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Keywords

Meteoric waters, hotsprings, geothermometry, sea water, geothermal

ABSTRACT

The Mwananyamala geothermal prospect is located outside the active volcanic Rift Valley in the Kenyan coast. A number of hotsprings occur in the area with temperatures ranging from 55-70°C and an average flow rate of approximately 90 l/s. This paper will characterize the thermal waters; estimating subsurface temperatures define sources of solutes in the fluids and determine whether mixing with sea water exists. As the results indicates, the chemistry of the waters is variably saline for most of the springs reflecting the existence of a mixing process occurring between the infringing sea water from Indian Ocean and the locally recharged unsullied groundwater. The thermal waters from the springs are distinct from ambient borehole waters in chemistry displaying a trend where the former intercedes between the sea and the borehole waters. The Na-Li geothermometry displays a subsurface temperature that ranges between 146°C and 164°C. In general, the results suggests the existence of a fairly deep, moderate-temperature geothermal system recharged by shallow circulating meteoric waters related to local groundwater as well as relatively deeper sea water. Hydrochemical water types are largely Na-Cl for the thermal waters and a variation of Na-Mg-HCO₃-Cl to Na-Mg-Cl for borehole water.

1. Introduction

Mwananyamala prospect is located at the Kenyan South Coast in Kwale district. Thermal activities manifest in form of hot springs. The main geological feature of the Mwananyamala corresponds to the sedimentary environment and consists of sediments of Triassic and Jurassic ages. These hot springs discharge slightly alkaline NaCl–NaHCO₃ waters from underground, suggesting the springs are most likely being controlled underneath by an intrusive hot body. The host rock is Mariakani sandstone which is weathered and sheared overlain by red concretions with radioactive elements among them iron, manganese and niobium. They are extruded by carbonatite forming the vent at the top of the hill. Mild altered grounds and hot/warm springs manifest geothermal in the area. Temperatures of up to 63°C were measured from the hot springs at Kitungure, 68°C at Mbunguni (with high H₂S gas smell and CO₂ gas emission) and 57.5°C at Maphombe. The area is faulted and the rocks are mainly dominated with Permo-Triassic sandstones. The geochemical survey conducted involved hotspring water sampling and analyses. In this paper chemical analysis from hotsprings and boreholes in Mwananyamala were used to evaluate the chemical characteristics of the fluids, estimate subsurface temperatures, define sources of solutes in the fluids and determine if mixing exists between sea water and Mwananyamala fluids.

2. Thermal Springs of Mwananyamala

The thermal activity occurs in four zones. Three occur in close proximity while the other occurs to the east of project area (Figure 1). Mwananyamala springs are not associated with high temperature geothermal activity such as fumaroles and altered ground. This hotsprings cover approximately 800 square metres

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Figure 1. Location of hot springs in the survey area.
to the north of Maji Moto I. The springs discharge along a stream in close vicinity to an igneous dyke with a north-south running trend within a sedimentary formation. There are multiple springs with green and brown algae observed along the flow. The springs have temperatures ranging from 55-70°C with a total flow rate of 90 litres/second.

2.1 Maji Moto Hot Spring I- Kitungure

The manifestations are visible along an area of approximately 100 square meters. They comprise numerous bubbling hot springs and a few cold springs. Emissions of gases from these pools are abundant. Calcite depositions are observed in small areas while pyrites are observed in the pools. The flow rate of the main hot spring was about 50 litres/second and a maximum discharge temperature of 70°C.

2.2 Maji Moto II-Chumboni

This manifestation is also visible along an area of approximately 500 square meters. It also encompasses multiples of hot springs with a few cold springs on swampy domes. It is characterized by calcite deposits in veins with growth of green and brown algae based on temperature levels. Pyrite and chalcopyrite are also observed in the hot springs. The general flow rate of the hotsprings is about 90 litres/second having a maximum recorded temperature of 70°C.

2.3 Maji Moto III-Chumboni

This hot springs cover approximately 800 square metres to the north of Maji Moto I. The springs discharge along a stream in close vicinity to an igneous dyke with a north-south running trend. There are multiple springs with green and brown algae observed along the flow. The springs have temperatures ranging from 50-65°C with a total flow rate of 50 litres/second.

3. Geological Setting

The general geology in the area chiefly consists of the sediments of Triassic to Jurassic ages, igneous rocks of Cretaceous age and the unconsolidated sediments of Tertiary to Quaternary ages. Triassic to Jurassic sediments is chiefly comprised of sandstone beds. Igneous rocks are widely observed in the form of intrusive rocks of varied type. Unconsolidated sediments are observed to be of Tertiary sediments and of colluvial, residual and alluvial sediments of Quaternary age. In summary, rocks in this area are largely of sedimentary origin and range in age from Permian (or possibly Upper Carboniferous) to Recent. Three well-marked divisions can be recognized:

1. The Cenozoic Rocks.
2. The Upper Mesozoic Rocks.
3. The Duruma Sandstone Series.

The Cenozoic (Quaternary & Tertiary) rocks rests unconformably upon an eroded surface of Mesozoic rocks with occasional overlap on to the Duruma Sandstones. Alkaline igneous intrusions at Dzombo Hill, where nepheline-syenites, ijolites and melteigites outcrop, and associated vent agglomerates and dykes are the only eruptive rocks of the area. The intrusions and volcanic activity associated with them have been referred to the Cretaceous or Tertiary.

The Duruma Sandstone Series is a correlative of the Karoo System of South and Central Africa consists of grits, sandstone and shales. The series is divisible into three broad lithological units with coarse sandstones and grit at the top and bottom of the succession, and finer sandstones and shales in the middle. These beds were mostly deposited under lacustrine or sub-aerial conditions, with materials having been derived from the Basement System rocks.

The Upper Mesozoic rocks are stratigraphically unconformable upon the Duruma Sandstones but their contact is highly faulted.

4. Methodology

Four borehole and two borehole water samples were collected and used in this undertaking. All the water samples were analysed for the major elements. According to Giggenbach (1992) Cl-SO4, HCO3 and Na-K-Mg ternary plots were used to classify the waters according to their dominant ions and to help in selecting waters suitable for estimating the prevailing reservoir temperatures. Cl-Li-B ternary diagrams were also plotted to establish the source of these waters. Chloride variation diagrams were also plotted to establish the sources of the solutes in the waters relative to the sea water.

5. Results and Discussions

5.1 Chemical Composition of the Hot Springs and Boreholes

<table>
<thead>
<tr>
<th></th>
<th>Hot Springs</th>
<th>Boreholes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maphombe</td>
<td>Majimoto I</td>
</tr>
<tr>
<td>Temp oC</td>
<td>55</td>
<td>57.6</td>
</tr>
<tr>
<td>pH</td>
<td>7.74</td>
<td>7.18</td>
</tr>
<tr>
<td>Cond(µS/cm)</td>
<td>10330</td>
<td>10160</td>
</tr>
<tr>
<td>TDS(ppm)</td>
<td>5160</td>
<td>5090</td>
</tr>
<tr>
<td>HCO3(ppm)</td>
<td>794.2</td>
<td>700.48</td>
</tr>
<tr>
<td>H2S(ppm)</td>
<td>0.07</td>
<td>0.032</td>
</tr>
<tr>
<td>Cl(ppm)</td>
<td>2273.2</td>
<td>2503.1</td>
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<tr>
<td>SO4(ppm)</td>
<td>3</td>
<td>1.6</td>
</tr>
<tr>
<td>SiO2(ppm)</td>
<td>33.3</td>
<td>45.5</td>
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<tr>
<td>K(ppm)</td>
<td>3.40</td>
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<tr>
<td>Na(ppm)</td>
<td>1774.5</td>
<td>2170</td>
</tr>
<tr>
<td>Mg(ppm)</td>
<td>18.55</td>
<td>33.41</td>
</tr>
<tr>
<td>Ca(ppm)</td>
<td>4.48</td>
<td>8.03</td>
</tr>
<tr>
<td>Li(ppm)</td>
<td>1.73</td>
<td>0</td>
</tr>
</tbody>
</table>

The chemical composition of the hot springs and borehole water is presented in Table 1 above. The pH of all the samples scatters around the neutral value with a range of 6.61 to 7.62. Total carbonates are almost uniform for the hot springs displaying a range of between 670 ppm and 794 ppm and for the boreholes.
ranging from 412 to 568 ppm, while chloride is the dominant anion
with readings of over 1800 ppm for hot springs and as low as 356-
850 ppm for the borehole waters. Anomalous values are observed
for calcium and magnesium especially in the thermal waters where
low values are expected due to their brackish characteristics.

The waters are highly mineralized but not to the levels of
Magadi and Homa Bay, other prospects in Kenya, which records
TDS values of over 45,000 ppm and over 30,000 ppm respectively.
Calcium and magnesium both have high concentrations
and are among the highest recorded in all the Kenyan geothermal
systems. Magnesium concentration range from 14 ppm to 138
ppm whereas calcium concentration lies in the range of 1.4 ppm
to 129 ppm. This suggests an intrusion of the sea water into the
waters of the prospect.

The shoeller diagram (Truesdell, 1991) for the hot springs
and borehole waters is a semi-logarithmic diagram representing major
ion analyses in meq/L. It also demonstrates different hydrochemical
water types on the same diagram. Figure 3 b shows that all
the hot springs show high concentrations of Na and Cl unlike the
boreholes which show relatively low concentrations Ca, Cl, Na and
HCO₃ which may be due to the dilution with the meteoric waters.
We can also note that the borehole waters have higher concentrations
in Mg and SO₄ than the hot springs. This can be attributed by
low temperatures in the boreholes favoring dilution gypsum and
also probably due to incorporation of Mg in secondary alteration
clay minerals. The low Ca in most of the springs can be probably
be attributed to the conversion of albite to anorthite with a slight
increase in Na. It is also evident from the diagram that there is
infringement of the cold groundwaters from the boreholes which
is of meteoric origin with the thermal waters form the hot springs.
This is seen from the cross crossing of the boreholes water with
the hot spring waters.

To evaluate the source of the solutes in the waters in com-
parison to the marine composition line, the thermal waters were
plotted on selected Cl variation plots. The solutes may indicate
simple dilution of the seawater or the dissolution of unfractio-}
ated marine suspensions (Issar et al., 1972). When there is a shift from

the marine composition line, this may be indicative of an additional
process taking place in the waters and/or the solutes sources were
involved in the generation of the solute composition (Sturchio et
al., 1996). Some of the potential sources of solutes contributing to
the chemistry of thermal waters are mixing of modern sea water
and/or residual marine formation waters; subsurface reaction with
regional sedimentary rocks i.e. aquifer rocks and dissolution of
marine aerosols and windblown rock dust in the recharge area
(Mazor and Mero, 1969, Fleisher et al., Sturchio et al., 1996).

In the Na/Cl plot (see figure 2), all the Mwananyamala waters
both borehole and hot spring plot slightly below the sea water
composition, indicating loss of the Na from the water which may
be attributed to water rock reactions within the aquifer. For the
Ca/Cl plot (figure 2), the waters plot below the sea water dilution
line for the Maji Moto I, Maji Moto III and Maphombe hot spring
but both the boreholes and Maji Moto II hot spring plot above the
dilution line, indication some enrichment of the Ca in this waters.
This may be attributed to the dissolution of the calcium bearing
minerals e.g. calcite and gypsum which are the typical rock that
describe the Duruma sandstones formation in the main rocks in the
area. The SO₄/Cl plot showed the borehole waters were enriched
in SO₄ and this may be related to meteoric leaching in the area
favoring the solubility the SO₄ bearing rocks in the area; however
the hot springs waters were majorly depleted off SO₄ as a result

![Figure 2. Chloride variation diagrams for the Mwananyamala waters.](image)

![Figure 3. Piper diagram showing hydrochemical facies for the hot spring and borehole samples and a schoeller diagram showing chemical composition of fluids in the area.](image)
of the decrease in the solubility of gypsum with increasing temperature. For the B/Cl plot, there is near equilibrium concentration of the B relative to Cl which is usually typical of Na-Cl type of water encountered in marine sedimentary rocks which probably have relatively high porosity and permeability (Shigeno and Abe 1983). All the waters plotted close to the sea water dilution line indicating sea water dilution.

The ionic composition of both borehole and hot spring water in the prospect is shown in a Piper trilinear diagram (Figure 3). Three primary hydrochemical facies; Na–Cl water-type for hot spring and Na-Mg-HCO₃-Cl & Na–Mg-Cl water-types for boreholes water.

5.2 Relative Cl-SO₄-HCO₃ Ternary Diagram

Figure 4 shows the relative Cl-SO₄-HCO₃ content for the Mwananyamala samples (Giggenbach, 1991). The hot springs plotted close to the chloride apex and are therefore considered mature chloride waters. They also plot along the chloride-bicarbonate margin due to the low amount of sulphate. They are therefore considered to be originating from deep geothermal reservoirs as proposed by Giggenbach, 1988. However, Nguluku borehole plots close to the maturity zone but slightly lower. This is probably due to its relatively high chloride concentrations and SO₄. Ndumbani borehole shows dissimilar behavior from hot spring and Nguluku borehole it plots on the peripheral waters indicating that they are discharging immature waters which are probably from meteoric sources.

5.3 Relative Na-K-Mg Ternary Diagram

Figure 5 shows the relative Na-K-Mg concentrations for the samples (Giggenbach et al., 1983). The entire hot springs waters plot in the partially equilibrated waters suggesting that the thermal waters suffer a dilution process or mixing with superficial waters. The waters plot on temperatures that scatter about 140°C same as those calculated from the geothermometers. They also plot adjacent to seawater indicating some relationship exists between these waters and the sea water. This highlights the B/Cl ratio which had suggested the contribution of the sea water in recharging the reservoir. All the borehole waters generally plot on the immature waters zone/non-equilibrium zone suggesting that all the boreholes were discharging cold water with no thermal component.

5.4 Relative Cl-Li-B Ternary Diagram

Figure 6 shows the chloride, lithium and boron ternary in the form presented in Giggenbach (1991a) is used to distinguish fluids from different sources, to reveal fractionation associated with boiling or mixing with fluids that have boiled, or fluids generated by different sources of high temperature steam. According to the diagram all the plot at the chloride apex but in slightly different locations suggesting that they originate from the same source with very slight composition and that the fluids are originating from an old hydrothermal system where there is low absorption of Cl and B.
6. Geothermometry

Main purpose for undertaking geothermometry was to estimate temperatures at depth, given concentrations of dissolved substances at the surface. This method assumes that the concentrations of the substances are preserved as the waters emarate to the surface. The method also measures the degree to which the substances were at equilibrium at depth (Fournier, 1991). Table 2 below shows the calculated temperatures, however, there is noteworthy disagreement in the application of solute geothermometers. Basing on this augment the quartz, Na/K, Na/Li geothermometer gave temperatures between 87-164°C. The K-Na-Mg ternary plots are used to select spring waters suitable for geothermometry and so is the ionic balance. Quartz geothermometer gave temperatures ranging from 87-107°C below the expected temperatures of over 180°C. This suggests that the waters would not have been in equilibrium with quartz indicating the values are not reliable and thus are not considered useable.

Table 2. Geothermometry temperatures.

<table>
<thead>
<tr>
<th>Hot Spring Name</th>
<th>quartz (F ‘77) b</th>
<th>Na/K (F’79) (Arm. ‘83) G’88</th>
<th>Na/Li (K’82)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maphombe hot spring</td>
<td>87</td>
<td>142</td>
<td>140 155 146</td>
</tr>
<tr>
<td>Maji moto II-Chumboni</td>
<td>106</td>
<td>148</td>
<td>146 161 162</td>
</tr>
<tr>
<td>Maji moto III-Chumboni</td>
<td>107</td>
<td>143</td>
<td>141 157 164</td>
</tr>
<tr>
<td>Maji moto I-Kitungure</td>
<td>99</td>
<td>124</td>
<td>123 138 -</td>
</tr>
</tbody>
</table>

7. Conclusions

Most of the Mwananyamala waters are as a result of mixing with the sea water with much of the water chemistry dependent on the water rock interactions and temperature. The minor changes in chemistry may be attributed to the interaction of the waters with different rock lithologies. Chemical conditions of the fluids in the area indicate that the solutes in both the thermal and borehole waters are derived from marine sedimentary rocks that are characteristic in the area. Geothermometry calculations gave temperatures ranging from 146-164°C according to the Na/Li geothermometer. The thermal waters plot at the mature waters and indicate an old hydrothermal system exist in the area.

There is mixing of the sea water with the fluids of Mwananyamala which is evidence from the CI/B relative ratio plot in relation to the sea water composition/dilution line.

References


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