochemist. Sampling equipment for sampling hot water, steam and gases is needed, and prepared in the field as instructed by the laboratory. Measurement of pH and dissolved gases must be analysed at the end of a field day. In remote areas a small field laboratory must be set up for this purpose. The major ions must be analysed in a well equipped laboratory. Selected samples may be sent to specialized laboratories for the analyses of minor elements. Specialised software is needed for calculating likely temperatures from *concentrations of chemical species. The chemical data should be stored in a centralized database.*

4. **Geophysics**: Preliminary resistivity survey might be considered to roughly map the size of the reservoirs and to see if resistivity indicates high temperatures. If the prospect areas are considered to be tectonically and/or volcanically active, a temporary deployment of a few seismic stations might be considered.

   A resistivity survey requires trained field crew, which is led by a skilled geophysicist and adequate equipment. The selection of a resistivity method can be site specific. Generally the central-loop Transient ElectroMagnetic (TEM) method is preferred, but if the terrain is difficult and accessibility limited, Direct Current (DC) methods (Schlumberger soundings) might be a better option. Special software is needed for processing and interpretation of the data. It is highly recommended that the data are processed and a preliminary interpretation is performed concurrently with the data collection. A preliminary seismic survey needs a seismologist and about four portable seismic stations. Specialized software is needed for locating the hypocentres of the earthquakes.

5. **Reports on inventory assessment**. A report should be written on each prospect considered. The report should state the result of the preliminary exploration and put forward arguments for and against a full surface exploration programme. If a prospect can be divided into different areas of foreseeable development, they should be ranked. If a full surface exploration programme is recommended, an exploration plan should be drawn up. The result of the individual field and surface inventory assessment should make a firm basis for the ranking of the prospects (and/or sub areas) for further investigations and decision on which prospects are chosen for detailed surface exploration.

1.3 Surface exploration

Once the prospects have been prioritised by the surface inventory assessment, the most promising area is taken for a full surface exploration. The survey plan that was drawn up under the inventory assessment will be further elaborated on. Even though the detailed plan is to some extent site specific, it will normally include most of the following components, but not necessary all.

Collection of all available information and maps:

- This includes reviewing of previous work in the prospect area, collection of topographic, geological geothermal and tectonic maps.

Geology:

- A detailed geological mapping is performed in the geothermal field and its surroundings. Geological strata, rock units, rock types and loose surface layers are mapped. In the case of volcanic areas, volcanism and extruded volcanic material as well intrusions, if cropping out, are mapped and dated in order to revile the volcanic history.
- Detailed mapping of tectonic features is performed. Faults are classified into normal, thrust and strike-slip faults and fissures. Calderas and other exotic structures are mapped. The tectonic history is studied by stratigraphy and dating.
- Detailed mapping of geothermal alteration on the surface is performed and alteration mineral analysed. The chronology of the surface alteration is studied in order to understand the temporal variation in the surface activity.
- An exhaustive mapping of thermal manifestations is performed and the physical properties of surface manifestations are measured and recorded, including temperature, flow rate,

conductivity etc. A good practice is to prepare a comprehensive geothermal database that accompanies the geothermal map (preferably GIS based).

- Emphasis is put on investigating the relation of the thermal manifestations to tectonic features and volcanism, if present. This is done to get ideas on heat sources, hydrology and flow paths in the reservoir.
- Detailed mapping groundwater, cold springs, lake levels and groundwater level. If the groundwater level is deep and little or no water on the surface, resistivity methods may be useful to map groundwater levels.

Experienced geologists carry out this study. Good topographic maps, compass, a portable combined temperature/pH/conductivity meter and a handheld GPS are needed, as well as geological maps. Rock units and alteration minerals are sampled. Thin sections are made and chemical analysis of rocks for petrological investigations so chemical laboratory is needed. Isotopic dating will be done in an isotope laboratory. Alteration minerals are analysed by XRD.

Geochemistry:

- Detailed sampling of thermal water, steam and gases. Majority of thermal surface manifestations are sampled or at least representative places.
- Detailed analyses of chemical elements (both for major and trace elements), chemical species and gases. Geothermometers are used to calculate likely reservoir temperatures and the nature of the heat source. Preliminary evaluation of possible scaling and/or corrosion problems in utilisation.
- Along with the chemical sampling, samples are take for stabile isotope studies.
- Analyses of stabile isotopes (hydrogen, oxygen and possibly carbon and sulphur). Isotope ratios and concentrations are used to infer the origin of the geothermal fluid in the reservoir.

This task is carried out by experienced geochemist. Equipment for sampling hot water, steam and gases is needed. The pH and dissolved gases must be analysed at the end of a field day. In remote areas a small field laboratory must be set up for this purpose. The major ions must be analysed in a well equipped laboratory. Specialized software is needed for calculating likely temperatures from concentrations of chemical species. Selected samples may be sent to specialized laboratories for the analyses of minor elements and stabile isotopes.

Geophysics:

- A detailed resistivity survey is performed in the surface exploration phase, because the resistivity of the subsurface rocks is, apart from direct temperature measurements, the most diagnostic parameter of geothermal activity that can be measured from the surface. A full resistivity survey consist of a shallow survey (< 1 km depth) and a deep resistivity survey (0.5 – 10 km depth). The shallow survey is preferably performed using central-loop TEM soundings, but DC methods (Schlumberger) can also be used. The prospect is covered with a dens net of soundings (about one sounding per km^2). The deep survey is normally done by Magneto-Tellurics (MT) and the area is covered with more coarse net of soundings. It is highly recommended that during the shallow survey, the data are processed and a preliminary interpretation performed concurrently with the data collection so that details can be filled in where needed.
- Gravity measurements give structural information and can also give indications on massive intrusions, which may act as heat sources. A Bouguer map should be produced to study density anomalies and selected profiles might be measured with dens station spacing for more detailed structural studies such as berried faults.
- Aero-magnetic and/or ground magnetic surveys should be performed. Aero-magnetic survey can map demagnetised rocks due to thermal alteration. Magnetic surveys give complementary structural information which helps in the interpretation of other data.

- A passive seismic survey should be performed. Other surface geophysical methods, such as resistivity surveys, give increasingly blurred picture with depth. They can revile the main structure and the outlines of the reservoir but lack the capability to delineate finer structures at depth. Active faults can be located by recording an locating earthquakes. The cooling of heat sources cam also produce micro-seismicity.
- Soil temperature and heat flow measurements can often map structures, such as faults or fissures which control flow of geothermal fluids but are not immediately recognised on the surface. Heat flow maps can also give information about heat sources and aid in the interpretation of other data.
- Drilling of shallow (< 300 m) thermal gradient holes into identified anomalies to confirm (or disproof) their interpretation.

A resistivity survey requires trained field crew, which is led by a skilled geophysicist and adequate equipment. Handheld GPS instruments are needed. The selection of a resistivity method for the detailed shallow survey can be site specific. Generally the central-loop TEM method is preferred, but if the terrain is difficult and accessibility limited, Direct Current (DC) methods (Schlumberger soundings) might be a better option. For the deep survey MT instruments are needed (not fewer than two, preferably five or more). Special software is needed for processing and interpretation of the data. A high quality gravity meter and differential GPS are needed for the gravity survey. Good topographic maps, preferably on digital form, for terrain correction are also needed and software for data processing and modelling. Handheld GPS and high quality magnetometer with reference station for diurnal corrections are needed. For detailed mapping differential GPS may be needed. Aero-magnetic surveys require an aeroplane equipped with magnetometer and a GPS positioning system. This is very expensive equipment and aero-magnetic surveys are normally contracted out by specialized companies. A passive seismic survey needs a seismologist at least five (the more the better) portable seismic stations. Specialized software is needed for locating the hypocentres of the earthquakes and to determine focal mechanisms. A software for relative location of events in earthquake swarms is desirable. For a soil temperature and heat flow surveys, thermometer sticks and hand drill for drilling shallow holes is needed. Handheld instrument for measuring thermal conductivity is needed for a heat flow study. Handheld GPS are likewise needed and even differential GPS for detailed surveys. Thermal gradient drilling requires drill rigs. These are costly equipment and the mechanical drilling is normally contracted from drilling companies. Temperature measurement reels are, however, needed and equipment for measuring thermal conductivities of the drilled rocks.

2. SURFACE EXPLORATION REPORT

Separate reports may be written on the different disciplines, stating technical details on data collection processing and interpretation. Then a final report is compiled, including the results of the different components and a joint interpretation of all results. This report should include:

- Geological map
- Tectonic map
- Geothermal map
- Resistivity maps at different depths
- Bouguer gravity map
- Magnetic map
- Map showing lateral distribution of seismicity
- Heat flow and soil temperature maps

All these maps should be filed in GIS database. The report should address the following subjects:

- Likely temperature of the reservoir fluids
- Likely heat sources
- Likely flow pattern of reservoir fluids
- Likely geological structure of the reservoir rocks
- Likely volume of abnormally hot rocs.
- Likely total natural heat loss
- A conceptual model of the geothermal system

The conceptual model is based on and should comply with all results of the surface exploration. The report should identify the most promising production areas. It should contain proposed location of at least the firs deep exploration well.

2.1 Environmental base line survey

Environmental base line survey aims at collecting basic information on the environment in which the prospect is found. The main emphasis is on studying the fauna and flora but this study also contains some geo-scientific components. Meteorological conditions are studied and in some cases concentration of emitted gases is studied.

Meteorological station is needed for this study and equipment for measuring gas emission may be needed.

REFERENCES

World Bank, 2009: World Bank geothermal web page: *www.worldbank.org.*