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OVERVIEW OF GEOTHERMAL SURFACE EXPLORATION METHODS

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ABSTRACT

The most commonly used geothermal exploration methods, geology, geophysics and geochemistry are briefly described. In geophysics much emphasis is laid on the electrical methods because resistivity of the rocks correlates both with temperature and alteration of rocks which are key parameters for the understanding of the geothermal system. In geochemistry the overview is based on the sampling of thermal waters, steam and gases and more emphasis put on the importance of good sampling techniques. Examples of data interpretations are given using prospects in the Kenya rift valley.

1. INTRODUCTION

Geothermal Exploration can be defined as the exploration of the subsurface in search of viable active geothermal regions with the goal of building a geothermal power plant, where hot fluids drive turbines to generate electricity. The objective of the exploration is to obtain as much information about the properties of the geothermal system as possible, prior to drilling. Such information includes:

- Temperature in the geothermal reservoir
- Permeability of the reservoir
- Areal extent of the thermal anomaly
- Depth to useful temperatures
- Location of the upflow zones
- Chemical composition of the fluids

It should be noted that successful surface exploration reduces the cost of later stages in the development and thus save a lot of money in the end. At the onset of a geothermal exploration project it is uncertain whether or not results will be economically, technically and environmentally feasible. Geothermal exploration therefore invariably necessitates risk money.

1.1 Essential feature for a geothermal system

Geothermal regions with adequate heat flow to fuel power plants are found in rift and subduction zones and in mantle plumes (Figure 1). The apparent indicators for essential features for the existence of a geothermal system(s) include:

Heat source – The source could be any of the following, shallow magmatic body, decaying radioactive elements or heat from overburdened pressures. Most if not all high temperature geothermal areas show a close connection with eruptive centres that have produced silicic lava.

Recharge system – As hot geothermal fluids are withdrawn from wells or from surface manifestations the hydrological balance of the system is restored or partially restored by the inflow of new recharge water
Permeable formation(s) – Structures that allow water to percolate to deeper levels and also host the gas, vapour and water found within the reservoir
Cap rock – Allows the retention of heat and restricts the upward movement of fluids from a reservoir. The caprock is simply a layer of rock of low permeability overlying the reservoir. It may be produced by self-sealing due to deposition of minerals from the solution mainly silica or by hydrothermal alteration of rocks to clays and/or zeolites.

In the following sections an overview of the most important methods used in geothermal exploration are briefly described and examples of their use given. However for a more thorough overview reference to the published works and text books is recommended.

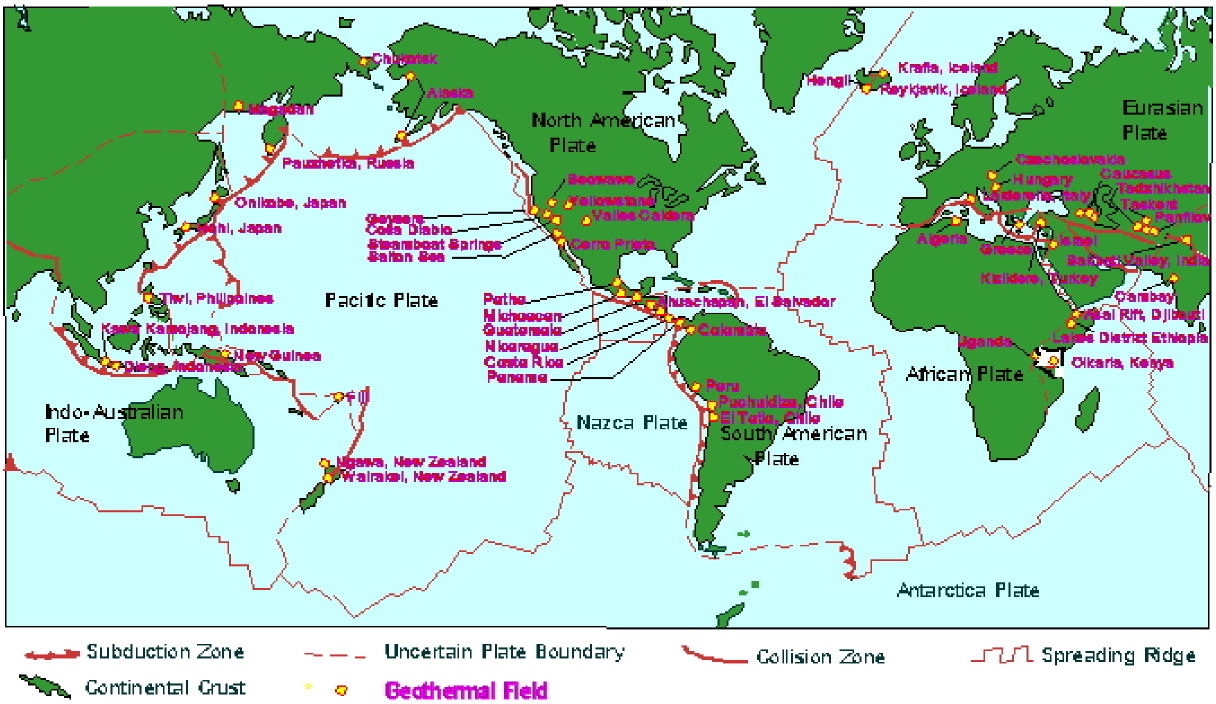


FIGURE 1: Geothermal fields of the world

1.2 Choice of exploration methods

Many factors influence choice of methods and include:

- Geological conditions
- Availability of surface manifestations
- Geographical setting – terrain etc.
- Cost
- Time factor (time required to produce results)
- Specific needs or requirements (projected use of the resources)

Geothermal surface exploration is a multidisciplinary task and mostly includes geology, geophysics and geochemistry and environmental baseline survey.

1.3 Geothermal exploration

Exploration begins with collection of all available information and selection of the area of interest. This includes reviewing of previous work in the prospect area, collection of topographic, geological, geothermal and tectonic maps. A reconnaissance visit is made basically to confirm the information at hand and an inception report with plan on exploration is prepared. It is at this point where the decision on exploration is made. There after a detailed surface exploration is implemented involving:

- Geochemical studies
- Geological studies
- Range of geophysical techniques
- Environmental baseline survey

Because of the uncertainty involved the exploration process is divided into several phases in order to minimize cost and maximize information for each phase (Figure 2). A decision is made after every phase.

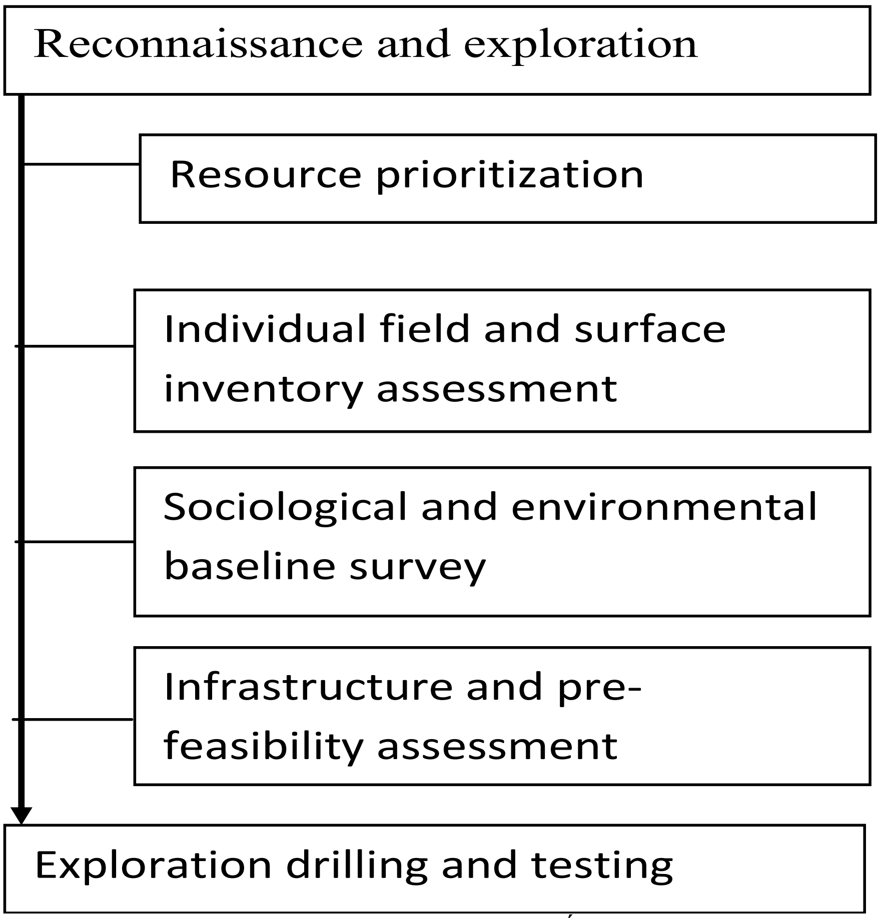


FIGURE 2: Surface exploration flow chart (from Árnason and Gislason, 2009)

2. METHODS OF EXPLORATION

2.1 Geological investigations

Reconnaissance geological mapping - 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.

Detailed geological mapping - 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 as intrusions, if cropping out, are mapped and dated in order to reveal the volcanic history (Figure 3). Detailed mapping of tectonic features is performed. Faults are classified into normal, thrust and strike slip faults and fissures (Figure 4). 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. 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 (Figure 5). If the groundwater level is deep and little or no water on the surface, resistivity methods may be useful to map groundwater levels.

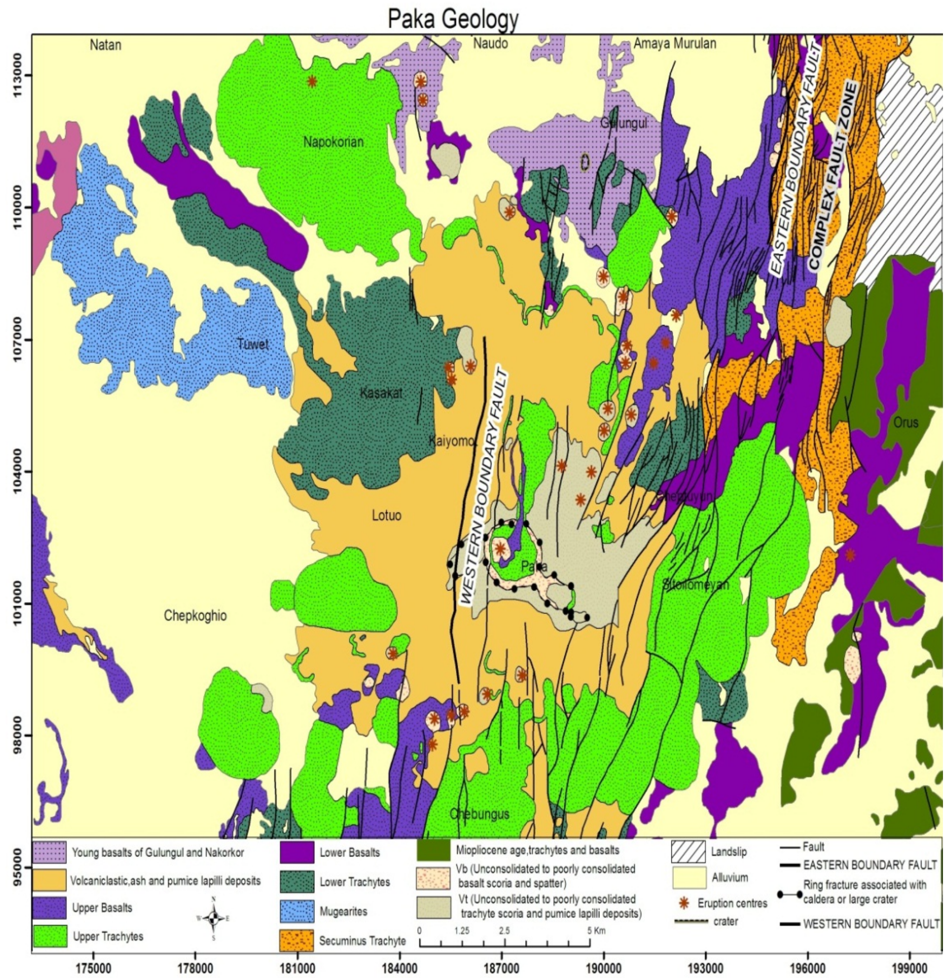
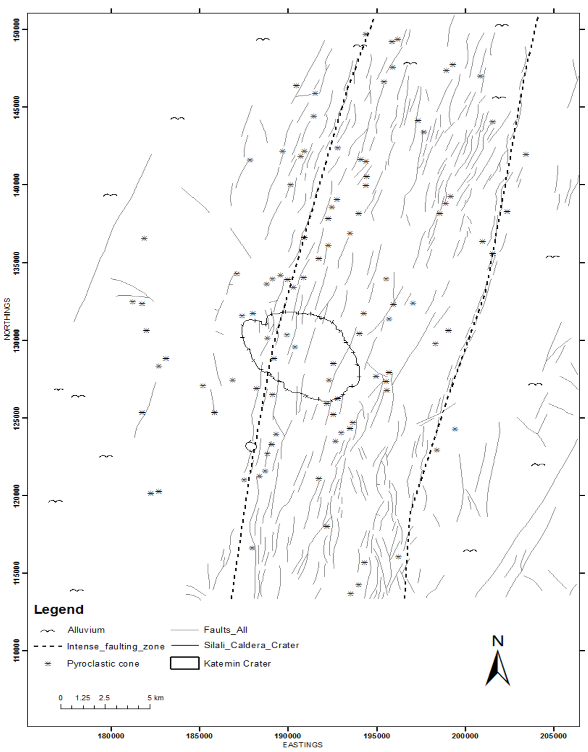
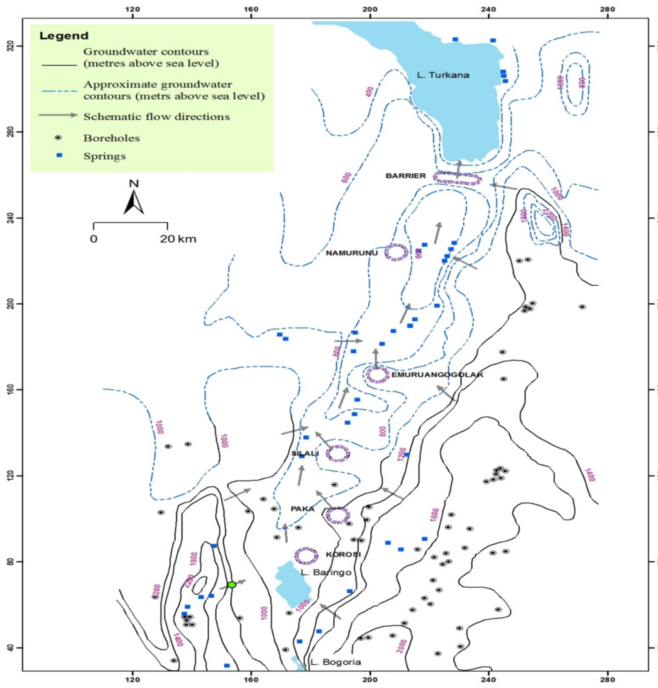


FIGURE 3: Geological map of Paka, Kenya





Geological mapping requires a skilled geologist (Figure 6). The required field facilities are: good topographic maps, aerial photographs, compass and a handheld GPS 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. Laboratory facilities are required for: thin sections for petrological investigations and surface alteration minerals. X-Ray Diffraction (XRD) and isotope dating facilities.

The expected geological findings are summarized as follows:

- Heat sources – magmatic intrusives etc.
- Permeability – possible fluid flow paths
- Reservoir – permeable rocks, faults, contacts
- Possible geo-hazard risks (e.g. power plant construction sites, surface piping etc.)
- Conceptualizing sub-surface conditions of an area (conceptual model)

2.2 Geophysics

2.2.1 Electrical methods

Electrical methods or resistivity methods are the most important geophysical methods in the surface exploration of geothermal areas, and as such the main methods used in delineating geothermal resources and production fields. The most important types are:

2.2.2 DC methods

The current is generated and injected into the earth through electrodes at the surface. The measured signal is the electrical field generated at the surface. The most common DC methods are:

Schlumberger sounding. It has been widely used for a long time and is still the most popular one. The electrodes are on a line, and the setup is mirrored around the centre. The pair of potential electrodes is kept close to the centre, while the pair of current electrodes is gradually moved away from the centre, for the current to probe deeper and deeper into the earth.

Dipole sounding or profiling. Various arrays exist and it was in extensive use in the 1970s into the 1980s.

Head-on profiling. This is a successful method for locating near-surface vertical fractures or faults. It is a variety of the Schlumberger profiling method with a third current electrode located far away at a right angle to the profile line.

2.2.3 Transient electro-magnetic (TEM)

The current is induced by a time varying magnetic field from a controlled source. The monitored signal is the decaying magnetic field at surface from the secondary magnetic field. This is the method that has replaced Schlumberger sounding as the routine method in the geothermal exploration of the uppermost 1-1.5 km of the earth. The Transient Electro-Magnetic method uses a controlled-source to create the signal to be measured. In the Central loop TEM sounding method, a constant magnetic field is built up by transmitting current through a big loop (grounded dipole). Then the current is abruptly turned off. A secondary field is thus induced, decaying with time. This decay rate is monitored by measuring the voltage induced in a receiver coil in the centre of the loop on the surface. Current distribution and decay rate recorded as a function of time depend on the resistivity structure below the measuring site. TEM data are presented on a bilogarithmic scale as DC data, but here the apparent resistivity is plotted as a function of time after the current was turned off.

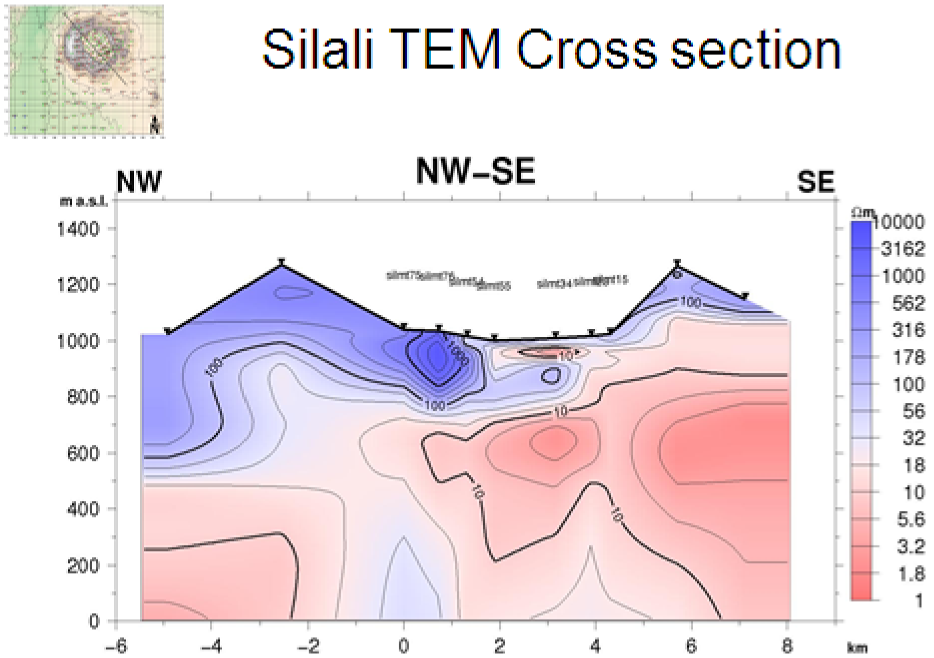


FIGURE 7: A NW-SE TEM resistivity cross-section of the Silali volcano, North rift, Kenya.

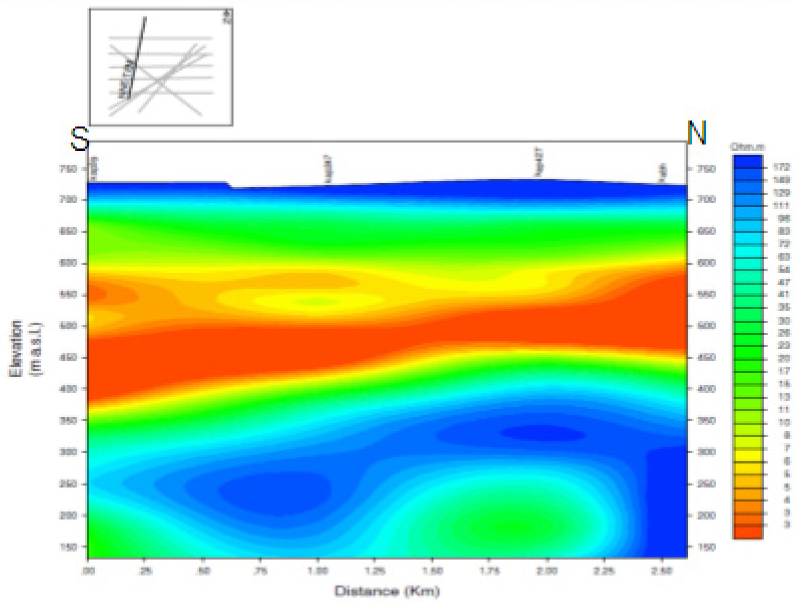


FIGURE 8: A North South TEM resistivity cross-section Kapendo North Rift.

2.2.4 Magnetotellurics (MT)

The current is induced by the time variations in earth's magnetic field. The measured signal is the electromagnetic field at the surface. MT or natural-source electromagnetic use the earth's natural electromagnetic field as its power source.

The variable natural magnetic field induces electrical currents in the conductive earth. By measuring the signal of the fluctuating magnetic field and the electrical currents (i.e. the electrical field) on the surface of the earth, it is possible to correlate this to the resistivity of the earth below the measuring site. The frequency of the signal relates to its probing depth, with low frequencies reaching deeper levels. Thus, frequencies of 0.00001 - 10 Hz are used for deep crustal investigations, while higher frequencies, like 10 - 1000 Hz, for the upper crust. MT is a powerful method to probe deep resistivity structures, which gives it an advantage compared to the other main electrical methods.

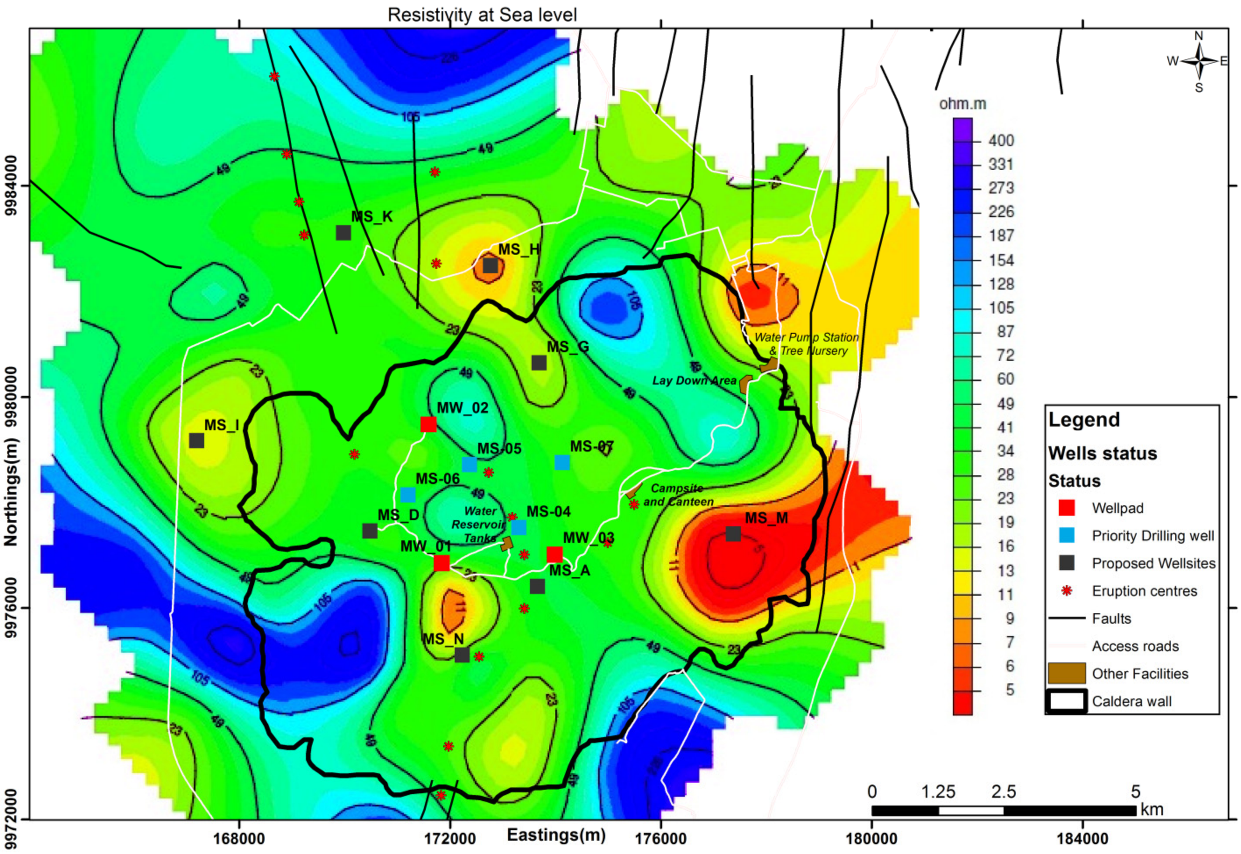


FIGURE 9: Resistivity at sea level

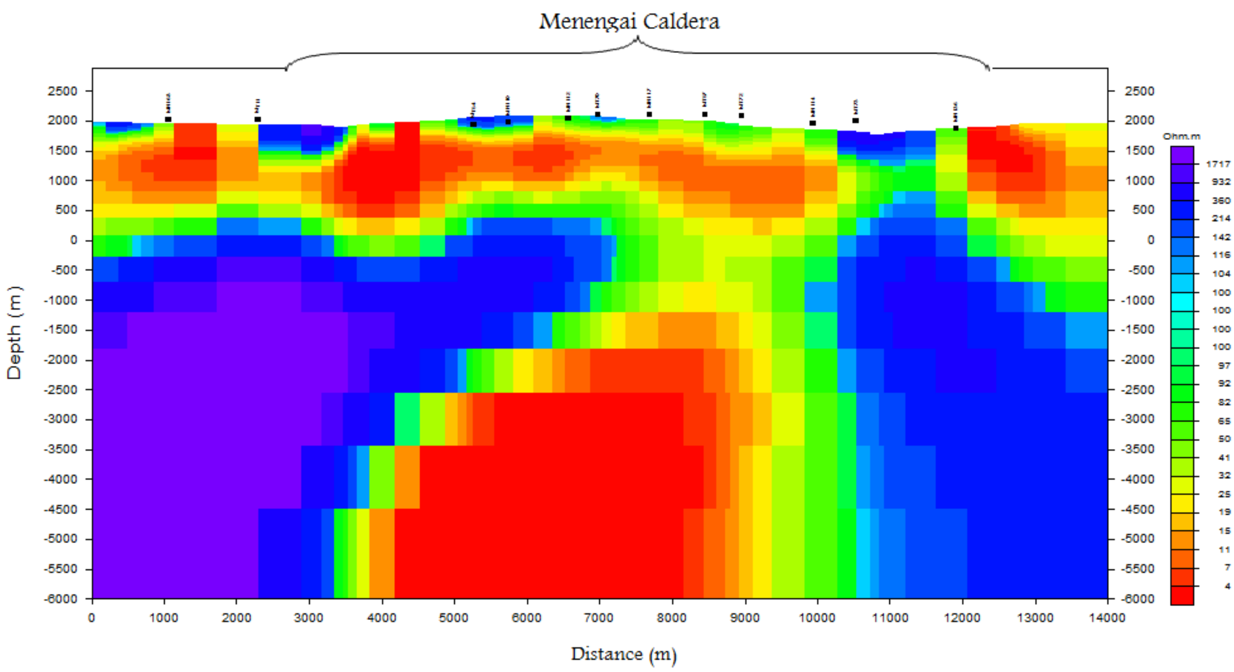


FIGURE 10: 2-D East-West MT resistivity cross section

2.2.5 Thermal methods

Thermal methods include direct measurements of temperature and/or heat, and thus correlate better with the properties of the geothermal system than other methods. However, as a near- surface method they are limited to shallow levels. To measure temperatures close to the surface, in the uppermost metre or so, is fairly simple. Knowledge about status at deeper levels is based on the existence of wells, usually shallow gradient wells (e.g. 30-100 m deep), from which the thermal gradient can be calculated and possibly the depth to the exploitable geothermal resource. Despite their limitations and their dependence on information from wells, thermal methods are important in geothermal exploration. They include the following:
Mapping of thermal distribution at the surface which include detailed geothermal surface mapping soil temperature measurements in the uppermost depth, airborne IR survey, temperature measurements in 20-100 m gradient wells used to delineate regional or local gradient anomalies.

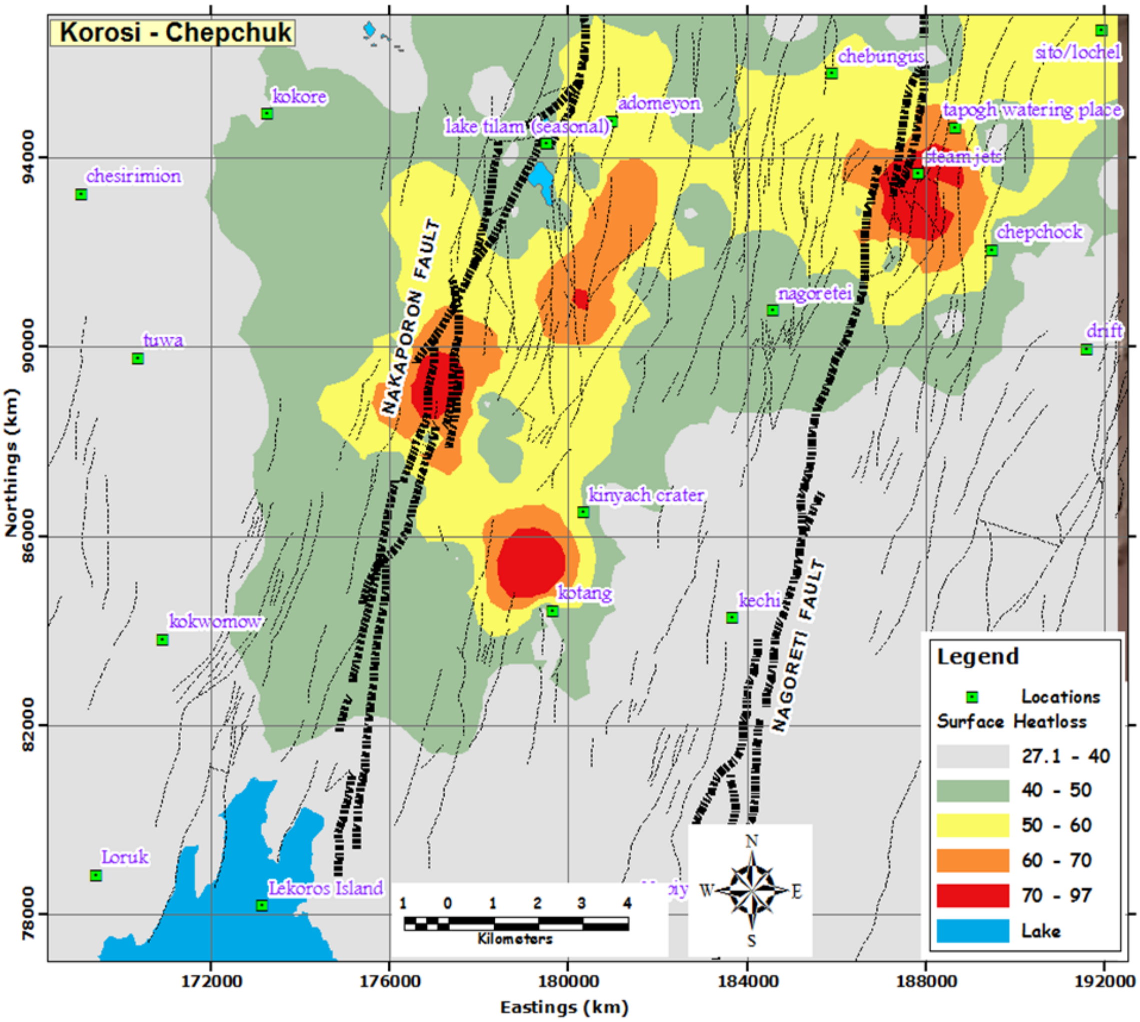


FIGURE 11: Ground heat measurements

2.2.6 Magnetic measurements

Magnetic methods are widely used in geothermal exploration. A magnetic anomaly is a local or regional disturbance caused by a change in the magnetization. In the exploration, magnetic measurements generally aim mainly at locating hidden intrusives and possibly estimating their depth, or at tracing individual buried dykes and faults. They may also aim at finding areas of reduced magnetization due to thermal activity. The magnetic field strength is usually presented in γ (gamma) or nT (nanotesla). Measurements are made using a Magnetometers which are fairly simple equipment and easy to use. Measurements aimed at larger anomalies such as mapping of deeper intrusions or outlining sedimentary basins are done through aeromagnetic surveys where the height and spacing of the profiles relies on the preferred data density.

2.2.7 Gravity measurements

Gravity measurements are used to detect geological formations with different densities. The density of the rocks depends mainly on the rock composition and its porosity, but partial saturation of the rocks may also influence the values. The density contrast leads to a different gravitational force which is measured and usually presented in mgal or 10-3 cm/s^2. Applications in geothermal exploration include mapping of basement depth, variations in sedimentary areas, intrusive rocks sometimes associated with a possible heat source, fault or dyke systems, and alteration/cementation due to thermal effects. Gravity measurements are also used in monitoring mass extraction in geothermal systems with production.

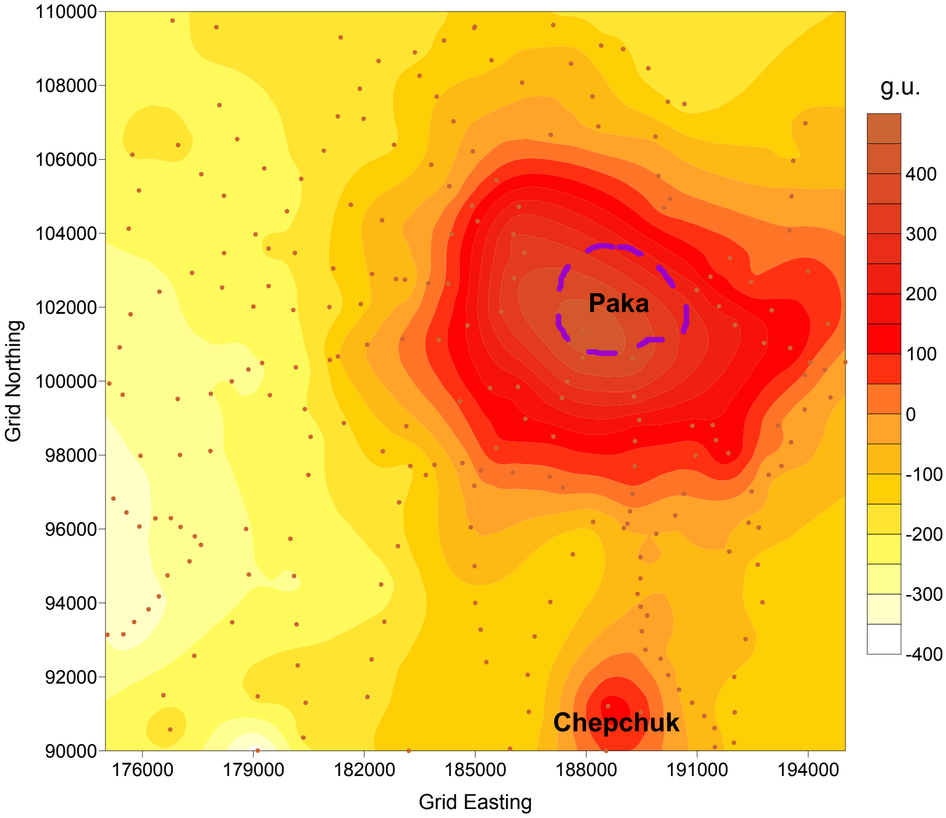


FIGURE 12: Paka Gravity Anomaly

2.2.8 Seismic methods

Seismic methods measure sound velocity distribution and anomalies in the earth as well as attenuation of the sound waves. They are divided into two groups, active methods where an external source is used to create sound waves, such as explosions or hammer devices, while passive methods detect the seismic activity in the earth and use that to get information on parameters that may be influential for the geothermal system. Seismic methods rely on elastic waves which have different velocities when travelling through different rock types, and are refracted or reflected at discontinuities in or between formations. Concentration of seismic events along Molo TVA, Solai graben , Kabarak area & inside the caldera. Hypocentre depths show decrease in seismicity at depths elsewhere.

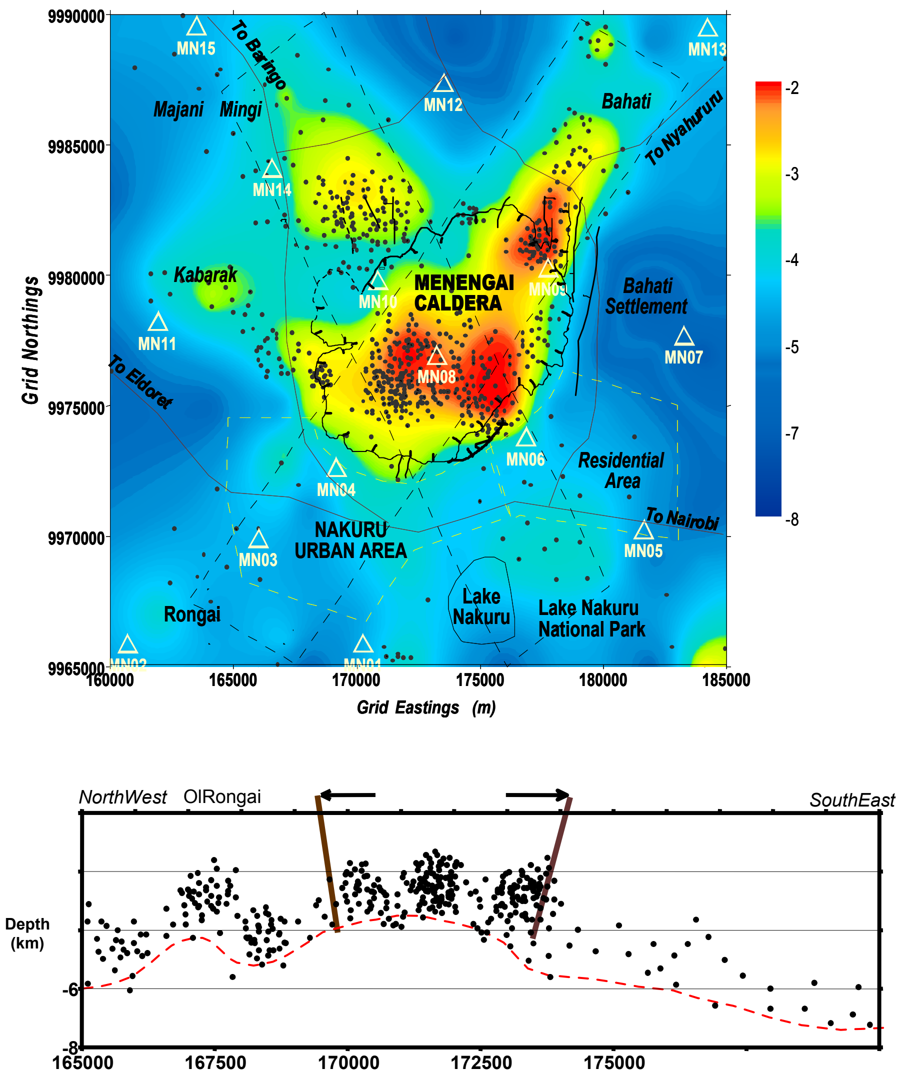


FIGURE 13: Micro-seismic depth distribution in Menengai area (Simiyu, 2001)

Geophysical survey requirements:

- Skilled Geophysicist and trained field crew
- Topographic maps
- TEM-for accessible areas
- DC-methods for inaccessible areas
- MT-for deep survey
- Magnetometer
- Gravimeter
- Seismometer
- GPS
- Software for processing and data interpretation

Summary of geophysical findings

- Probable location of a heat source
- Depth of reservoir
- Reservoir parameters
- Delineation of possible resource area
- Conceptual reservoir model

2.3 Geochemistry

2.3.1 Introduction

The principle purpose of geochemical surveys is to predict subsurface temperatures, obtain information on the origin of geothermal fluids and to understand flow directions. The most important contribution of geochemistry to geothermal resource assessments is chemical geothermometry. Geothermometry is the application of geochemistry to infer reservoir temperatures from the composition of geothermal fluids. Geothermal fluids that can be found at the surface above geothermal systems include steam, boiled or cooled geothermal solutions, mixed waters, and steam heated surface waters. The concentration of many dissolved constituents of geothermal solutions is controlled by temperature sensitive equlibria and the chemical signature of the fluids can survive transport to the surface. Different kinds of chemical geothermometers have been developed for gases in steam, geothermal solutions, and mixed waters. In some areas that are targets of geothermal exploration, there may be no surface manifestations. Geochemical techniques that involve identification of anomalies in the soil components that are characteristically high in geothermal fluids such as carbon dioxide, radon or mercury have been developed for such conditions. Geochemical exploration involves three steps namely sampling, analysis and data interpretation.

2.3.2 Water and gas surveys

Before a sample is analysed it must be collected or sampled. Bad sampling techniques can invalidate a survey and are far more expensive to correct than analytical errors. Laboratory errors can be corrected by re-analysis of the sample, but if the sample is unrepresentative or contaminated the analytical results will lack significance, regardless of the accuracy and precision of the analytical methods used. It is therefore worthwhile to adopt standardized methods of sampling.

2.3.3 Pre-field preparation

Water sample bottles can be made of a variety of glass and plastic materials and not all are suitable for geothermal waters. Possible problems which must be considered include:

- Contamination of water from the bottle material (boron from borosilicate glass)
- Contamination of the water from prolonged contact with atmospheric gas
- Loss of volatiles through the vessel walls or through the cap seal
- Loss of trace constituents by adsorption on to the vessel wall

To overcome these potential difficulties the sample bottles be non-contaminating, airtight, not gas permeable and well cleaned. Glass could contaminate the samples with inorganic constituents while at the same time are heavier and less robust. Plastics are gas permeable and can contaminate the sample with some trace metals and organics. Teflon is robust and inert and would be an ideal choice for the plastic bottles but is too expensive for routine use. High density polythene bottles are a good compromise between cost and inertness.

An effective sealing valve is essential for any vessel used in gas sampling, as air contamination must be avoided. Giggenbach 300mL- volume cylindrical, round bottomed glass flask with a Quick fit Rotaflo Teflon stop cock is widely used. In addition to the sample bottles and flasks sampling equipment should not contaminate the samples.

FIGURE 14: Sample analysis in the GDC labs (on the bench are the high density polythene bottles)

2.3.4 Geochemistry activities in surface exploration

Detailed sampling of thermal water, steam and gases is undertaken. Majority of thermal surface manifestations are sampled mostly the representative ones. After the field sampling a detailed analyses of chemical elements (both for major and trace elements), chemical species and gases is carried out both in the field as well as in the laboratories. 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 utilization is inferred. Along with the chemical sampling, samples are taken for stable isotope studies. An analysis of stable isotopes (hydrogen, oxygen and possibly carbon and sulphur) is carried out. Isotope ratios and concentrations are used to infer the origin of the geothermal fluid in the reservoir. Soil gas survey is carried out where geothermal surface manifestations are not sufficient for the study. The geothermometry calculations are based on the following solutes, gases and isotopes.

Chemical

(Silica,Na/K,Na/Ca,Na/Mg,Na/Li)

Gas

(CO_2,H_2S,H_2,CH_4)

Isotope

(Isotopes of 13C/12C,D/H ,O^{18}/O^{16})

The geochemistry methods aims at: predicting reservoir temperatures, characterize thermal fluids, determine the source of thermal fluids and delineate permeable zones of the reservoir among others. 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 is required for this purpose. The major ions are 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.

FIGURE 15: Gas and condensate sampling

FIGURE 16: Soil gas sampling

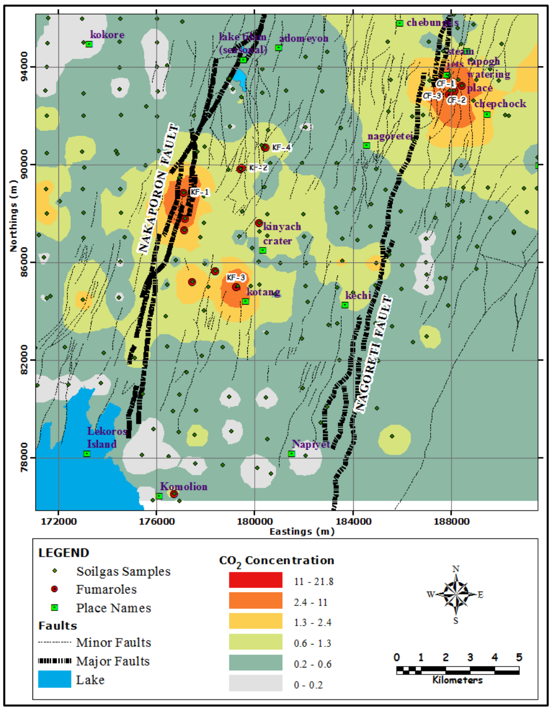


FIGURE 17: CO_2 distribution in Korosi/Chepchuk prospect

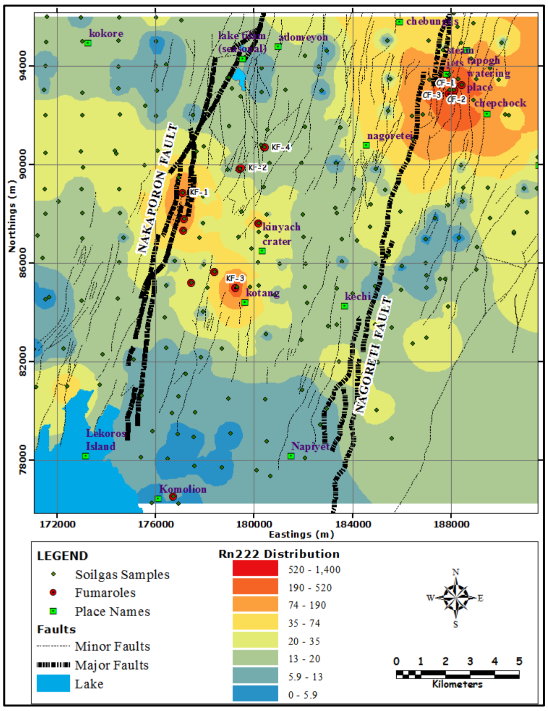


FIGURE 18: Radon gas distribution in Korosi/Chepchuk prospect

3. 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 physical, biophysical, social economic and environment data. The collected data are finally used in the preparation of Environment Social Impact Assessment (ESIA) report.

READING MATERIAL

Arnorsson, S., 2000: Isotopic chemical techniques in geothermal exploration development and use. *Internal Atomic Energy Agency*, Vienna, 309 – 339.

Arnason, K. and Gislason, G., 2009: Geothermal surface exploration. UNU – GTP and La Geo, El Salvador.

Fridriksson, T. and Armannsson, H., 2007: Application of geochemistry in geothermal resource assessment. *Short Course on Surface Exploration for Geothermal Resources*, UNU-GTP and La Geo, El Salvador.

GDC, 2010: Paka volcano: investigations for its geothermal potential. Unpublished report geothermal resource assessment.

GDC, 2010: Silali volcano: investigations for its geothermal potential. Unpublished report geothermal resource assessment.

GDC, 2010: Korosi/Chepchuk volcano: investigations for its geothermal potential. Unpublished report geothermal resource assessment.

Georgsson, L.S., 2009: Geophysical methods in geothermal exploration. *Short Course on Surface Exploration for Geothermal Resources*, UNU-GTP and La Geo, El Salvador.

Glover, R. and Bacon, L., 2000: Chemical changes in natural features and well discharge at Wairakei, New Zealand. *Proc. World Geothermal Congress*, Kyushu, 2081 – 2086.

Glover, R.B., Mroczek, E. K. and Finlayson, J. B., 1999: Changes in major gas concentration in the Karapiti thermal area in response to development in Wairakei. *Proc. 20th NZ Geotherml Workshop*. 7 - 13.

Lagat, J., Muturia,C., Wanjie, C. and Mabea, G., 2010: *Menengai prospect: Investigations for its geothermal potential*. A geothermal resource assessment project report with environmental management plan and financial proposal. GDC internal report.

Nicholson, K., 1993: *Geothermal fluids: Chemistry and exploration techniques*. Springer-Verleg, Berlin Heldederberg.

Opondo, K. M., 2009: *Olkaria Domes geochemical conceptual model*. Internal report, Ken Gen.