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OVERVIEW OF GEOTHERMAL SURFACE EXPLORATION METHODS

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ABSTRACT

Geothermal surface exploration invariably entails a multi-geoscientific process, which are holistically aimed at defining the geometry and characteristics of the geothermal system prior to drilling. The scientific disciplines commonly involved are geology, geochemistry, and geophysics. Geological approach generally aims at understanding the various lithologies, volcanological evolution, structural controls, and hydrological regimes of the system. Geophysical exploration helps in determining the geometry (shape, size and depth) of the heat sources, reservoir and cap rock. It also aims at imaging structures that are responsible for the geothermal system, and delineating the areal extent of the geothermal resource. The most commonly used geophysical methods are electromagnetic/electric, gravity, magnetics and seismics. These methods ultimately depend on the various intrinsic properties of rocks such as resistivity/electrical conductivity, density, magnetic susceptibility, elastic moduli/velocity respectively. Geochemical exploration relies mostly on sampling and analysis of water, steam and gas from the thermal manifestation in order to characterize the fluids, estimate equilibrium reservoir temperature, determine the origin, evaluate mixing scenarios, determine the suitability of the fluids for the intended use and locate recharge areas and direction of fluid flow. Additional geochemical studies entails soil diffuse degassing measurements aimed at identifying gas leakages that usually mimic active faults and structures.

1. INTRODUCTION

Geothermal energy has become a viable alternative and sustainable source of energy in many countries. The energy is commonly manifested on the terrestrial surface in the form of fumaroles, hot springs, geysers, steaming grounds and altered grounds. The economically usable geothermal energy is that which occurs close to the earth's surface where it can be tapped by drilling wells up to 3,000 m below the earth's surface. Such shallow heat sources are in most cases attributed to volcanic activity, which are commonly associated with plate boundaries, which is reminiscent of the East African Rift system and other geodynamic environments. The essential components of a geothermal system include; heat source, permeable reservoir, cap rock and recharge regime. Ideally, multiple geoscientific disciplines such as geophysics, geology and geochemistry are commonly employed in the geothermal exploration, in order to define the aforementioned components.

1.1 Objectives of geothermal exploration

The objective of geothermal exploration is to obtain adequate information about the properties and features of a prospective geothermal system before embarking on drilling. Most of the information include but not limited to:

- Identify areas with potential geothermal energy;
- Estimate equilibrium reservoir temperatures;
- Characterize thermal fluids;
- Define the geometry (shape, size and depth) of the resource;
- Rank the prospect areas in order of development priority;
- Develop a conceptual model;
- Locate suitable drilling targets; and
- Determine the pre-exploitation values of environmentally sensitive parameters.

1.2 Phases of geothermal development

Geothermal development is essentially a sequential and a systematic process of exploring of productive sites with the ultimate aim of geothermal power production. The development phases begin with reconnaissance and exploration, pre-feasibility, feasibility and finally power plant construction (Figure 1). Árnason and Gíslason **(**2009) deduced that successful surface exploration reduces the cost of later stages in the development and thus saves a lot of money in the end. At the onset of a geothermal exploration project it is normally uncertain whether results will be economically, technically and environmentally feasible. Geothermal exploration therefore invariably necessitates risk. It is with respect that, exploration process is commonly carried out on a step-by-step basis, and is divided into several phases in order to minimize cost and maximize information for each phase. Each of these phases gradually eliminate the less interesting areas and focus on the most promising ones.

The exploration programme should 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. Ideally before kicking off, an exploration exercise it is pertinent to begin with collection of available information from previous work, topographic, geological, structural and geothermal maps of the prospect area of interest. It is common practice that reconnaissance provides preliminary information about the geological and structural settings, most suitable sites and location of the thermal surface expressions as well as their characteristics. An inception report is normally prepared after obtaining the valuable information from the reconnaissance and a detailed exploration plan subsequently developed. Detailed exploration entails extensive geological and geochemical studies, a range of geophysical techniques including gravity, magnetic and resistivity surveys. 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 **(**Árnason and Gíslason, 2009).

2. EXPLORATION METHODS

The various scientific disciplines employed in geothermal exploration are geological studies geochemical studies, various geophysical techniques and environmental baseline survey.

2.1 Geological studies

Geological studies invariably starts at the incipient reconnaissance stage, which entails preliminary mapping of the lithologic units and structures, mapping of thermal surface manifestations and possibly relate to the structures and or volcanism in the prospect of interest.

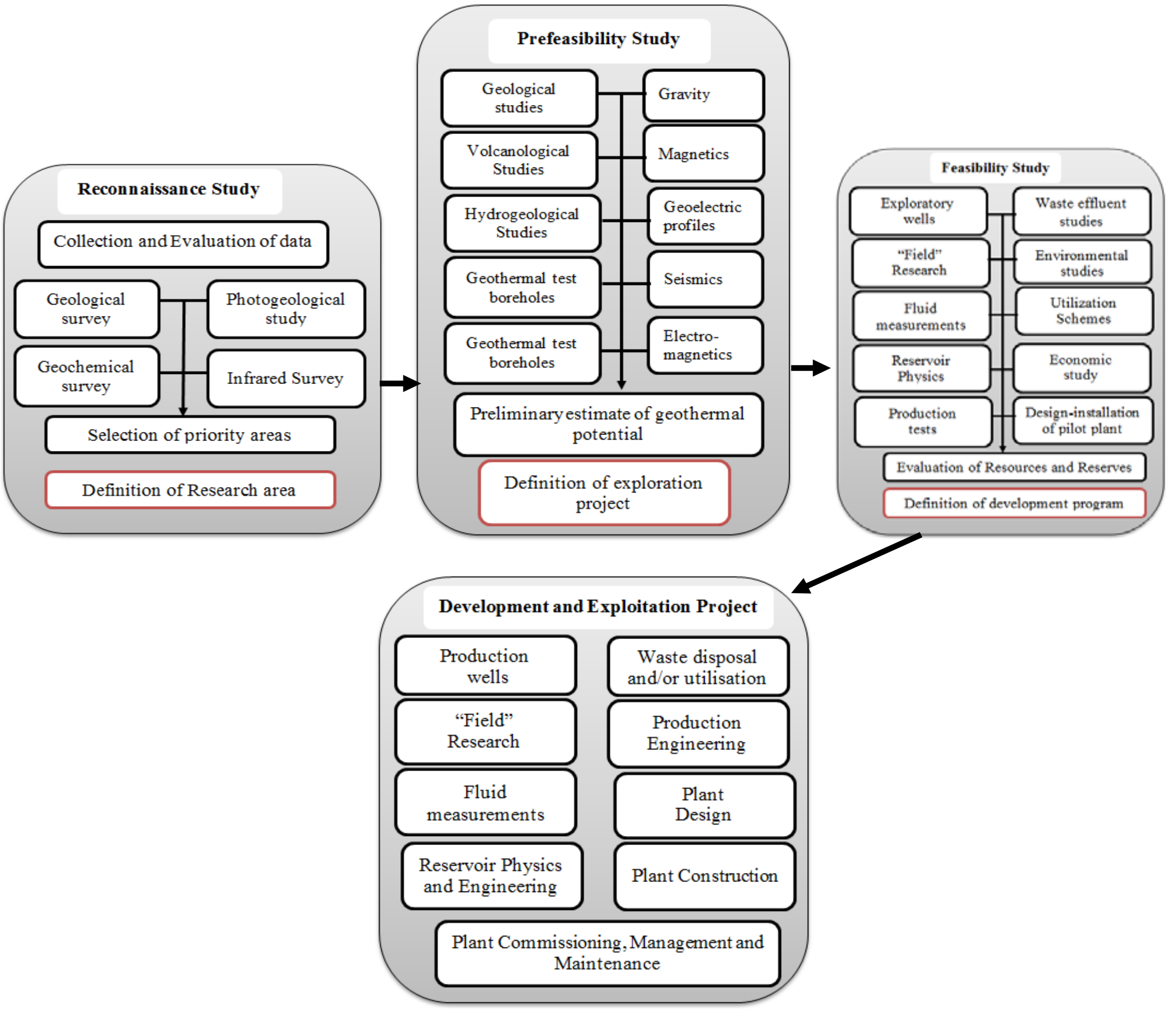

FIGURE 1: Simplified geothermal development flow chart (mod. from Manzella and Pipan, 2009).
Many factors influence choice of methods and include: geological conditions, availability of surface manifestations, geographical setting – terrain, cost, time factor (time required to produce results), specific needs or requirements which is tied to the projected use of the resources (Árnason and Gíslason, 2009; Wanjie, 2012)

Detailed geological studies is performed in the geothermal field and its surroundings (Árnason and Gíslason, 2009). This comprehensively entails mapping rock units, types (Figure 2) and their chronological sequence. Petrological and petrochemical rock analysis is performed to be able to distinctively understand the rocks units. Structural mapping is done in the effort to distinguish the types of faults and fissures that transect the geothermal prospect of interest, and be able to discern the structural controls of the system. In cases of volcanic settings, eruptive centres, calderas, fissures, rock units, intrusions are mapped and radiometrically dated in order to understand the volcanological evolution and the stratigraphy.

Detailed mapping of geothermal alteration on the surface is performed and alteration minerals analysed using XRD. 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. **(**Árnason and Gíslason, 2009).

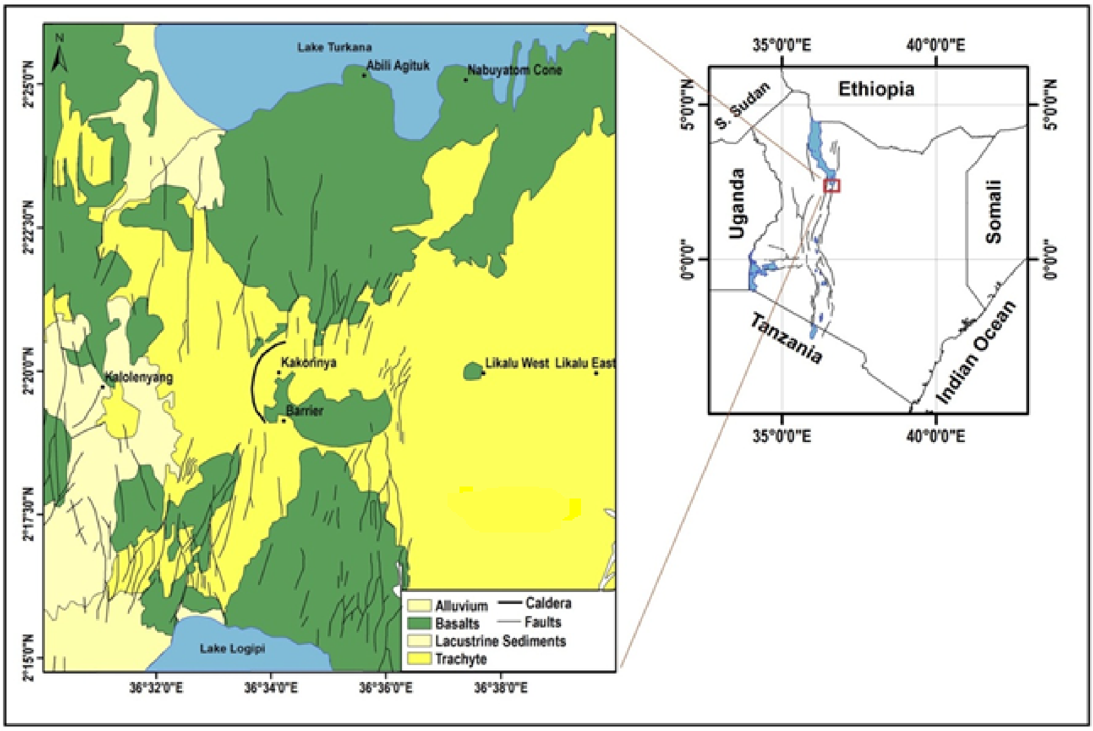

FIGURE 2: Simplified geological and structural map of Barrier Volcanic Complex (modified from GDC, 2011)

2.1.1 Photogeology and remote sensing

Photogeological maps and remote sensing images can be used to carry out mapping of geological structures during the reconnaissance and/or the detailed mapping. They serve as an important tool in mapping structures and/or thermal manifestations and other geological features of interest especially and makes it easy to access the remote, highly inaccessible rugged terrains and unexplored areas. The applications of remote sensing to geothermal exploration relies on spectral and spatial properties of airborne and spaceborn remote sensing platforms, i.e. LIDAR (Light Detetion and Ranging), ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) (Figure 3).

The imagery of optical, near-Infrared and thermal-Infrared (Figure 4) region of the electromagnetic spectrum can be used to identify surface expressions of geothermal resources (Pipan, 2009). The geothermal manifestations such as sinter/tufa, hydrothermal alteration products (clays, sulfates), thermal anomalies have distinct spectral signatures that can facilitate recognition on the remote sensing imagery.

2.1.2 Hydrological studies

Hydrological studies are performed in order to understand the recharge, flow regime (out flow and water budget) into the system. This is normally achieved by detailed mapping of groundwater (water rest level), cold springs, lake levels and groundwater level and ultimately developing a potentiometric map.

2.2 Geochemical studies

Geochemical exploration for geothermal resources involves sampling, analysis and interpretation of discharge of thermal fluids from fumaroles, hot springs and steaming grounds. The main objectives of geochemical studies are to characterize the thermal fluids, establish their origin, flow direction (upflow, outflow), evaluate mixing scenarios, estimate the equilibrium reservoir temperature and determine the suitability of the fluids for the intended use.

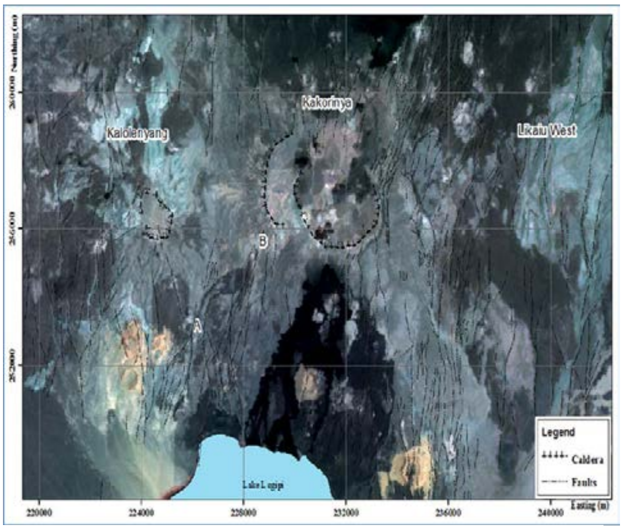

FIGURE 3: ASTER imagery of the Barrier Volcanic Complex (Mutua and Mibei, 2011)

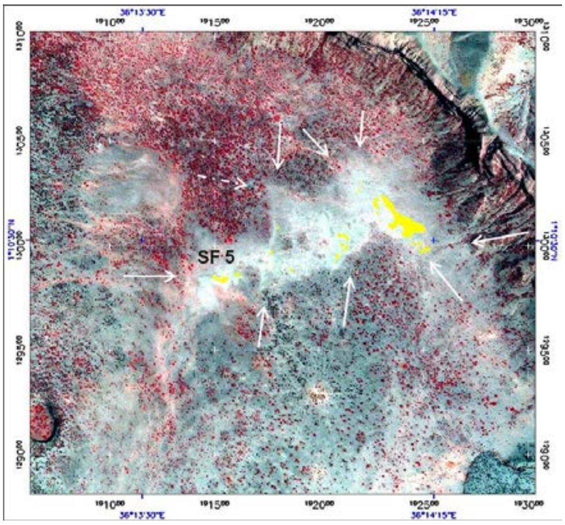

FIGURE 4: Spot image for thermal infrared for Silali caldera (GDC and BGR, 2012)

Fumarole and hot spring sampling procedures are those described by Arnórsson et al. (2006), while the analysis of the essential chemical parameters usually done as described by (Ármannsson and Ólafsson, 2006; 2007; Arnórsson et al., 2006). The following subsection provides more details on the information obtained from geochemical surveys.

2.2.1 Classification of thermal fluids

Geothermal waters have been classified with respect to their anion and cation contents into alkali-chloride water, acid sulphate water, acid sulphate-chloride water and bicarbonate water. The ubiquitous Giggenbach (1991), Cl-SO_4-HCO_3 ternary diagram (Figure 5) is used in the classification of waters based on the major anions. The Giggenbach (1988) Na-K-Mg ternary diagram (Figure 6) involving the simultaneous use of a Na/K and $K/Mg^{0.5}$ ratio is used to establish the equilibrium between the fluids and hydrothermal minerals and ultimately determine the suitability of the waters for ionic solute geothermometry.

2.2.2 Tracing the origin and mixing scenarios

Geothermal fluids are most commonly meteoric and oceanic water although fluids in andesitic geothermal systems, near subduction areas often contain significant proportions of evolved connate and

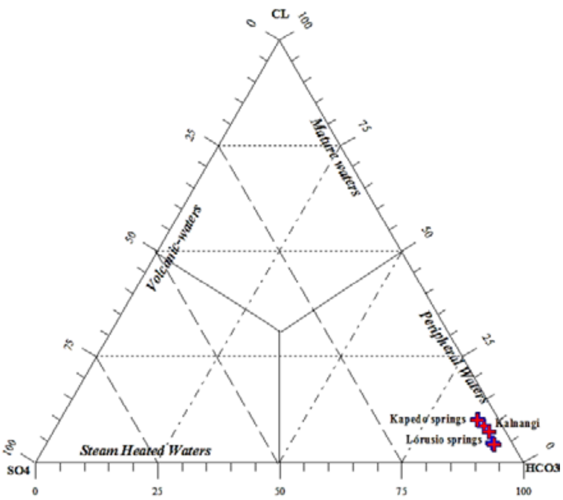

FIGURE 5: Cl-SO_4-HCO_3 of Silali

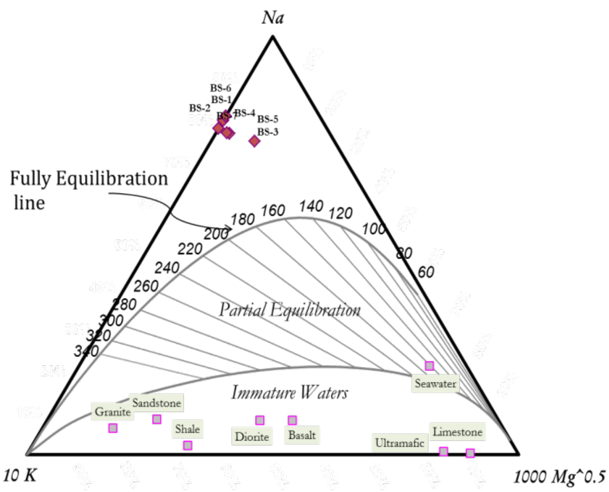

FIGURE 6: Na-K-Mg of the Logipi

magmatic waters (Ármannsson and Fridriksson, 2009). The knowledge of the origin of geothermal waters is very important in geothermal studies because it helps in discriminating the chemical properties of the thermal waters and also their sources of recharge (Oyuntsetseg, 2009). Stable isotopes studies (especially ^2H and ^{18}O) (Figure 7) play an important role in hydrogeological investigations of both thermal and non-thermal waters because the isotopes carry imprints of the origin of the waters.

Additionally conservative constituents (Cl, B) can be used for tracing origin, mixing and flow of geothermal fluids. Gas ratios can also be used to recognize flow directions and upflow zones (Nicholson, 1993). Furthermore, mixing models have been developed to allow estimation of the hot water component in mixed waters emerging in springs or discharged from shallow wells. There are essentially three kinds of mixing models: 1) the chloride-enthalpy (Figure 8) mixing model (Truesdell and Fournier, 1977); 2) the silica-enthalpy warm spring mixing model (Fournier, 1977); 3) the silica-carbonate mixing model (Arnórsson, 2000).

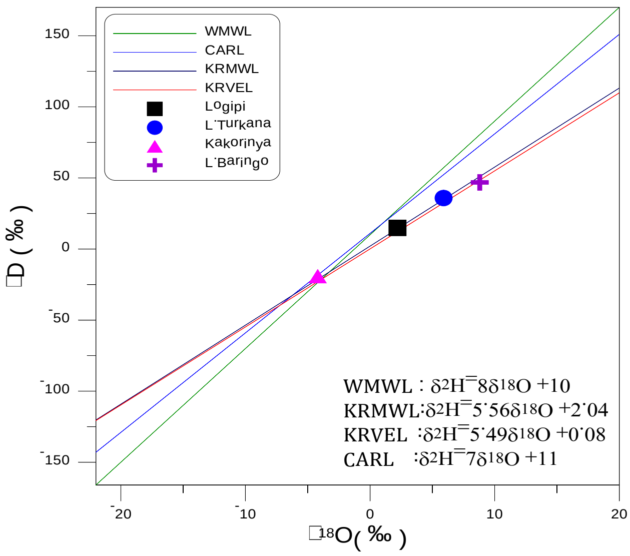

FIGURE 7: ^2H and ^{18}O plot for the BVC fluids (modified after Dunkley et al., 1993)

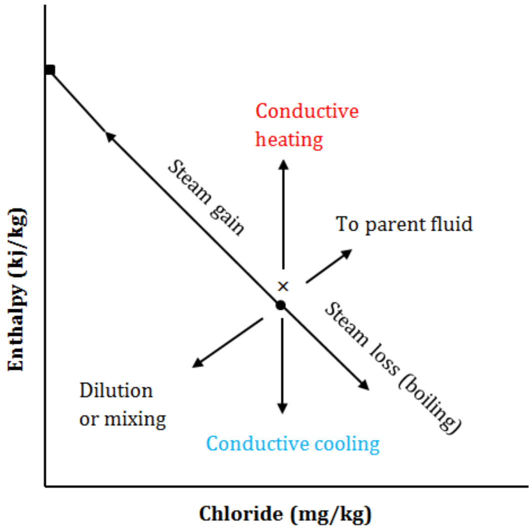

FIGURE 8: Chloride-enthalpy mixing model (modified after Nicholson, 1993)

2.2.3 Estimation of reservoir temperature

Rock forming constituents (e.g. SiO_2, Na, K, Ca, Mg, CO_2, H_2) are used to predict subsurface temperatures and potential production problems such as deposition and corrosion (Ármannsson and Fridriksson, 2009). Many chemical and isotopic geothermometers are used to estimate the aquifer temperatures beyond the zone of secondary processes like boiling, cooling and mixing on the basic assumptions that the sampled fluids are representative of the undisturbed aquifers where local equilibrium conditions are achieved.

2.2.4 Soil diffuse degassing measurements

Soil diffuse degassing measurements of CO2, ^{222}Rn,^{220}Rn, and Hg is critical in delineating permeable zones (gas leakages) of the system that are associated with fractures, fissures and other geological structures. Measurements of the diffuse flow of CO_2 through soil in geothermal fields can be useful for the purpose of delineating fractures or other structures that direct flow of fluids in the geothermal reservoir (Fridriksson, 2009).

2.2.5 Determination of the suitability of utilizing the fluids

The chemistry of the fluids provides a great insight in evaluating the appropriate uses of the fluids depending on the likelihood of scaling and corrosion. In this regard speciation programs are normally used to determine the equilibrium speciation and activity of the chemical species in the effort to predict the potential scaling and corrosion. The most common speciation programs are WATCH, Geochemist Work Bench, CHILLER, TOUGHREACT, FRACHEM and SUPCRT92.

2.3 Geophysical studies

Geothermal anomalies are linked to geophysical anomalies because changes in temperature and geothermal gradient can change subsurface physical properties that influence measurements at the surface (Pipan, 2009). In this respect, a geothermal system generally causes inhomogeneities in the physical properties of the subsurface, which can be observed to varying degrees as anomalies measurable from the surface. The changing physical properties can be measured using different geophysical methods and instruments (Table 1).

TABLE 1: Physical properties and the corresponding geophysical methods and instrument

Physical property	Geophysical method	Common equipment
Electrical conductivity/resistivity	Electromagnetic/electric	MT/TEM
Density	Gravity	Gravimeter
Magnetic susceptibility	Magnetics	Magnetometer
Elastic moduli/velocity	Seismics	Seismometer

It is worth noting that, some of the geophysical methods such as gravity, magnetics and seismics which are traditionally known to be used in the exploration of hydrocarbons are also used in geothermal exploration because they give valuable information on the subsurface geological structures and features. Geophysical methods in geothermal exploration basically aim at determining geometry (shape, size, depth) of the heat source, reservoir, cap rock. Additionally the methods aim at imaging structures that are responsible for the geothermal system, fluid pathways, stress field and delineating the areal extent of the geothermal resource. The following subsection provides more details on the various geophysical techniques used in the geothermal exploration.

2.3.1 Electric / Electromagnetic survey

Electric and electromagnetic methods provide the electrical resistivity (ρ) or its reciprocal electrical conductivity (σ) of the subsurface. The electrical resistivity depends basically on: temperature, pressure, clay content, rock mineral association, porosity structure, saturation- fluid content, salinity of the fluid and fluid movement. It is worth noting that, resistivity decreases with increasing porosity and increasing saturation. These indeed make it easier for resistivity survey in particular to locate anomalies that are directly related to the presence of geothermal fluids.

Electromagnetic (EM) sounding methods used in geothermal exploration are natural-source induction methods (magnetotellurics and audiomagnetotellurics), and controlled-source induction methods (CSMT, TEM), while electric methods (DC methods) include Schlumberger and Wenner sounding methods, the dipole–dipole and the bipole–dipole mapping method.

Deeper probing is commonly done by magnetotellurics (MT) while shallower probing is usually done using the central loop TEM method, (or DC methods). TEM soundings also help in the static shift correction of the MT data.

2.3.2 Gravity survey

Gravity survey measures variations in the Earth's gravitational field caused by differences in the density of sub-surface rocks. 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 dense station spacing for more detailed structural studies such as buried faults (Rivas, 2013). Density reduction due to partial melts may also be detected by gravity anomalies. Positive gravity anomalies usually imply higher density values which are normally associated with plutonic intrusions and dykes, deposition of silicates from hydrothermal activities during greenschist metamorphism, while negative gravity anomalies implying lower densities values caused by higher porosities or by highly fractured parts of a rock, alteration minerals produced by circulation of hot water (Pipan, 2009). The primary use of gravimetric measurements is to help constrain the structural context of an area, outline trends of faults or the depth of the basement.

2.3.3 Magnetic survey

Magnetic measurements are performed using magnetometers either at the surface or airborne, if the objective is regional mapping and the measurements are dependent on the magnetic susceptibility of geological materials. Magnetic surveys can map demagnetized rocks due to thermal alteration and surveys give complementary structural information, which helps in the interpretation of other data. Pipan (2009) deduced that high-resolution aeromagnetic (HRAM) surveys have a resolution in the subnanotesla scale, such that magnetic surveys are no longer restricted to magmatic rocks but can also be used to map intrasedimentary faults with elevated magnetite concentrations that generate small anomalies. Such HRAM surveys are often used in hydrocarbon exploration.

The magnetic susceptibility of a rock and the temperature at which it disappears depend strongly on the rock components, the more or less magnetic minerals (Rivas, 2013). The most useful magnetic minerals are magnetite, ilmenite, hematite and pyrrhotite. Silicate minerals, rock salt (halite) and limestones (calcite) have a very low magnetic susceptibility and are therefore not useful for magnetic measurements. Demagnetised rocks confirm the existence of a hot rock mass in the crust. The presence of dykes is revealed by high susceptibility. On the other hand circulation of hydrothermal fluids causes alterations in the rock which lead to a reduction in susceptibility. This reduction is a consequence of the destruction of the magnetite contained in the rocks. That way, units of volcanic rocks and lava flows can easily be distinguished from hydrothermally altered rock units, which make geomagnetic surveys a useful tool for geothermal prospecting at high enthalpy volcanic reservoirs (Pipan, 2009).

2.3.4 Seismic survey

Seismic survey depends on the elastic properties influencing the propagation velocity of elastic waves. Anomalously hot mass of rock delay the transit of the compressional (p) waves from earthquakes and reduce the amplitude of the shear (s) waves. Seismicity analysis gives information about fractured zones, active faults and some indications of the heat source of the system. The spatial distribution of the seismicity could also indicate the extension of the geothermal reservoir. Cooling of the heat source can produce micro-seismicity (Árnason and Gíslason, 2009). It can be a good practise, if a considerable number of seismic stations are deployed in geothermal prospects that are located in active geodynamic settings.

Results from volcano-seismic studies of many geothermal fields show that they are possible resource mapping tools for geothermal exploration and reservoir monitoring. The volcano-seismic approach can be useful as a stand-alone tool for analysing geothermal resource both at the exploration and exploitation stage that is cost effective in the long term (Simiyu, 2009; Rivas, 2013).

2.3.5 Heat flow measurements

The primary objective of heat flow measurements is to estimate amount of heat energy being lost naturally, analyse the distribution of heat loss features and locate hidden fracture zones. Heat loss is related to temperature gradients. Heat loss mechanisms are conduction, convection and radiation. In geothermal settings, heat is lost through conduction-mainly in contact with the system rock bodies, through convection: mainly through discharging fluids e.g. fumaroles, steaming ground, hot springs etc. High heat loss anomalies usually coincide with the structural trend and/or areas with thermal manifestations.

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 (Árnason and Gíslason 2009).

2.4 Conceptual model and well siting

Conceptual model is a descriptive or qualitative model incorporating, and unifying, the essential physical features of the systems in question (Grant and Bixely, 2011). A geothermal conceptual model (Figure 9) can incorporate information such as; size, temperature (indicated by isotherms), two-phase and steam-dominated zones, secondary aquifers, reservoir, permeable flow structures (faults, fractures, horizontal layers, etc.), flow patterns including upflow, outflow and recharge (indicated with arrows), processes like mixing, chemical buffering or boiling, internal flow barriers like dikes or sealing, the cap-rock, the nature of the heat source. These information can be derived from the various geoscientific disciplines.

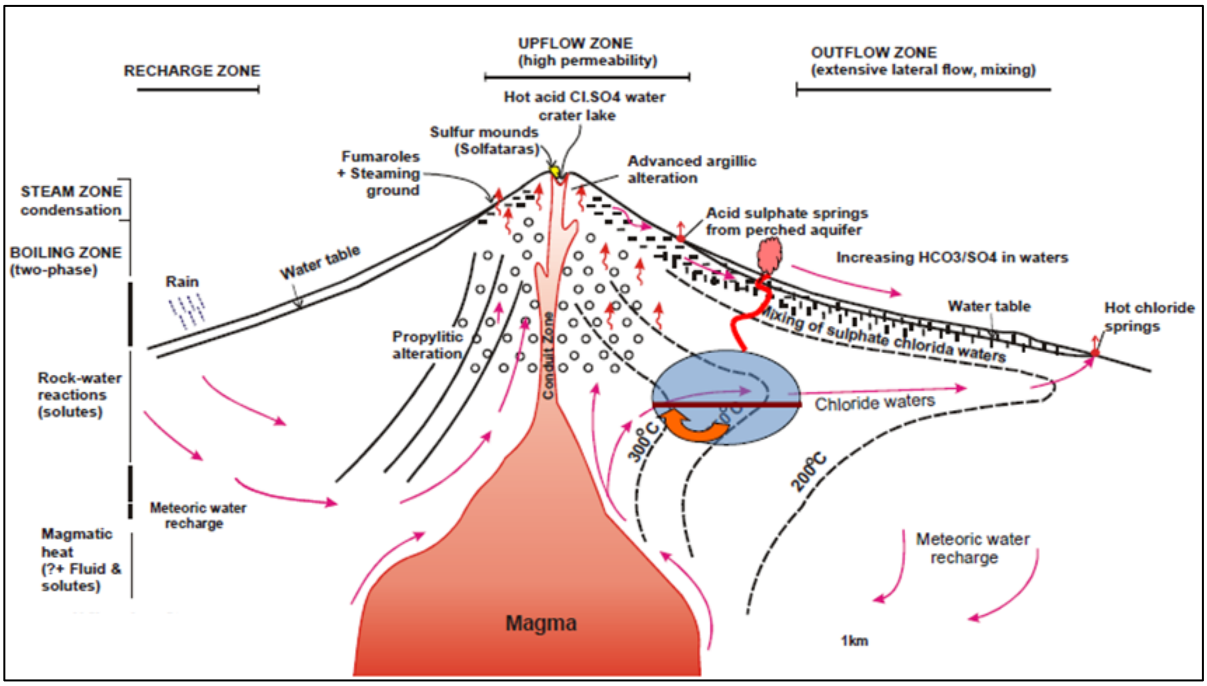

FIGURE 9: Conceptual model of volcanic geothermal system (modified after Nicholson, 1993)

The process of developing a geothermal conceptual model entails but not limited to reviewing of all geoscientific resource data, developing relevant ideas and possible alternatives, drawing cross-sections and maps, studying geothermal system analogs and coming up with a story that binds the model. Mortensen and Axelsson (2013) affirmed that conceptual model aims at highlighting the distribution of temperature, pressure, permeability and fluid chemistry within the geothermal reservoir in order to delineate the direction of fluid flow and circulation (e.g., hot upflow, outflow and colder recharge) symbolized with arrows.

Data integration of the geoscientific disciplines can either be GIS based or through other sophisticated software in order to develop a suitability model that can help in locating the suitable drilling targets. Different weights can be put on the various geoscientific methods depending on the amount of information each discipline gives about the system in question. Árnason and Gíslason (2009) deduced that a good practice is to prepare a comprehensive geothermal database that accompanies the geothermal map. 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 (magmatic or intrusive), hydrology, and flow paths in the permeable reservoir.

2.5 Environmental baseline survey

Geothermal is one of the most environmentally benign, renewable and indigenous energy resource in the world. During its exploitation, waste gases that include carbon dioxide and hydrogen sulphide and brine are released into the atmosphere. However, in most cases, the gas concentration levels are within the World Health Organization (WHO) permissible exposure limits, the brine can be re-injected fully, and by re-injecting the brine apart from disposal, it has an added benefit of recharging the reservoir as well. Nevertheless, sustainability and mitigation of environmental effects should be outlined and optimized prior to major financial commitment.

Environmental Baseline Survey (EBS) is invariably carried out and the output subsequently used in fully-fledged Environmental Social Impact Assessment (ESIA) study for the envisaged geothermal energy development project. The EBS involves socio-economic aspects of the project area, the meteorological conditions, the flora and fauna, water resources etc. Geothermal potential is generally localized in remote, arid and semi-arid regions in the Kenyan perspective. In the spirit of evaluation of the socio-economic pros and cons (Figure 10), the positive effects by and large do outweigh the negative effects of geothermal development.

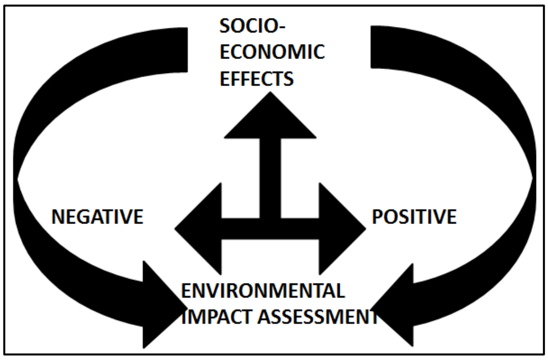

FIGURE 10: The Pros and cons of the socio-economic effects of geothermal project

3. CONCLUSIONS

- Geothermal exploration is indeed a multi-geoscientific process, which entails geology, geochemistry and various geophysical techniques, and in essence no single method can comprehensively unravel a geothermal system.
- The multi-skills process aims at determining the features and properties of a geothermal system; heat source, reservoir, cap rock, recharge and permeable regime.
- The epitome of exploration is to determine the existence of a geothermal resource and subsequently identify suitable drilling sites based on integrated data.
- Geothermal exploration is a sequential and a systematic process, and normally carried out on a step-by-step basis with each of the phases involved aimed at gradually eliminating the less interesting areas and focusing on the most promising ones.
- Successful surface exploration will save big money when geothermal project enters development phase.
- Sustainability and mitigation of any possible environmental effects should be outlined and optimized prior to major financial commitment.

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