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GEOCHEMICAL MONITORING PRACTICES

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ABSTRACT

Identifying a clear goal for any monitoring campaign will lead to selection of appropriate scientific sampling and analytical techniques. A geothermal monitoring program without a clear sense of purpose may not meet resource protection needs. Goals of geothermal monitoring efforts include determining if the production of fluid from geothermal wells will measurably affect the discharge of a hydrothermal feature. Geothermal reservoirs undergo physical and chemical changes during drilling and fluid discharge which manifest in the fluid chemistry. Overexploitation of geothermal reservoirs leads to rapid drawdown of reservoir pressure and a corresponding decline in well output and power generation. Predicting undesirable processes like scale formation and corrosion, practicing sound environmental practises are important reasons why geochemical monitoring should be carried out in a geothermal field which leads to sound formulation of management practices of the field.

1. INTRODUCTION

Geothermal systems in the Kenyan rift are located in the vicinity of volcanic centres (Figure 1) and therefore associated with gases/volatiles and fluids that need to be monitored. In these centres, there are surface manifestations indicative of the presence of a hydrothermal system that creates vital signs that can be monitored. These emit heat and discharge hydrothermal water. The water contains chemicals and gases and therefore location, area, heat, water, and chemistry become critical vital signs to monitor. Although these vital signs are observable at the surface, they also provide information about the subsurface hydrothermal system. Volatiles are an essential component in volcanic systems. Since volatiles play an important role, their behaviour can be examined to provide a better understanding of volcanic activity and therefore the geothermal system. Volatiles escape from magma bodies through manifestations like fumaroles and hot springs, often located on a volcano's flanks. Studies of volcanic gas can furnish important insights on the sources of magmas, how magmas move upward to the surface, the influence of hydrothermal systems, and the types of eruptions—for example, explosive vs. effusive—that are observed. The amount of gas dissolved in magma determines, in large part, whether an eruption will be violent or not.

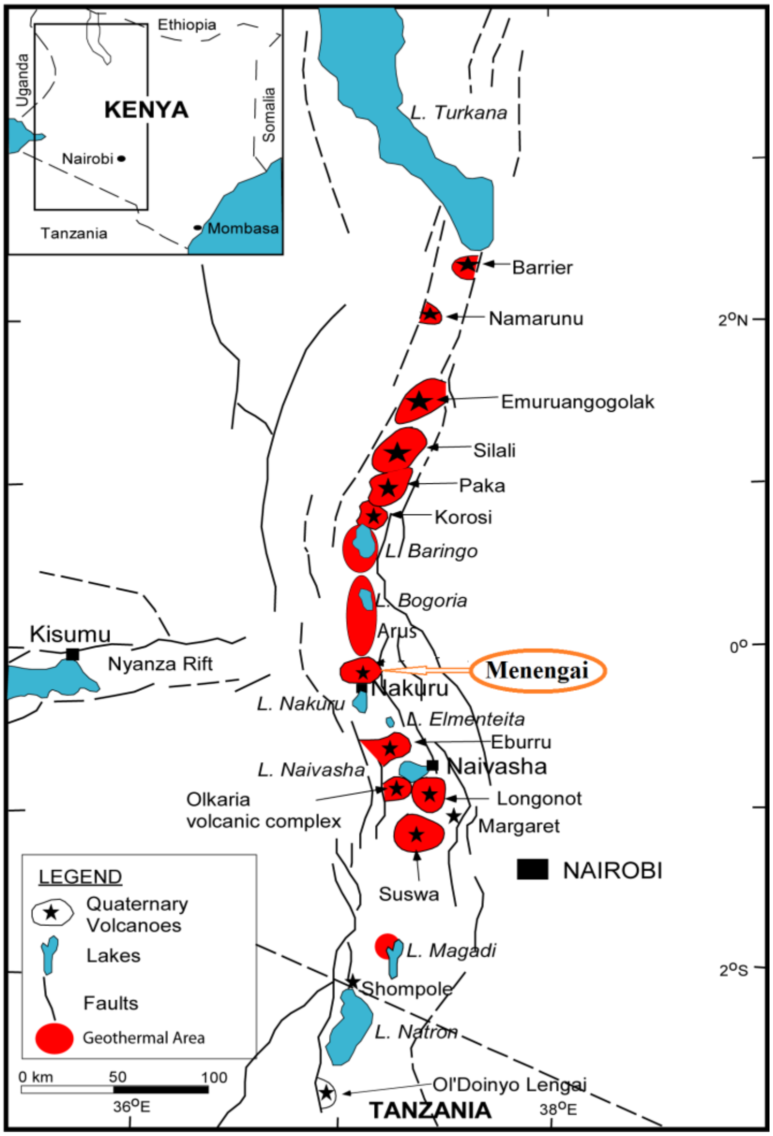

FIGURE 1: Location of Menengai geothermal field and other geothermal areas in Kenya

2. GEOCHEMICAL MONITORING

Geothermal reservoirs undergo changes during drilling and fluid discharge. The changes manifest in the chemistry of geothermal fluids. This can be monitored from the geothermal wells and other surface manifestations located in the vicinity of the geothermal field like domestic water use boreholes, fumaroles and gas vents, springs and nearby streams. The whole system of fluid quality monitoring is aimed at the generation of reliable data, i.e. data that accurately reflect the actual status of the variables which influence geothermal fluid quality. Simply generating good data is not enough to meet objectives but the data must be processed and presented in a manner that aids understanding of the spatial and temporal patterns in fluid quality, taking into consideration the natural processes and characteristics of a reservoir, and that allows the impact of geothermal drilling and fluid utilization to be understood and the consequences of management action to be predicted.

Over exploitation of geothermal reservoirs leads to rapid drawdown of reservoir pressure and a corresponding decline in well output and power generation. Information on the response of the reservoir to the production load with respect to the source of the fluids recharging producing aquifers (Arnórsson et al., 2000) can thus be evaluated and mitigation to changes in temperature or pressure made. Fluid discharged from wells penetrating rocks is a mixture of many components that have traveled different distances from their original points before the reservoir was penetrated to the wellbore. The concentrations of dissolved solids and gases in the discharge of wells penetrating such rocks, is the product of the chemical composition of each source component and its relative contribution to the well discharge. A change in the relative amounts of these components will lead to a change in the composition of the discharged fluid unless their chemical composition was the same.

Data on fluid compositions may provide useful information on the depth level of producing horizons in individual wells. These data provide information as regards recharge and enhanced boiling which in turn have proved valuable to map cold water recharge into single liquid water reservoirs. In addition, this information provides an in depth evaluation into quality of fluid including scaling and corrosion tendencies as the fluid is exploited. Gas compositions can also be used to estimate the initial steam fraction in the aquifer fluid. Some of the reasons, therefore for geochemical monitoring include:

a. Ability to recognize hydrothermal processes by monitoring manifestations i.e. fumaroles, springs and boreholes;
b. Monitoring of the response of geothermal reservoirs to the production load;
c. Monitor pressure declines in exploited geothermal reservoirs which can lead to decreased yield of wells and sometimes incursion of cold groundwater into the reservoir;
d. Predicting undesirable processes like scale formation and corrosion;
e. Sound environmental practises; and
f. Helping in formulate management practices of a geothermal field.

2.1 Monitoring plan

Before a monitoring campaign is embarked on, a plan should be put in place to deal with management and efficiency of what the whole process will entail. The single most critical issue is the goal of the study. The factors to consider are the manifestations present in the field (fumaroles, gas vents, springs, streams, wells both domestic and high temperature), representativeness of the manifestations and their relation to what results are needed from the monitoring campaign, logistics of sampling/analysis and the data storage.

If personnel do not identify a clear goal for monitoring, then it will not be possible to select appropriate scientific techniques and analyses. A geothermal monitoring program, without a clear sense of purpose, may not meet resource protection needs. Goals of geothermal monitoring efforts include determining if the production of fluid from geothermal wells will measurably affect the discharge of a hydrothermal feature e.g. hot spring; determining if the development of known geothermal area might affect an entire hydrothermal area; and evaluating seasonal variability of hydrothermal features. Another issue in designing a geothermal monitoring plan is the budget. This will guide on how many features to sample, frequency in a given year (for example) the monitoring plan will be undertaken, and the sampling and analytical methods available.

2.2 Sampling and analysis

The rationale for selecting what elements to be monitored in a geothermal field are as listed in Table 1.

TABLE 1: Rationale for selecting different elements and gases to monitor in a geothermal field

Element / gas	**Reason for its choice**
Conductivity	Used as a simple general indication of bulk change in total concentration of dissolved cations and anions. High amounts of dissolved minerals and salt concentration in water yield high conductivities. Measurements of electrical conductivity can provide estimates of the hydrothermal fluid's purity and contribute to understanding its flow path.
pH	Varies with the proportion of deep to shallow components. Changes in the pH may indicate changes in the flow path of the geothermal fluid, changes in the temperature of the geothermal fluid, loss of CO_2, or anthropogenic activities.
Na^+, K^+, Ca^{2+}, SiO_2	Used as geothermometers.
Mg^{2+}	Indicates mixing with low temperature surface waters. Present in very low concentration due to solubility considerations
Cl^-	Determines dilution or contribution of deep thermal water that has high chloride content.
SO_4^{2-}	Indicates contribution of shallow steam heated waters formed by oxidation of S^{2-}
Fe, Al	Evaluate the subsurface mineralogy.
HCO_3^-	Increases with greater ground water components in samples. Helps distinguish deep steam heated and ground water components (when used together with Cl^- and SO_4^{2-}).
Hg, F^-, Fe, Al	Analysed if environmental effects of the discharge are to be considered.
Rb, Cs, Zn, Au	Host rock characterisation i.e. the elements, often when compared with other elements in various combinations of ratios (Nicholson, 1993), may provide useful information about the types of rocks that the fluids have interacted with in the subsurface.
CO_2, H_2S	Used as geothermometers and are also major geothermal gases.
O_2	Not present in deep geothermal fluids. Its presence is used to check whether a gas sample is contaminated.
CH_4	Although present in geothermal fluids, it can also indicate shallow organic decomposition.
He	Indicates a mantle component if in elevated concentrations.
Isotopes	Used for various reasons, e.g to • identify mantle input ($^3He/^4He$); • assess water source (^{15}N, $^{18}O/^{16}O$, ^2H, ^{13}C, ^{34}S) • date water (^3H, ^{14}C, ^{36}Cl)

2.2.1 Gas chemistry monitoring

Fumaroles

The spectacular emanations of gas (fumaroles) that are seen in the geothermal systems or fields are visible manifestations of the presence of magma at depth. However, gas observed escaping at the surface is not derived from the magma only but is a mixture from different sources that have interacted during the lifetime of the geothermal system. A certain percentage of the gas is derived from magma, which will be initially rich in components such as sulfur and carbon dioxide. Gas chemistry associated with geothermal systems gives information on the sources of magmas, movements of the magmas upward to the surface, the amount of gas dissolved in a magma that determines whether an eruption will be violent or not and also the influence of the magma on the hydrothermal system being exploited.

Soil gas

Soil gas surveys for the gases that do not react with the country rock (CO_2, Rn) can give different insights into a geothermal system. The diffuse degassing of the gases are monitored by measuring their concentration in soil to provide information on the overall permeability of a volcanic edifice, the potential for lateral degassing apart from the main volcanic vent and the ability of a volcano to diffusely release large quantities of gases.

2.2.2 Fluid chemistry

Fluids emanating from springs, streams and wells (both domestic and geothermal) should be monitored as is done for the gases emanating from different manifestations in a geothermal system. These fluids give more information in addition to the gases monitored. Some of the information that can be monitored includes dilutions in the reservoir, physical and chemical effects of exploitation of a field (e.g. the changes in temperature, pressure), cold water inflows as seen when there are lower Cl and higher SO_4 measured, boiling in the wells and equilibration of the fluid in the reservoir.

2.3 Reservoir monitoring

Arnórsson et al., (2000) states that the chemical data on fluids and steam sunk into a boiling reservoir provide useful information on the response of the reservoir to the production load as regards recharge and enhanced boiling. These data has proved valuable to map cold water recharge into single liquid water reservoirs and provides information on the quality of the fluid including scaling and corrosion tendencies. Geothermal reservoirs undergo changes resulting from steam exploitation during production that could be physical and/or chemical. Reservoir monitoring should start with power plant commissioning to obtain the information through a carefully planned monitoring program on the effects of water / steam extraction.

As the steam is converted to electricity for use, different areas on the flow diagram of the steam extraction need to be monitored (Figure 2). This enables monitoring of the quality of the fluid extracted, the separated steam and the re-injected fluid. Overexploitation of geothermal reservoirs leads to rapid drawdown of reservoir pressure and a corresponding decline in well output and power generation. When production is more than the reservoir recharge, pressure drop is experienced and vice versa. Pressure drop can be large, small, and fast or slow depending on the nature of the system. This pressure decline manifests in further changes like decrease in well discharge, changes in surface activity, lowered water level in wells, increased boiling (in high enthalpy systems), increased recharge into the system (usually cold water) and in the worst of cases, surface subsidence that may result in damage to surface installations and equipment.

Cold water recharge leads to changes in chemical composition of the reservoir fluid, usually dilutions, and changes in temperature/enthalpy of reservoir fluid. Temperature changes are measured using various types of sensors or by monitoring the geothermometers. Monitoring of measured and calculated temperatures can give a good insight into the reservoir. Truesdell and Fournier (1977) made comparisons of the measured and calculated temperatures and concluded that equilibrium is only observed in the well if all the temperatures are closely related or equal e.g. $T_{meas.} = T_{quartz}$. Other conclusions they brought forward are as given in Table 2.

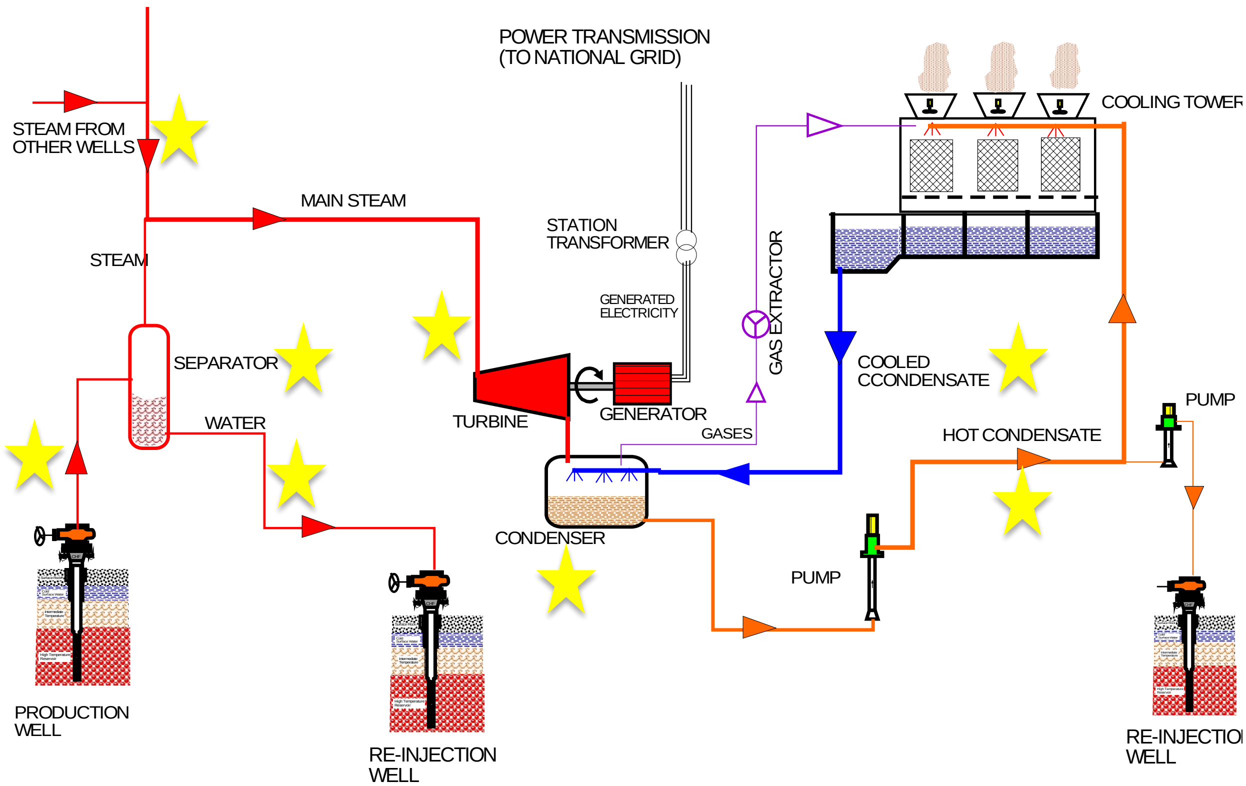

FIGURE 2: Flow diagram of a geothermal power generating station. The yellow stars represent the places where chemical monitoring should take place to ensure good quality steam is extracted and fluids re-injected back into the reservoir

TABLE 2: Temperatures relations to geothermal reservoir processes

Temperature comparison	**Conclusion**
$T_{NKC} > T_{Qtz} = T_{Meas.}$ $T_{Qtz} > T_{NKC} > T_{Meas.}$	Boiling in the flowing well
$T_{NKC} > T_{Meas.} = T_{Qtz}$	Mixing of hot geothermal fluids with cooler waters near the well bore.
$T_{NKC} = T_{Qtz} > T_{Meas.}$	Mixture of equilibrated liquid with steam cap
$T_{NKC} > T_{Qtz} > T_{Meas.}$	Cooler more dilute fluid mixing with equilibrated brine

Where T_{NKC} refers to temperature calculated from the Na, K and Ca geothermometer, T_{Qtz} from the quartz geothermometer and $T_{Meas.}$ is the measured temperature from well logging.

Steam purity should be checked at moisture separators before it enters the turbine house. The samples are tested for moisture carry-overs in steam as can be indicated by elemental concentrations of Cl, TDS, SiO_2 and Na. Solid scales may deposit in steam flow pipes as the fluid is extracted and moves on towards the separators or towards the re-injection point (Figure 3). In the cases where the deposition occurs in the line from the well onto the steam separators, steam delivery is drastically reduced. Scale formation can be predicted from monitoring chemistry data as the fluid moves from the reservoir towards the wellhead. In addition to the reservoir monitoring of producing fields, environmental monitoring of potentially harmful elements in waste water e.g. Pb, Zn, As, B, Li, Hg; and gases, mostly H_2S, CO_2 needs to be put in place. Other environmental concerns apart from chemical pollution include surface disturbances, noise, thermal pollution, protection of sites and social and economic effects in the areas where the geothermal exploitation is taking place.

FIGURE 3: Silica scale forming in a steam delivery line (Photo courtesy James Wambugu)

From the study gathered from the reservoir monitoring plan, the management gets information that they use for planning a geothermal field. This can be helpful in decisions concerning:

a. Brine re-injection – should the brine re-injected be hot or cold;
b. Location of the wells used to re-inject and for how long the injection will take place;
c. The need to drill more replacement wells, retire some wells; and
d. The need to increase installed capacity by installing additional generating units.

3. CASE STUDY

3.1 Geohazard monitoring in the Menengai geothermal field

The main objectives for this study were to create a baseline for fluid chemistry in the regions surrounding the Menengai geothermal field (Figure 1) in view of the ongoing drilling for geothermal steam and future exploitation of the Menengai geothermal field, characterize the fluids that are feeding or are peripheral to the geothermal system, and monitor any changes that might arise due to exploitation of the geothermal resource in the Menengai field. Borehole sampling in the area was divided into five regions namely northern, southern, eastern and western with an addition of the GDC water boreholes located in the caldera (Figure 4).

Water samples were collected from the boreholes in the aforementioned regions in three major sampling campaigns: March-July 2011, September – November 2011 and February – July 2012. The samples were analyzed for various parameters including TDS, pH, CO_2, H_2S, SiO_2, Na, K, Ca, Cl, SO_4, F, and NH_3 using different methods suitable for each parameter. Borehole temperatures were also recorded.

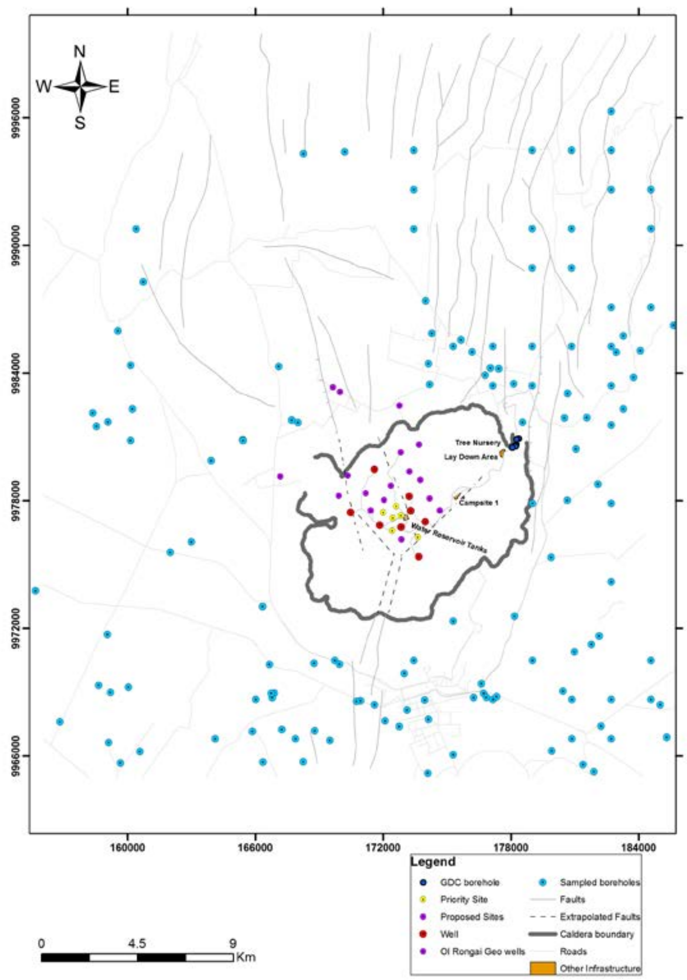

FIGURE 4: Location of boreholes considered for the geohazard monitoring study in the Menengai geothermal field

3.2 Chemical characteristics of the borehole water

This sampling program was carried out to monitor the changes that may have occurred in the borehole waters due to the drilling program being undertaken in the Menengai caldera. Figure 5 shows the contour maps depicting the distribution of various major parameters like borehole temperature, SiO_2, Na, CO_2, H_2S, Cl, SO_4, F and Ca) measured from the waters of boreholes in the Menengai region.

There seems to emerge a clear trend (NW-SE) for most of the parameters and the correlation of the measured temperatures to the silica concentrations suggest elevated temperatures in the region west of the caldera.

The waters from the boreholes were also classified based on the relative concentrations of the three major anions Cl, SO_4 and HCO_3 by use of ternary/piper diagrams. The Cl-SO_4-HCO_3 ternary diagram is one diagram for classifying natural waters (Giggenbach, 1991). Using it, several types of thermal water can be distinguished: mature waters, peripheral waters, steam-heated waters and volcanic waters. Figure 6 provides an indication of the relative concentrations of the major anions.

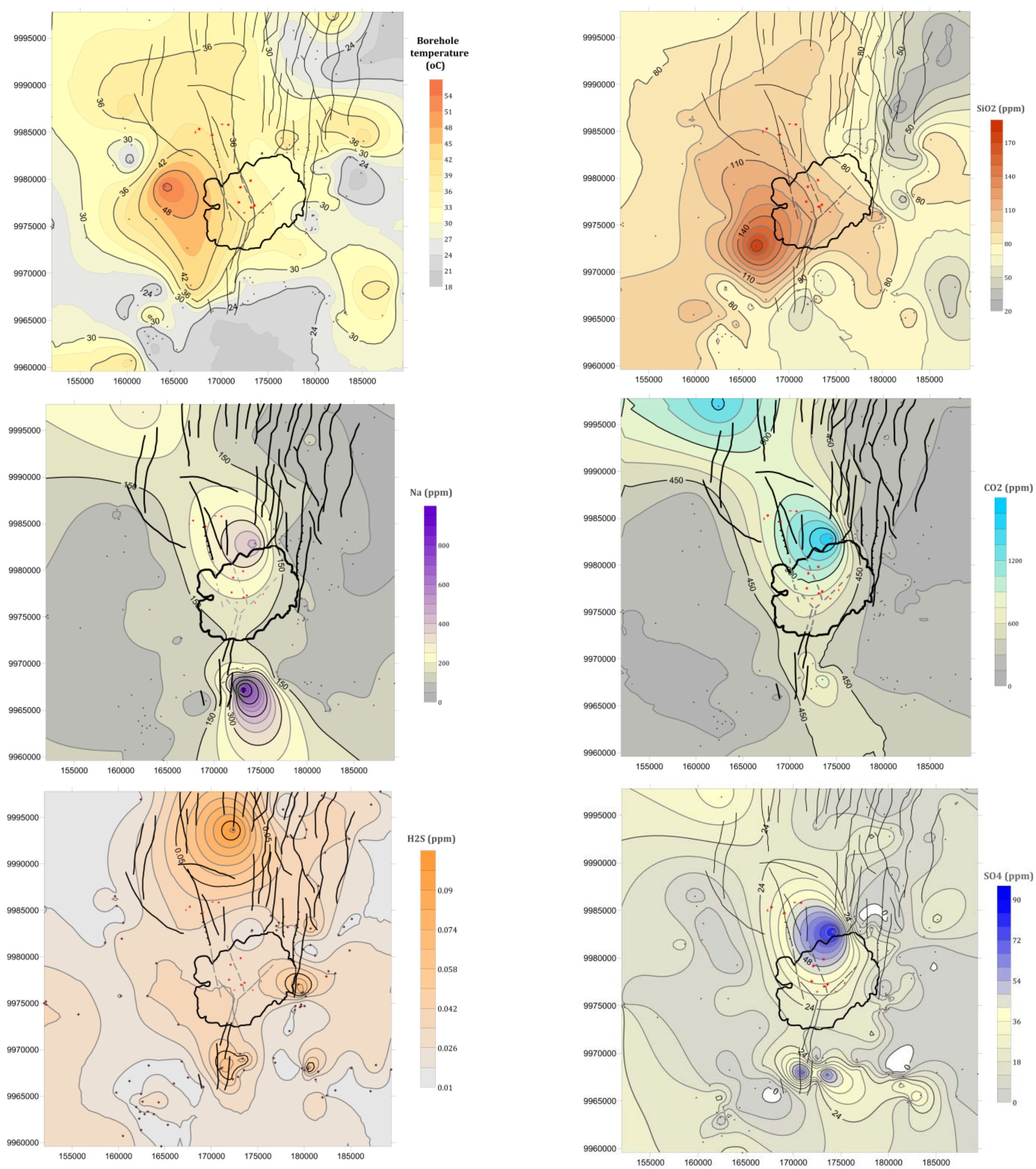

FIGURE 5: Contour maps depicting distribution of some of the various parameters of borehole waters in the region surrounding the Menengai geothermal field

The borehole waters surrounding the Menengai geothermal field plot in the region of high HCO_3-peripheral waters and low chloride (Figure 6) illustrating that the fluids in these borehole reservoirs are bicarbonate waters and correspond to peripheral waters. It should thus be noted that bicarbonate-rich waters originate through either dissolution of CO_2-bearing gases or condensation of geothermal steam in relatively deep, oxygen-poor ground waters.

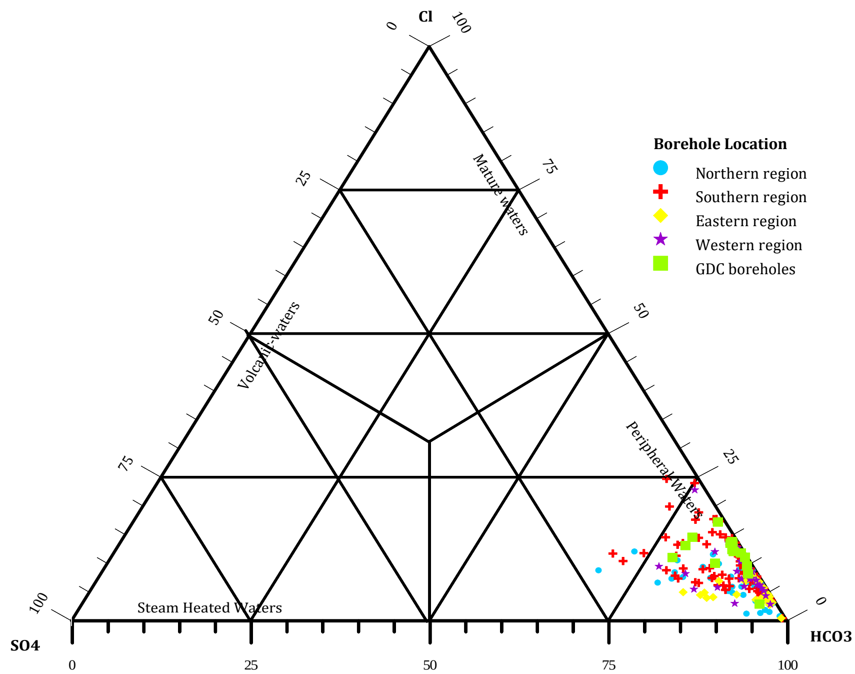

FIGURE 6: Relative Cl-SO_4-HCO_3 contents from the boreholes considered for geohazard monitoring surrounding the Menengai geothermal field

3.3 Conclusions

From the initial geohazard study of boreholes in the area surrounding the Menengai geothermal field, no major chemical changes were observed during the monitoring period. This case study being the baseline creation of the geohazard monitoring program, there was need to establish a continuous sampling campaign (which is in place) in case any changes in the chemical and physical parameters of the borehole waters occur due to the drilling ongoing in the Menengai geothermal field. A majority of the boreholes sampled discharged above ambient temperature waters with most having TDS less than 1,000 ppm. There seems to emerge a clear trend (NW-SE) for most of the parameters suggesting correlation to the Molo TVA.

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