Paper to be presented at *Workshop for Decision Makers on Geothermal Projects and Management,* organized by UNU-GTP and KengGen in Naivasha, Kenya, 14-18 November, 2005

ACTIVITIES CARRIED OUT DURING PRELIMINARY STUDY, APPRAISAL STUDY AND PROJECT DESIGN

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ABSTRACT

Development of geothermal resources is carried out in three major stages which can be summarized as preliminary, appraisal studies and project design. During all these stages, various geological, geophysical and geochemical studies are carried out mainly to define the heat source, fluid characteristics and the reservoir model. The fluid characteristics in terms of chemistry are fundamental elements in geothermal power plant design. The preliminary stage is comprised of three phases which are aimed at identifying the resource, investigating the specific geothermal prospect areas to locate suitable drilling targets and finally to discover a geothermal reservoir by exploration drilling. After the preliminary stage, appraisal study is carried out by drilling more wells and evaluating the reservoir to prove sufficient steam production for power generation. Production drilling and testing of the produced fluids is done and finally project planning follows. Both geological and geophysical studies are useful in locating the buried structures which are suitable targets for drilling productive geothermal wells. Geological information collected is useful in defining the reservoir extent, its boundary formations and the structures that control fluid movement. Geochemical methods are useful in almost all the stages of the project development. Preliminary studies give information on sub-surface temperatures expected in a particular prospective area even before actual deep drilling is done. The discharged fluids are subjected to further chemical analysis to assess their suitability for the intended use. Location of feeder zones in the production wells can also be estimated by use of the chemical composition and calculated geothermometry temperatures of the well fluids. The chemical characteristics of the discharge fluids are used in the initial design of a power plant for electricity generation or for other purposes which the geothermal fluids may be intended to be used.

1. INTRODUCTION

Geothermal energy has become a viable alternative source of energy in many countries endowed with its potential. Many developing countries rely heavily on hydro-based power and expensive fossil fuel for their daily energy requirements. Geothermal energy could become an even better alternative provided more efficient, reliable and cost effective methods are routinely used during both the exploration and exploitation stages. Geothermal energy is derived from systems found in regions with a normal or slightly above normal thermal gradients and especially in regions around plate margins where the thermal gradients may be considerably higher than the average values.

A geothermal system is made up of three main elements: a heat source, a reservoir and a fluid which acts as a carrier for transporting the heat. The heat source can either be shallow magmatic intrusions associated with high-temperature systems, or high thermal gradients where fluids are heated by deep circulation as typical for low-temperature systems. The reservoir can be described as a volume of hot permeable rocks from which the circulating fluids extract heat. The reservoir is often overlain by a cover of impermeable rocks and connected to a surficial recharge area through which the meteoric waters can replace or partly replace the fluids that escape from the reservoir by natural means. The geothermal fluid is water in the liquid or vapour phase depending on its temperature and pressure. This water often carries with it chemicals and gases such as carbon dioxide (CO_2), hydrogen sulphide (H_2S), methane (CH_4) etc.

Development of geothermal resources broadly comprises preliminary studies, appraisal studies and field development. Preliminary studies include: reconnaissance survey of a field, prospect investigation and exploratory drilling. The appraisal stage involves appraisal drilling, reservoir evaluation and feasibility studies while the field development stage involves production drilling, well testing and power plant construction. Several geo-scientific studies are carried out during these development stages in order to realize the goal of harnessing geothermal energy. The major geo-scientific studies carried out include: geology, geophysics and geochemistry of the identified prospect. The details of geological, geophysical and geochemical activities in preliminary, appraisal and project design stages are the subject of this paper.

2. PRELIMINARY STUDIES

Preliminary studies of a geothermal prospect are mainly carried out in three stages: reconnaissance survey, prospect investigation and exploration drilling. The objectives of preliminary studies (field exploration) in a geothermal prospect include:

- Identifying whether a geothermal field exists in a given area by undertaking geophysical prospecting, analyzing, testing or measuring geological and geochemical materials and features from the prospect area that are useful in understanding the hydrothermal systems.
- To estimate the size and extent of the geothermal resource in terms of heat source and hydrogeological controls
- To determine the type and characteristics of geothermal fluids in the system. This is important in order to assess the problems associated with geothermal production like scaling potential.
- Locate productive zones in order to set production targets during production drilling and design production casing depths.
- Estimate the temperatures of the reservoir where the fluids are coming from by use of geothermometry techniques.
- Recommend drilling targets for deep probing in the prospect.

In all these stages, a lot of geological, geophysical and geochemical work is carried out (Fridleifsson, 2002).

2.1 Geological activities during field reconnaissance studies.

Both geological and hydrogeological studies are the starting point of any exploration programme. Their basic function is to identify the location and extent of potential areas to be investigated in greater detail. This is done by carrying out available background literature review, carrying out a regional geological mapping of the area and making use of any available material which will aid in interpretation of the regional structures, stratigraphy, tectonic and volcanological history of the area.
During detailed prospect investigation, a geological study is done to characterize and to develop a preliminary model of a geothermal system. A detailed geological mapping of the area is done where

all structural, lithological, volcanological and geothermal features are examined in the field. The nature of buried structures is revealed by remote techniques like geophysical measurements. All geothermal manifestations are mapped, rock and fluid samples collected for laboratory analysis in order to understand the nature of the reservoir. All the available information is re-interpreted to realistic or possible sub-surface structures and the ones that are thought to be controlling the geothermal system are picked for modelling of the system. The locations for these chosen features or structures are the ones recommended for further investigation by direct probing by deep drilling.

2.2 Geophysical activities during field reconnaissance studies

A wide range of geophysical surveying methods exists for exploration for geothermal energy. The type of physical property to which a method responds dictates the application. The most commonly used methods include:

- Seismic methods;
- Gravity measurements;
- Magnetic measurements;
- DC electrical resistivity methods;
- Transient electromagnetic (TEM) and Magneto telluric (MT) methods.

At the interpretation stage, ambiguity arising from the results of one survey may often be removed by consideration of results from a second survey method.

2.2.1 Seismic monitoring

Seismic waves can be used to study the distribution of the subsurface interfaces of geologic interest leading to location of geothermal resources (Hamilton *et al*., 1973; Simiyu, 1999). Since 1996 (Mariita *et al*, 1996) a continuous micro-seismic monitoring network at Olkaria field, Kenya, to study the earthquake distribution and wave properties has been run across the geothermal field. The main objectives are to carry out an analysis of the wave parameters so as to determine earthquake location and to relate these locations to the presence of structures that are associated with reservoir fluid flow patterns such as faults. Finally, these seismic properties are related to the direct physical parameters of pressure and temperature.

2.2.2 Gravity surveying

In gravity surveying, subsurface geology is investigated on the basis of variations in the earth's gravitational field generated by differences of density between subsurface rocks. A subsurface zone whose density is different from that of the surroundings causes a localized perturbation in the gravitational pull known as a gravity anomaly. Volcanic centres, where geothermal activity is found, are indicators of cooling magma or hot rock beneath these areas as shown by the recent volcanic flows, ashes, volcanic domes and abundant hydrothermal activities in the form of fumaroles and hot springs. There is a correlation between gravity highs with centres of recent volcanism, intensive faulting and geothermal activity. Interpretation of gravity data, used in conjunction with seismic data, has been used to locate the heat source and permeable zones as drilling targets (Ndombi, 1981).

2.2.3 Magnetics

The aim of a magnetic survey is to investigate subsurface geology on the basis of the anomalies in the earth's magnetic field resulting from the magnetic properties of the underlying rocks. In general, the magnetic content (susceptibility) of rocks is extremely variable depending on the type of rock and the environment it is in. Common causes of magnetic anomalies include dykes, faults and lava flows. In a geothermal environment, due to high temperatures, the susceptibility decreases. Over Olkaria field, Kenya both ground and aero-magnetic data have been used to investigate the presence of a geothermal resource in combination with gravity (Bhogal and Skinner, 1971). From the aeromagnetic maps several of the anomalies can be clearly correlated with surface expressions of volcanism such as craters, domes or cones, localised basaltics lavas or plugs. From these maps (Figure 1) most of the volcanic centres tend to lie in areas with magnetic highs (positives).

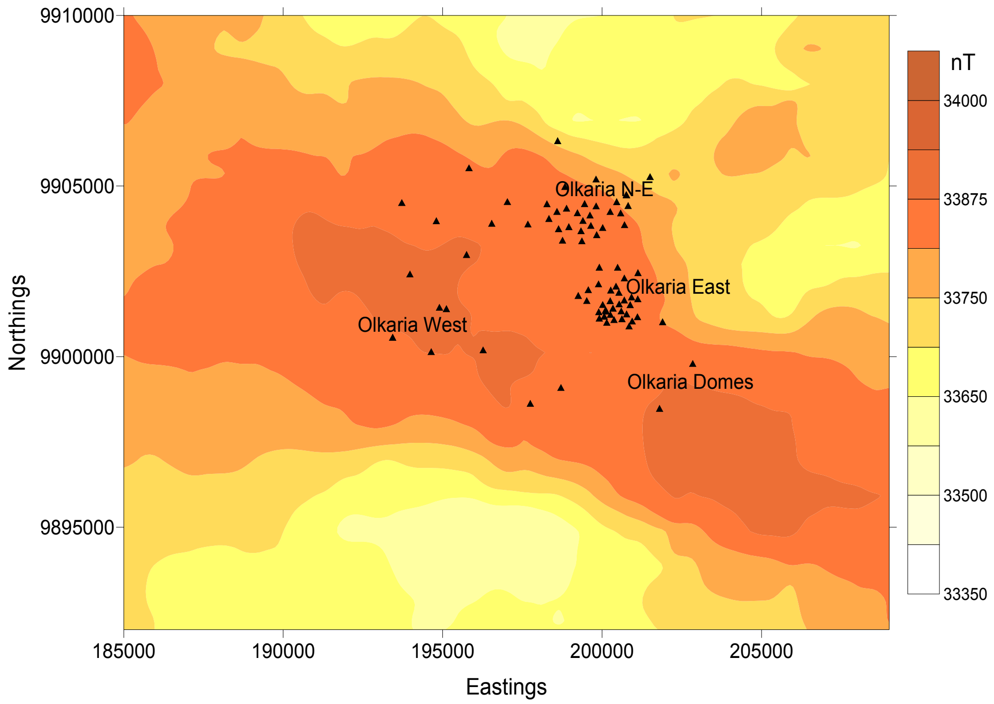

FIGURE 1: Total magnetic intensity over Olkaria and surrounding areas

2.2.4 Electrical and electromagnetic surveying

There are many methods of electrical and electromagnetic surveying that are useful for indicating regions of anomalous electrical conductivity and horizontal and vertical discontinuities. The objective of resistivity data interpretation is to delineate the resistivity variation with depth assuming that the earth is electrically homogeneous and the resistivity only varies with depth, and relate them to hydrogeological and thermal structures associated with geothermal reservoirs. A resistivity survey of a geothermal field reflects the thermal alteration of the field, hence the temperature. Elevated temperatures lead to increasing alteration of minerals in the rocks of the subsurface leading to a lowering of resistivity. At still higher temperatures resistive mineral alteration forms that can lead to higher resistivity values at deeper levels in the central part of the geothermal system.

At Olkaria direct current resistivity methods have been used for reconnaissance mapping, location of faults for drilling targets and to define the boundaries of geothermal reservoirs (Onacha, 1993). In recent years we have favoured Transient Electromagnetic (TEM) and Magneto telluric (MT) sounding methods. The depth of penetration of TEM soundings is not very great, being limited by the frequency range that can be generated and detected. For the Olkaria situation, our experience is that the maximum depth is about 500 m to 1 km (Figure 2).

In the MT method, use is made of natural current fields induced in the earth by time variations in the earth's magnetic field. Due to this, the technique does provide more information on subsurface structure, as its depth of penetration is much larger than TEM. The depth is dependent on the resistivity of the substrate. On other hand, interpretation of data is not as simple.

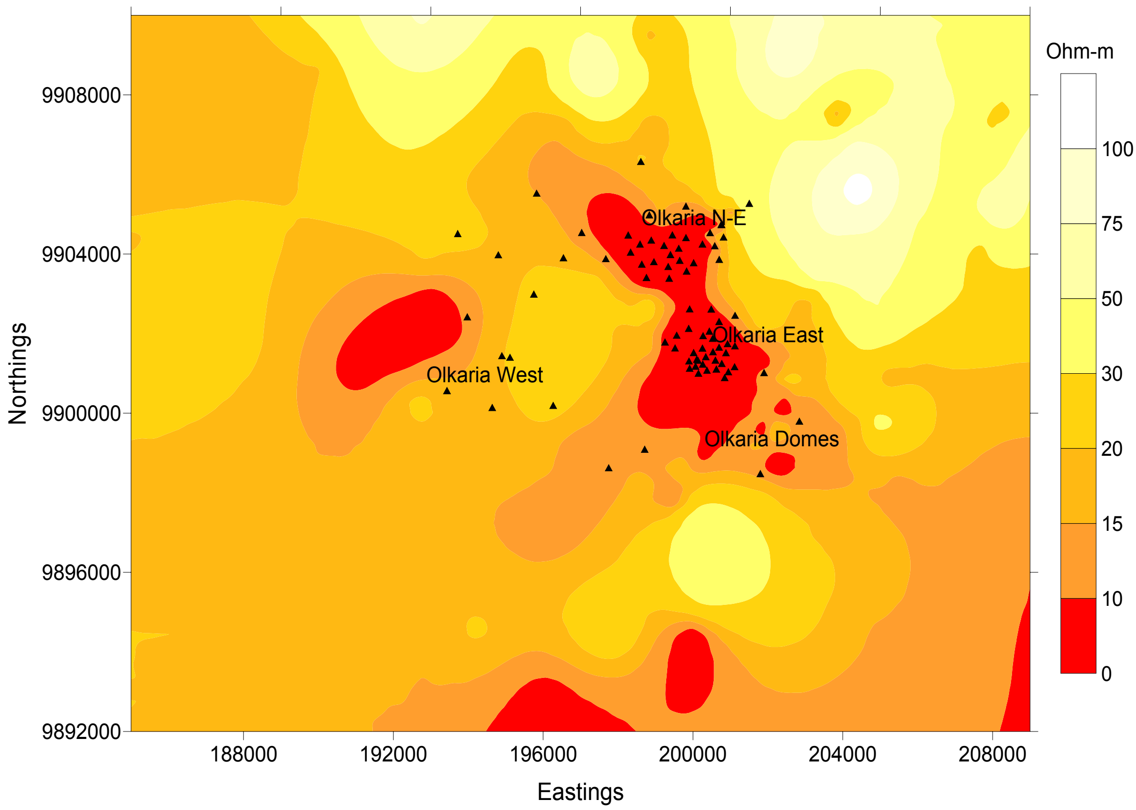

FIGURE 2: TEM resistivity distribution at 1400 masl over the Greater Olkaria geothermal field and surrounding areas, note that the present production fields are underlain by low-resistivity anomaly

2.3 Geochemical activities during field reconnaissance studies

The existence of a geothermal reservoir is indicated by the presence of hot springs, steaming grounds and fumaroles. Exploration has, however, revealed that hidden reservoirs also exist which are not manifested on the surface. The principal purpose of geochemical surveys is to predict sub-surface temperatures, to obtain information on the origin and characteristics of the geothermal fluids and to understand sub-surface fluid flow patterns and directions. It has been proven that under natural conditions, the concentrations of many components in the geothermal fluid reflect thermal conditions at depth. Before conducting any expensive geochemical and geophysical prospecting, a preliminary reconnaissance survey is conducted which describes the location, geological setting and type of thermal manifestations. Once the occurrence and type of geothermal manifestations are known, a strategy on what type of geochemical prospecting is suitable for the area under investigation should be planned. Most of geothermal manifestations occur in form of hot/warm springs, fumaroles, altered steaming ground, geysers, steam jets or gas vents. Geochemical surveys provide useful data for planning exploration and its cost is relatively low compared to other more sophisticated methods such as geophysical surveys. Geochemical surveys should therefore be utilized as much as possible before proceeding with other more expensive methodologies. Essentially such survey involves three stages:

- Sample collection (water, steam condensates, gases, rock samples);
- Chemical analysis;
- Data interpretation.

Samples are collected from available manifestations or wells in the study area and chemical/isotopic analyses conducted on the samples. The chemical analytical data obtained is interpreted on the basis of temperature estimations and water-rock interaction. Water samples are analysed for all major chemical components (Na, K, Mg, Ca, Si, B, SO_4, Cl, F, H_2S, CO_2, ^2H, ^{18}O), pH of the water and occasionally

Al and Fe. The gas samples are analysed for presence of gases known to occur in magmatic environments. Such gases include CO_2, H_2S, CH_4, H_2, N_2, NH_3 and Ar. The concentration of these parameters is used to infer (Arnórsson, 2000).

- Reservoir temperatures where the water and gases are being released. This is possible only when equilibrium between the reservoir rocks and the geothermal fluids has been attained during water-rock interaction in the reservoir.
- Reservoir processes, since most of the ions present in the water samples are known to participate in reactions forming hydrothermal minerals, their concentrations can be used to infer this.

Geochemistry is extensively applied in all phases of geothermal exploration and development. However, during detailed prospect investigation, a geochemical survey is conducted mainly to acquire information which can be used to determine the following parameters in a prospective area:

- To estimate sub-surface temperatures by using chemical and isotope geothermometers as well as mixing models;
- To identify the source of the water, largely by using isotope techniques;
- To estimate the extent of the resource;
- To assess chemical characteristics of the geothermal fluids present and their suitability for electric power production or other non-electrical uses;
- To develop a conceptual model of the area;

For areas which are not characterized by surface manifestations, soil gas surveys are conducted to reveal buried structures like faults/fissures associated with a geothermal system. Such soil gas surveys target such gases as CO_2 and mercury which is known to be characteristically high in geothermal fluids. In some cases radon isotope (Rn-222) radioactivity is used to infer buried fractures/faults. Radon –222 is one of the daughter products of Uranium –238 decay series and has a short half-life of 3.82 days. Uranium –238 is known to occur in magmatic components and therefore high radon-222 counts would be interpreted to infer buried fractures and by extension reservoir permeability. Geochemical information obtained is used to delineate anomalous areas which are then recommended for further probing by deep drilling. The best sites are then drilled after considering all geo-scientific data available from geology, geophysics and environmental baseline information. The drilled well (s) are then discharged and fluid samples collected for geochemical analysis.

2.4 Drilling of the first deep wells

After recommending and citing probable drilling targets, a few deep geothermal wells are drilled in recommended sites for exploring the deep structures of the system with the following objectives (Franzson, 2003):

- To prove the existence of a geothermal reservoir;
- To characterize the reservoir in terms of its geometry, i.e. type of reservoir rocks, their depths, thickness and their permeability;
- To locate fluid feed zones and probable temperatures by studying well profiles in terms of hydrothermal mineral assemblages;
- To determine the thermal history of the reservoir by examining and analyzing the well samples;
- To model the field by using the available sub-surface data in terms of temperatures and orientation of the structures which may control the fluid movements in the sub-surface.

Well profiles have been studied to correlate sub-surface temperatures with hydrothermal mineral assemblages in Olkaria Domes field, Kenya during exploration drilling. Figure 3 shows such profiles for well OW-902 in this field. Calcite and pyrite are found at relatively shallow depths and indicate temperatures between 150 and 250°C while epidote occurs at deeper levels and indicates higher temperatures.

The results of the well discharge chemistry is used to:

- Estimate reservoir temperatures from where the fluids are being released;
- Assess fluid flow patterns in the reservoir;
- Locate recharge zones into the reservoir;
- Locate feed zones where the hot fluids are entering the reservoir;
- Develop a conceptual model for the field.

The chemistry of the well discharge fluids have been used to locate feed zones in wells drilled in Olkaria Northeast field, Kenya (Wambugu, 1996). Various geothermometry functions were used to calculate fluid temperatures which were within the actual measured temperatures in the wells as shown in Table 1 below.

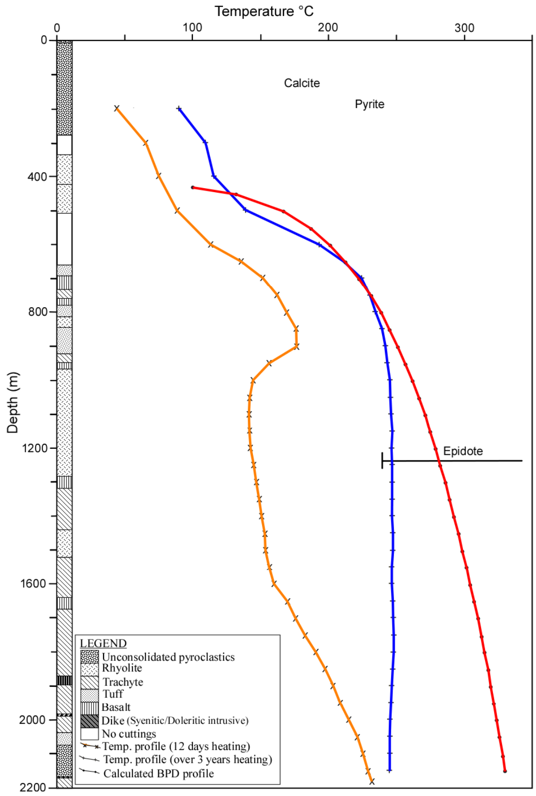

FIGURE 3: Plot of lithology and measured, interpreted hydrothermal minerals and fluid inclusion temperatures vs.depth, well OW-902

TABLE 1: Location of aquifer feed zones for Olkaria Northeast wells

Well no.	Feed zone	Temperature (°C)							
	m a.s.l.	Meas.	Quartz	Chalc.	Na/K	H_2S	CO_2/H_2	TCO_2	H_2
OW-701	1433-1353	230-240	238.1	224.4	293.4	277	301	261	289
	1107-1053	240-245							
	*1053-853	250-270							
OW-705	1305-1205	240-250	262	249.4	228	292	294	286	291
	*1155-850	260-270							
	Below 400	300-320							
OW-706	1298-1148	220-230	267.8	254.9	281.4	278	294	274	288
	1048-948	250							
	748-648	260-270							
	*548-448	280-300							
OW-707	1303-1203	230-240	273.5	260.1	262.3	283	270	276	270
	*803-703	260							
OW-710	1419-1219	200-230	195.2	175.4	286.5	277	281	259	274
	*819-619	260-270							
OW-711	1455-1205	205-220	254.4	241.8	285.7	271	297	248	284
	*755-405	230-270							
OW-713	1336-836	250-260	258.9	246.3	245.6	285	282	277	280
	*486-386	270-280							
OW-714	1306-1056	230-260	270	256.9	270.8	257	290	257	280
	*606-506	270-275							
	250 to –341	280-300							
OW-716	1369-968	240-259	206	187.8	276.3	257	300	257	287
	*269 to –30	270-299							

* Indicates the major feed zones in the well; –30 Means 30 m below sea level (m a.s.l.)

3. APPRAISAL STUDIES

Appraisal studies of a geothermal prospect involve evaluating the characteristics of a prospective well field by drilling more deep wells to be able to use to quantify the potential of the field. The size and extent of the reservoir is determined during this stage.

3.1 Geological activities during appraisal studies

The results of detailed geological studies carried out during exploration drilling are used to site suitable targets for drilling appraisal wells. These should be able to intersect the major geological features confirmed from the study of the well logs of the exploration wells. The major geological features controlling the system are interpreted and they include structural boundaries, permeable and impermeable formations. During drilling of appraisal wells, samples are collected and are analysed further and the information obtained used to make sub-surface section models and a 3-dimensional picture of the field and reservoir is built. The model should be able to indicate:

- Reservoir extent in terms of area;
- Boundaries of the reservoir formations;
- Fluid movement controlling structures;
- More understanding of the nature of the heat source.

3.2 Geophysical activities during appraisal studies

The methods discussed for reconnaissance survey are still employed in this stage of geothermal development. More emphasis during this stage is on resistivity and micro-seismic surveys and more details in the results are necessary.

3.3 Geochemical activities during appraisal studies

During the field appraisal stage, geochemical investigations contribute valuable information including:

- Locating the level of producing aquifers by evaluating the chemical composition of the well discharge fluid and also the drill returns collected during well drilling;
- Temperature of the reservoir and variation of the feed zones. Multiple feed zones can be identified by their different chemical composition and temperature which also contribute to well cyclic patterns;
- Steam to water ratio in the reservoir which identifies type of reservoir (water- or steam-dominated);
- Assessment of the quality of the water and steam in relation to the intended use and also for environmental concerns;
- Predicting scaling tendencies in both the production and re-injection wells and in the surface equipment like pipelines;
- Understanding the fluid flow patterns in the reservoir by analyzing the different chemical compositions of different well discharges. This will also indicate the size or extent and orientation of the reservoir and the recharge direction;
- Improving on the conceptual model of the reservoir.

The conceptual model is updated as more information becomes available.

4. PROJECT DESIGN

The programme for geothermal resource development is usually developed on a step-by-step basis from reconnaissance to detailed investigations, appraisal studies and feasibility studies. During each of these phases the less interesting areas are eliminated and concentration is on the most promising ones. The size and budget of the entire programme should be proportional to its objectives and to the planned forms of utilization. The results of the various surveys of each phase should be used to reassess the programme. The feasibility study aims at examining the economic impact of developing a geothermal field. Due to the risks (uncertainty) involved in geothermal exploration and development it is advisable to divide the preparation work into phases in order to minimize cost and to maximize information for each phase. At the end of each phase, a decision is made as whether to continue or to terminate the project. The following are the main phases in the development of a geothermal project:

- Surface exploration to determine extent of geothermal reservoir, sub-surface temperatures and others like permeability control;
- Exploration drilling to obtain direct information on reservoir temperature, pressure, permeability and reservoir fluid chemistry;
- Appraisal (production) drilling to evaluate the characteristics of a prospective well field;
- Preliminary power plant design to analyse the economics of the project and make a decision on power plant construction.

Broadly the project design phase involves three main stages: production drilling, production well testing and project planning.

4.1 Geological activities during project design

Geological information obtained during exploration is used to site wells for production drilling which should target the most productive features/structures for the success of the project. All the available wells are logged during drilling and the stratigraphic and petrographic records of all depths for each well kept. Such records are useful in understanding production characteristics of each well like locations and nature of feed zones which forms a good basis in understanding the reservoir. The well log information is useful during well field design and construction and later date programmes like well rehabilitation (e.g. well deepening) and decision to site targets for drilling replacement wells. Determining the casing depths in production wells is based on the geological information obtained from the well logs.

4.2 Geophysical activities during project design

Geophysical activities are usually minimal during this stage of project development, unless more information is found needed on some specific geophysical parameters in selected areas, or production fields. However, continuous micro-seismic survey is important such while considering the siting of the power plant.

4.3 Geochemical activities during project design

During the preliminary design of a geothermal project several geochemical activities are carried out as follows:

- Selection of area of interest by conducting surface geochemical field surveys as described above.
- From the surface exploration results, a decision is made on the detailed investigation. The detailed work gives indirect information about the reservoir temperature, permeability and fluid chemistry (characteristics). The results obtained are used to site exploration wells, which are

drilled and tested. This gives direct information on reservoir temperature and fluid characteristics.

- From the exploration results, a decision is made on appraisal drilling and preliminary design. Well measurements and testing are conducted and results give further information on reservoir temperature, pressure, permeability and scaling and corrosion tendencies of the well fluids.
- Well flow testing is done to assess the production capacity of the reservoir and its response to production load. Chemical characteristics of the wells at this stage reveal the discharge patterns of each well by identifying the wells with the most stable production from the cycling ones. The output of the wells with the most stable production are the ones considered in the design.
- The results on well testing are used to make a decision on the design. During and after production drilling, wells are discharged and tested to determine the water to steam ratio in the well fluids for power plant design (or other intended) utilization. These measurements allow for the assessment of the size and production characteristics of the well field.
- The results obtained are used as a basis for the engineering design of the power plant. Decisions on further production drilling and well field production monitoring are also made to assess the response of the reservoir to exploitation.
- Tender documents for construction are then sent out followed by construction and finally power production.

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