Interpretation of geochemical data from wells in the western geothermal field of Romania

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Abstract

The western geothermal field of Romania is a low temperature geothermal area. In this paper data from four production wells are presented. The chemical composition of these waters was analysed by standard methods and subsequently classified by the use of the Cl-SO$_4$-HCO$_3$ triangular diagram. Another basic diagram, Na-K-Mg, was used to classify waters according to the state of equilibrium at given temperatures. The geothermal waters are bicarbonated-sodium-chloride type. Chemical geothermometers were used to predict subsurface temperature. The calculated quartz geothermometer values for the geothermal well waters indicate reservoir temperatures higher than values for chalcedony geothermometers and Na/K geothermometer values are very different. The silica-enthalpy mixing model was used to try to define the source temperature of the hot water component. The results could be an evidence of mixing with cold waters in all the fields taken for study. The WATCH program was used to interpret the equilibrium state of the reservoirs and to predict scaling tendencies. The saturation index for calcite exceeds 1, which indicates that CaCO$_3$ scaling problems will occur.

Keywords: reservoir temperature, western Romania, scaling potential.

1 Introduction

In the present study, the chemical characteristics of geothermal waters from four wells in three geothermal fields in western Romania are described. The main emphasis is on estimating the scaling potential of the water as well as temperature of the respective reservoirs. Due to the importance of the geothermal water, it is necessary to know its chemical characteristics in order to enable the most economic way of utilizing it.

The geothermal fields of Bors, Ciumeghiu and Sacuieni are situated in the vicinity of the town of Oradea in western Romania.

- The Bors geothermal field is situated some 6 km to the northwest of Oradea. It has a surface area of 12 km$^2$ and the reservoir is limited or closed. Water from wells Bors-529 and Bors-4155 is used for the present study.
- The Ciumeghiu geothermal field is located south to Oradea. The reservoir consists of gritstone at an average depth of 2200 m. For the present study water from well Ciumeghiu-4668 is used.
- The Sacuieni geothermal field is located to the north of Oradea. It has seven exploration wells and four of them are production wells as well. Only well Sacuieni-4058 has been producing lately and is used for this study.

2 Characterization of geothermal waters

The analytical methods used for the determination of the main constituents of the geothermal water samples are presented in Table 1. The results of the laboratory analysis are summarized in Table 2 (Stănășel, 2002).

For an initial classification, in terms of the major anions Cl, SO$_4$, and HCO$_3$, a
triangular diagram (Giggenbach, 1991) was used.

Table 1: Methods of chemical analysis.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Methodology</th>
<th>Constituent</th>
<th>Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>Glass electrode pH meter</td>
<td>H₂S</td>
<td>Titration with Hg(CH₃COO)₂; dithizone as indicator</td>
</tr>
<tr>
<td>SiO₂</td>
<td>UV/VIS silico-molybdate complex</td>
<td>Fe</td>
<td>Spectrophotometric determination at λ=510 nm, using o-phenantroline reagent added</td>
</tr>
<tr>
<td>B</td>
<td>Spectrophotometry at 420 nm; azomethine H/ ascorbic acid reagent added</td>
<td>F</td>
<td>pH millivoltmeter and selective electrode</td>
</tr>
<tr>
<td>Na</td>
<td>Flamephotometric determination</td>
<td>Cl</td>
<td>Titration with AgNO₃; K₂CrO₄ as indicator</td>
</tr>
<tr>
<td>K</td>
<td>λ=589; 767 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>Titration with EDTA</td>
<td>SO₄</td>
<td>Titration with Ba(ClO₄)₂; Thorin as indicator</td>
</tr>
<tr>
<td>Mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>Electrometric titration</td>
<td>TDS</td>
<td>Gravimetric</td>
</tr>
</tbody>
</table>

Table 2: Chemical Composition of Geothermal Waters, in mg/l.

<table>
<thead>
<tr>
<th>Component</th>
<th>529</th>
<th>4155</th>
<th>4668</th>
<th>4058</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured temp. of water</td>
<td>90</td>
<td>119</td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>pH</td>
<td>7</td>
<td>7.5</td>
<td>7.9</td>
<td>8.1</td>
</tr>
<tr>
<td>CO₂</td>
<td>1068</td>
<td>1520</td>
<td>2045</td>
<td>2122</td>
</tr>
<tr>
<td>H₂S</td>
<td></td>
<td></td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>49</td>
<td>79.2</td>
<td>98.2</td>
<td>78.9</td>
</tr>
<tr>
<td>SiO₂</td>
<td>127</td>
<td>120.5</td>
<td>181</td>
<td>62.9</td>
</tr>
<tr>
<td>Na</td>
<td>4230</td>
<td>5200</td>
<td>2250</td>
<td>1610</td>
</tr>
<tr>
<td>K</td>
<td>385</td>
<td>218</td>
<td>33</td>
<td>21.3</td>
</tr>
<tr>
<td>Mg</td>
<td>13.2</td>
<td>25</td>
<td>4.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Ca</td>
<td>122</td>
<td>130.2</td>
<td>45.6</td>
<td>13.2</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>6320</td>
<td>7198</td>
<td>1902</td>
<td>911</td>
</tr>
<tr>
<td>SO₄</td>
<td>115</td>
<td>140</td>
<td>47</td>
<td>5.9</td>
</tr>
<tr>
<td>Fe</td>
<td>9.6</td>
<td>5.2</td>
<td>0.14</td>
<td>0.25</td>
</tr>
<tr>
<td>TDS</td>
<td>11210</td>
<td>12200</td>
<td>6574</td>
<td>11647</td>
</tr>
</tbody>
</table>

On the triangular diagram Cl-SO₄-HCO₃ (Figure 1,a) waters from Bors plot near to the chloride corner and in the field of mature geothermal waters. The waters from Ciumeghiu, well 4668 and from Sacuieni, well 4058 as shown by the ternary diagram, are peripheral geothermal waters. The bicarbonate content of waters from Sacuieni is high.

The Na-K-Mg triangular diagram clarifies better the origin of the waters as shown on (Figure 1,b). According to the diagram the samples from Bors geothermal field are only partly equilibrated, whereas samples from Ciumeghiu and Sacuieni are close to equilibration. Partial equilibration may be due to reactions with wall rock during upflow from the reservoir or could result from mixing of waters of different compositions. The water from Ciumeghiu, well 4668 appears to be well equilibrated at temperatures of 100-110°C according to the Na-K-Mg ternary plots of Giggenbach (1988).
Geothermal waters from Bors are classified as sodium-chloride and medium bicarbonated waters, waters from Ciumeghiu are bicarbonated-sodium-chloride waters and geothermal waters from Sacuieni are bicarbonated-sodium water with a medium chloride content. These waters are partially equilibrated according to Giggenbach and Arnorsson diagrams.

3 Estimating the deep water temperature

The wellhead temperatures measured during sampling were: 90°C at Bors-529, 119°C at Bors-4155, 84°C at Ciumeghiu and 84°C at Sacuieni-4058. The ionic balances (Table 3) for the samples calculated by the Watch program (Bjarnason, 1994) gave values ranging from –3.93 ±0.69, which are acceptable and the data could be used for the interpretation. The temperatures resulting from geothermometers, which were calculated by the Watch program are presented in Table 3.

Table 3: Data resulted by Watch program calculations.

<table>
<thead>
<tr>
<th>Well</th>
<th>Wellhead temperature, ºC</th>
<th>Ionic balance</th>
<th>Chemical geothermometers, ºC</th>
<th>Quartz</th>
<th>Chale.</th>
<th>Na/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bors-529</td>
<td>90</td>
<td>-0.03</td>
<td>148.5</td>
<td>122.9</td>
<td>189.4</td>
<td></td>
</tr>
<tr>
<td>Bors-4155</td>
<td>119</td>
<td>0.69</td>
<td>142.0</td>
<td>115.7</td>
<td>117.9</td>
<td></td>
</tr>
<tr>
<td>Cium-4668</td>
<td>84</td>
<td>0.35</td>
<td>161.6</td>
<td>137.5</td>
<td>57.1</td>
<td></td>
</tr>
<tr>
<td>Sac-4058</td>
<td>84</td>
<td>-3.93</td>
<td>108.3</td>
<td>78.5</td>
<td>52.9</td>
<td></td>
</tr>
</tbody>
</table>

The reservoirs temperatures indicated by the calculated chalcedony geothermometer are closer to the production temperatures of the waters than the values given by the other geothermometers. At Sacuieni-4058 the calculated temperature based on the chalcedony geothermometer almost correspond to the wellhead temperature.

In order to estimate the reservoir temperature the silica enthalpy mixing model (Truesdell and Fournier, 1977) was also used for comparison and further classification. The cold water point is assumed to represent the hypothetical cold water (temperature: 10°C and SiO₂ 20ppm) in the study area. The intersection point
with the solubility curve for chalcedony gives the silica content and the enthalpy of the deep hot water component and its temperature is obtained from steam tables.

Based on the silica-enthalpy mixing model a reservoir temperature of 180°C for well Bors-529 and 145°C for well Bors-4155 was obtained. This temperature is higher than the reservoir temperatures obtained by the geothermometers (Table 3), indicating probable mixing in the upflow zones. These two wells are situated close to each other and there might be some mixing of deep water in the reservoir.

The temperature of the geothermal reservoir at Ciumeghiu (Figure 3,b) was found to be 175°C assuming a steam loss before mixing, and about 160°C if there is no steam loss. The wellhead temperature is lower probably due to mixing with cold water during infiltration.

At Sacuieni-4058 the temperature calculated for the hot water by mixing model is 104°C. The plot is very close to the solubility curve of chalcedony. The difference is assumed to be due to the contact of the hot water with the rocks.

For all the studied wells the source temperature of the hot water component is higher than the measured wellhead temperature. The difference in temperature is due to mixing with cold water in the upper layers or only due to contact by the cold rocks. When the temperature calculated by the chalcedony geothermometer and by the mixing model is close to the temperature measured at the wellhead (as for well Sacuieni-4058) the wellhead temperature has kept the same value in time (Stănășel, 2002).

4 Scaling prediction

The potential scaling problems when utilizing geothermal water depends on the type of water as well as the temperature and the changes the water undergoes in the installations. Therefore, a reliable analysis of the water and a simulation of the changes occurring during the utilization are needed to predict possible scaling. In this paper the WATCH program was used to calculate the concentrations of resulting species, activity products and solubility products when the equilibrated fluid is allowed to cool conductively from the reference temperature to some lower temperatures. The scaling potential is estimated by calculating logQ/K, where Q means the ionic activity corresponding to different minerals in the brine and K the theoretical solubility of the respective minerals. Figure 3 presents the mineral equilibrium diagrams for the selected wells.

Figure 2: Dissolved silica-enthalpy diagrams, (a)-(b).
At wellhead temperature, the water from well Bors-529 is supersaturated with respect to chrysotile and talc, and quartz is close to saturation. Calcite is supersaturated at all temperatures. Amorphous silica, anhydrite and wollastonite have...
negative saturation indexes and can not possibly precipitate. The system is in equilibrium with chalcedony at the wellhead temperature.

The diagram for Bors 4155 shows that logQ/K for calcite exceeds 1 at the wellhead temperature, which is considered to be very dangerous with respect to scaling. Anhydrite, amorphous silica, and wollastonite are undersaturated and there is an equilibrium with chalcedony at the measured temperature. Quartz is slightly supersaturated at the wellhead temperature. Chalcedony and quartz become supersaturated at lower temperatures. A potential chrysotile scaling could be expected. Talc is supersaturated, but this does not create problems.

At Ciumeghiu, the precipitation of calcite seems to be inevitable at the wellhead temperature and at lower temperatures. Chrysotile, goethite, quartz, chalcedony and magnetite are also supersaturated at the measured temperature, but at low temperatures chrysotile and goethite become undersaturated.

The diagram for Sacuieni 4058 shows that anhydrite, amorphous silica and wollastonite are undersaturated. The equilibrium temperature for chalcedony is very close to the measured temperature. The water is close to saturation with quartz and it is saturated with chrysotile and talc at the wellhead temperature. Calcite is supersaturated at 84°C. If the temperature of geothermal water were to decrease calcite would still remain supersaturated and chrysotile become undersaturated; chalcedony and quartz lie close to the saturation line.

5 Conclusions

The geothermal waters from the studied area could by geochemical studies be classified as sodium-chloride-bicarbonate waters with a high mineralisation, that reaches maximum for the wells from Bors.

Considering the major anions, the waters from Bors are classified as mature waters, whereas those from Ciumeghiu and Sacuieni are classified as peripheral. Taking into account the major cations the geothermal waters are classified as partially equilibrated, with the Ciumeghiu and Sacuieni waters falling near to Giggenbach’s (1988) line for fully equilibrated waters and the water from Bors is almost equilibrated after Arnorsson’s (1991) line.

The chalcedony geothermometer gives the best values at low temperature as compared to the quartz and Na/K geothermometers. The dissolved silica-enthalpy diagrams for determining the temperatures of hot water components mixed with cold water, indicate higher temperatures than the results given by the chalcedony geothermometer, which indicates a mixing of the hot water from the reservoir with the infiltrated cold water in the upper layers.

Knowing the chemical composition one can estimate the scaling potential during geothermal utilization by computer simulation. The results can be used to make changes in the production cycle. In this way it is possible to interfere to prevent the scale before it occurs.

Acknowledgements

I wish to thank for having the opportunity to be at Orkustofnun, where the specialists shared their knowledge and helped me with chemical computer interpretation of data as well.
6 References


Western states geothermal databases CD

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Abstract

The Geo-Heat Center recently completed the task of producing a state resource database for six states in the west. These states were: Alaska, Nebraska, North Dakota, South Dakota, Texas and Wyoming. The databases were placed in a standard format for ease of use, which included the original state databases (Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington). The reports of the original state teams and the new information from the additional six states documents a total of 11,775 wells and springs in the databases with the new states producing 2,731 more entries. The number of collocated sites increased to 404 from the previous 271 for the 10 states. The total of wells and springs with a temperature over 50°C (122°F) went from 1723 to 2211, which is an increase of 28%. Some of the information included are depth, temperature, flow and water chemistry. All of this information is available on a CD.

Keywords: temperature, chemical compositions, database, identified resource, well spring, flow rate.

1 Introduction

Low- and moderate-temperature geothermal resources are widely distributed throughout the western and central U.S. as can be seen in Figure 1. There are also a few low-temperature geothermal resources that occur in the east

![Figure 1. Geothermal Resources Areas of the United States.](image)

There have been several major efforts in assessing the potential for low-temperature geothermal resources in the U.S. The first major effort in the 1980s included 17 states, which resulted in geothermal resource maps, prepared by the National Geophysical Data Center of the National Oceanic and Atmospheric Administration (NOAA), that are still being used today. The latest effort, which
included 10 of the 17 original states, was in the early-1990s, and which resulted mainly in individual digital databases of all known geothermal wells and springs for a total of over 9,000 wells and springs. The 10 states were: Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, and Washington (Lienau and Ross, 1996).

The state databases that were completed in the 1990s were designed for use on personal computers, and have the capability of being accessed and managed by using readily available commercial spreadsheets. The only problem was the databases were produced in several different formats and no two states were set up in the same format; although, there was a general guideline for the format of the information.

The low-temperature resource assessment completed in 1990s included another task. The task was to complete a statewide study of collocated geothermal resources with the only criteria being a collocated community with a resource temperature above 50°C (122°F) and located within 8 km (5 miles) of a community (many of which have <1,000 population). There were 1,723 wells and springs identified with a temperature over 50°C (122°F), with 1,469 of them located within 8 km (5 miles) of a community. There were a total of 271 communities identified within the 10 western states.

The oldest, most versatile and most common use of geothermal energy is direct-use applications; although, most people associate geothermal with power generation. Direct-use applications include: greenhouse heating, aquaculture pond and raceway heating, space and district heating, industrial applications such as food processing, and resort and spas. The fastest growing direct-use applications in the U.S. are greenhouses and aquaculture, which can be seen in Figure 2.

![Figure 2. Geothermal direct-use growth in the U.S.](image)

The Geo-Heat Center was recently tasked through a contract with the Department of Energy to complete a state resource database, including collocated communities, for six more states in the west. These states are: Alaska, Nebraska, North Dakota, South Dakota, Texas and Wyoming. The Geo-Heat Center was further tasked to include the original state databases into a standard format for ease of use. Research for the databases included finding reports and other information on wells and springs...
for those states, and also to ask knowledgeable people in those states where to obtain additional information.

The reports of the original state teams and the new information from the additional six states documents a total of 11,775 wells and springs in the databases with the new states producing 2,731 more entries. The number of collocated sites increased to 404 from the previous 271 for the 10 states. The total of wells and springs with a temperature over 50°C (122°F) went from 1723 to 2211, which is an increase of 28%. A summary of the numbers by state is shown in Table 1. All of this information is available on a CD, as described below.

**Table 1. Summary of the Western States Geothermal Databases.**

<table>
<thead>
<tr>
<th></th>
<th>Number of Wells and springs</th>
<th>Number of Chemistry entries</th>
<th>Number of Collocated communities</th>
<th>Number of Direct-use sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Databases</td>
<td>1,251</td>
<td>2,491</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Arizona</td>
<td>989</td>
<td>683</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>California</td>
<td>168</td>
<td>443</td>
<td>15</td>
<td>39</td>
</tr>
<tr>
<td>Colorado</td>
<td>1,555</td>
<td>620</td>
<td>51</td>
<td>73</td>
</tr>
<tr>
<td>Idaho</td>
<td>292</td>
<td>288</td>
<td>18</td>
<td>34</td>
</tr>
<tr>
<td>Montana</td>
<td>455</td>
<td>365</td>
<td>30</td>
<td>330</td>
</tr>
<tr>
<td>Nevada</td>
<td>361</td>
<td>823</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>New Mexico</td>
<td>2,195</td>
<td>208</td>
<td>32</td>
<td>628</td>
</tr>
<tr>
<td>Oregon</td>
<td>964</td>
<td>885</td>
<td>23</td>
<td>17</td>
</tr>
<tr>
<td>Utah</td>
<td>814</td>
<td>195</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Washington</td>
<td>9,044</td>
<td>7,001</td>
<td>271</td>
<td>1,252</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New Databases</td>
<td>238</td>
<td>242</td>
<td>17</td>
<td>14</td>
</tr>
<tr>
<td>Alaska</td>
<td>87</td>
<td>0</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Nebraska</td>
<td>128</td>
<td>139</td>
<td>1</td>
<td>0</td>
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<tr>
<td>North Dakota</td>
<td>821</td>
<td>4</td>
<td>58</td>
<td>6</td>
</tr>
<tr>
<td>South Dakota</td>
<td>1,101</td>
<td>0</td>
<td>43</td>
<td>3</td>
</tr>
<tr>
<td>Texas</td>
<td>356</td>
<td>182</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>Wyoming</td>
<td>2,731</td>
<td>567</td>
<td>133</td>
<td>44</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>11,775</strong></td>
<td><strong>7,568</strong></td>
<td><strong>404</strong></td>
<td><strong>1,296</strong></td>
</tr>
</tbody>
</table>

2 Western states geothermal database CD

The Geothermal State Resources CD can contain up to five databases for the 16 states as stated above. The five databases are:

1. *Wells and springs* - Which contains all the known wells and spring for that state with a temperature typically > 20°C (68°F);
2. *Chemistry* - This database contains the most common fluid chemistry for the sites listed in the *Wells and springs* database. There are a couple states where no chemistry information was available (Texas and Nebraska);
3. Other information - This database contains additional information found in the original databases but did not fit in the original two categories;

4. Direct-use sites - This database contains known locations of existing direct-use sites for each state. The states of Arkansas, Georgia, Hawaii, New York and Virginia are also included since they all have direct-use; and

5. Collocated sites - Contains information on population centers located within 8 km (5 miles) of a known resource with a temperature above 50°C (122°F).

The databases are available in three different formats for use over a wide range of spreadsheets and database programs. The three formats are listed below.

1. QuattroPro 8 extension *.wb3
2. Microsoft Excel 97 extension *.xls
3. Comma delimited Text extension *.csv

Background information on each state database can be found in the “Information” file. This file includes where the information was obtained, summary of each database included for the state (such as how many entries in the wells and springs database), a listing or the column headings for each database, and which of the column headings has no information for that state.

There are two more white paper files that may be available for each state. The first one is the original state team report for the 10 original states. Seven of the original reports are available online at the website DOE Information Bridge <http://www.osti.gov/bridge/>. As the other state reports become available they will also be placed on the CD. The second white paper file contains a listing of references that provides more information for each state.

To be able to view these white paper files, you must be able to view an Adobe PDF file. If a person does not have the program Adobe Reader or similar program to read the white papers files, the installation files have been included on the CD in the directory Adobe. The files are available for both Windows and Mac computers.

3 What each state database contains

The Wells and springs databases are available in both SI (site-a) and US (site-b) units. The column headings for this database are:

a. Site ID - Corresponds to the other databases Chemistry and Other for easy reference between them
b. Site Name - Name given to the well or spring in the original databases
c. Type - well, spring or other (for example, California lists several types of wells)
d. Latitude
e. Longitude
f. County
g. Quad - Some states listed Quadrangle information which represents Township N/S and Range E/W. Some of the states used both references.
h. Township - Part of the legal land description which includes columns h, i, j, k, l, m
i. North or South - Part of the legal land description which includes columns h, i, j, k, l, m
j. Range - Part of the legal land description which includes columns h, i, j, k, l, m
k. East or West - Part of the legal land description which includes columns h, i, j, k, l, m
l. Section - Part of the legal land description which includes columns h, i, j, k, l, m

a. Quarter Section - further defines the location of the well or spring. Part of the legal land description which includes columns h, i, j, k, l, m
b. Depth
c. Temperature
d. Flow
e. TDS - Total Dissolved Solids
f. Chemistry - if there is available chemistry in the chemistry database (yes or no).

The Chemistry database has information on the more commonly reported chemistry entries in the original databases. The column headings are:

a. Site ID - Corresponds to the other databases Wells and Springs and Other for easy reference between them
b. Date Sampled - Corresponds to the date the sample was taken as reported in the databases. Some wells and springs have more than one chemistry entry.
c. Sample Name - Some of the chemistry entries were given identifying names
d. Site Name - Name given to the well or spring in the original databases
e. Type - well, spring or other (for example, California lists several types of wells)
f. Latitude
g. Longitude
h. Temperature - reported in Degrees C
i. TDS - Total Dissolved Solids
j. Field pH
k. Lab pH
l. Field Conductivity
m. Na - Sodium (milligrams per liter, mg/L)
n. K - Potassium (milligrams per liter, mg/L)
o. Ca - Calcium (milligrams per liter, mg/L)
p. Mg - Magnesium (milligrams per liter, mg/L)
q. Fe - Iron (milligrams per liter, mg/L)
r. Sr - Strontium (milligrams per liter, mg/L)
s. Li - Lithium (milligrams per liter, mg/L)
t. B - Boron (milligrams per liter, mg/L)
u. SiO₂ - Silica (milligrams per liter, mg/L)
v. HCO₃ - Bicarbonate (milligrams per liter, mg/L)
w. SO₄ - Sulfate (milligrams per liter, mg/L)
x. Cl - Chlorine (milligrams per liter, mg/L)
y. F - Fluoride (milligrams per liter, mg/L)
z. As - Arsenic (milligrams per liter, mg/L)
aa. Calc TDS - Calculated Total Dissolved Solids
bb. Br - Bromide (milligrams per liter, mg/L)
c. NO₃ - Nitrate
dd. NA + K
The Other database contains additional information that was not included in the Wells and springs database or the Chemistry database. This information was either not consistently reported in all the state databases or was newly discovered in the development of the newer state databases. Some examples of column headings are drilling date, well status, reference, and SWL (static water level).

The Collocated databases were developed using the Wells and springs databases. The criteria for being a collocated community are a geothermal resource with a temperature of at least 50°C (122°F) and located within 8 km (5 miles) of a community. Database information includes: location and resource characteristics, including well data.

The Direct-Use database contains known direct-use applications located in the U.S.; although, we believe there are a significant number of projects utilizing geothermal energy that are not included in this database. The direct-use applications are: district heating, space heating, aquaculture, greenhouses, industrial, snow melting, resorts/pools and agriculture applications. Database information includes: location, resource characteristics, capacity, energy use, load factor and contact.

4 How to obtain this information

The databases, which can be obtained in part or as a whole set on a CD, are available through the Geo-Heat Center. The cost for information for one state is $10 and for all 16 of the western states is $25. To obtain a copy of the CD, contact the Geo-Heat Center by phone (541-885-1750), fax (541-885-1754), email (geoheat@oit.edu), or mail (Geo-Heat Center, 3201 Campus Drive, Klamath Falls, OR 97601).

5 Other databases or maps that are now available

The Idaho National Engineering and Environmental Laboratory (INEEL) (http://geothermal.id.doe.gov) has recently produced several states maps using the data from the Western States CD and other information. The two state maps that have been completed and now available for downloading are Idaho and New Mexico.

The GeoPowering the West (http://www.eren.doe.gov/geopoweringthewest/) initiative is also producing several factsheets available for downloading. The states that have been completed to date are Nevada, Idaho and New Mexico.

The Idaho Department of Water Resources (http://idahogeothermal.org) has produced a website for Idaho Geothermal Resources. Their website includes information such as an overview, technical report and references, an interactive geothermal map and special regulatory information.

The Utah Geological Survey (http://www.ugs.state.ut.us/) just completed the CD “Geothermal Resources of Utah, a Digital Atlas of Utah's Geothermal Resources” which was compiled by Robert E. Blackett and Sharon I. Wakefield. This CD includes geothermal reports, maps and a bibliography that can be viewed in PDF format, several spreadsheet formats of the thermal wells and springs, and maps that can be view in either ArcExplorer and ArcView.

Acknowledgments

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We would also like to thank the following people for their contributions - Shirley Liss, Henry Heasler, Leslie Youngs, James Cappa, James Witcher, Leland Mink, John...

6 References

Geothermal resource potential of Himachal Pradesh, India

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Abstract

Himachal Pradesh Geothermal sub-provinces (HPG) form a part of the large Himalaya Geothermal Province, which covers an area of over 1500 sq km enclosing more than 150 thermal manifestations, with surface temperatures varying between 57 and 97°C. High geothermal gradients (>260°C/km) and high heat flow values (>180 mW/m\(^2\)) are characteristic of HPG. Besides wet geothermal systems, the province is endowed with hot dry rocks at shallow depths. With such high geothermal gradients and heat flow values, HPG is well suited to commission geothermal based power projects and also to initiate feasibility study to tap hot dry rock resources. HPG geothermal resources can immediately be utilised to support several food processing industries and capture the entire fruit market of the country as well as that of the world.

Keywords: Himalaya Geothermal Province, hot dry rock, geothermal power, geothermal energy, food processing.

1 Introduction

The Himalaya Geothermal Province extends from northwestern part of India (Ladakh) to its northeastern part (Assam) covering an area greater than 1500 sq km and encloses over 150 thermal manifestations. They fall between the Main Boundary Thrust (MBT) and Indo-Tsangpo Suture Zone (ITSZ), which are parallel to the Indo-Asia collision zone. Himachal Pradesh geothermal sub-provinces form a part of this large Himalaya Geothermal Province. Thermal manifestations around Puga, Parbati and Kullu valleys are known for their high temperatures. Several workers (Sehgal 1963; Jangi et al., 1976; Gupta et al., 1976; Giggenbach et al., 1983; GSI, 1991; Alam, 2002) have carried out preliminary investigations in these areas. Recently, as a part of Indo-Italian collaborative research programme, detailed investigation on the thermal waters and thermal gases from thermal manifestation along Parbati and Kullu valleys have been carried out to understand the geochemical evolution of the thermal waters and gases and assess the geothermal potential of these sub-provinces. The results of this investigation will appear elsewhere. In the present paper, the geothermal resources potential of Himachal Pradesh geothermal sub-provinces (HPG) is discussed. Thermal manifestations occurring at Tattapani, Puga, Beas, Parbati, Sutluj, Bhagirathi and Alaknanda constitute these sub-provinces (Chandrasekharam, 2001a). The heat source available in these sub-provinces is best suited for developing power projects as well as for direct utilization (Chandrasekharam, 2001a). Further, these provinces are also best suited for initiating a hot dry rock feasibility study (Chandrasekharam, 2001b; 2002).
2 General Geology of HPG

HPG falls between the MBT and ITSZ (Figure 1) located at an altitude extending between 1160 and 3660 m above mean sea level (Jangi et al., 1976). The temperature in summer varies between 27 and 14°C and winters are severe with snowfall varying between 60 cm and 2 m. The annual rainfall is about 120 cm (Srikantia and Bhargava, 1998).

![Map of northern part of the Himalayas](image)

Figure 1. Geothermal manifestations in northwestern part of Himalayas.

The Manikaran Quartzite intercalated with phyllite constitutes the uppermost Formation of the Rampur Group (Srikantia and Bhargava, 1998). Schist and gneiss of the Kullu Formation of the Chail Group tectonically overlies the Manikaran Quartzite (Sinha et al., 1997). The Manikaran Quartzite is underlain by metabasics, grey and green phyllite, with bands of carbonaceous schist (Jangi et al., 1976). The Manikaran Quartzite is highly jointed (shear joints with joint spacing of about 3-5 cm) and the contact between the quartzite and phyllite represents a thrust. The thrust zone is marked by tightly folded schist, which are highly crushed and at places been transformed into high-grade gneiss containing garnet. At places carbonaceous schist and graphite lenses are seen along this thrust. Folding pattern in these rocks is intricate and complex. The phyllyte shows drag and overturned folds and puckering with the drag fold axes trending N-S and NE-SW and overturned folds axes trending N-S and E-W. The regional dip of the Manikaran Quartzite is NE with dip amount
ranging from 30 to 50°. These joints are of great significance since all of them are the channels for upraising thermal waters and thermal gases in the region.

3 Geothermal manifestations and heat source in HPG

HPG experiences high geothermal gradient, reaching values as high as 260°C/km and high heat flow values of 70 - >180 mW/m² (Ravi Shanker, 1988). The surface temperature of the thermal springs varies from 57 to 98°C (GSI, 1991; Alam, 2002) and at some places (e.g. Manikaran) steam emergence is commonly seen. Recent investigation on thermal waters from Manikaran in Parbati valley (Alam, 2002) shows that the thermal waters issuing here can be considered as a mixture of two end members, one represented by paleo-brine rich in Na-Cl and the other represented by calcium carbonate rich water produced by the interaction of meteoric water with calcite veins traversing the lithological formation. The estimated reservoir temperatures (Na-K thermometry) vary from 260°C (GSI, 1991) and 310°C (Alam, 2002). Thermal water flow rates measured from the shallow exploration bore-wells, drilled by the Geological Survey of India, varies from 200 l/m to more than 1000 l/m (GSI, 1991).

Besides subduction tectonic regime, high heat flow and geothermal gradients in this region is due to younger shallow magmatic activity within MBT and ITSZ. This younger magmatic activity is represented by large number of granite intrusive, whose age vary from 60 to 5.3 Ma (Schneider et al., 1999a,b; Searle, 1999a,b; Le Fort and Rai, 1999; Haris et al., 2000; Harrison et al., 1998, 1999; Chandrasekharam, 2001b; 2002). These granites occurring as lopoliths, sheets and dykes (leuco-granites), with thickness varying from a few meters to several meters, are either exposed on the surface or covered by a layer of sedimentary formation. Permian granite of 268 Ma also occurs in the western Zanskar (Noble et al., 2001).

International Deep Profiling of Tibet and the Himalayas (INDEPTH) project located ‘seismic bright spots’ in Tibet region (east of HPG), which are attributed to the presence of magmatic melts and or saline fluids within the crust (Makovskky and Klemperer, 1999). Highly saline fluids are also found in Ladakh granite (~60 Ma) as inclusions, which are attributed to the high volatile content in the granitic melts (Sachan, 1996). Though INDEPTH investigation has not been carried out, considering the proximity of INDEPTH site in Tibet, probability of occurrence of such seismic bright spots within the HPG is high. This inference gains strength from the 1 Ma anatexis process recognized in Nanga Parbat (Fig.1; Chichi Granite Massive) in Pakistan Himalayas (Schneider et al., 1999c). Similar processes must be in operation on the eastern side of Nanga Parbat also. These evidences confirm that the present day observed high heat flow value (>100 mW/m²) and geothermal gradient is related to subduction tectonic related crustal melting process at shallow depth.

4 Regional Stresses in HPG

Regional stress analysis based on earthquake focal mechanism, bore-hole blow-outs and hydro-fracturing (Gowd et al., 1992) indicates that the entire Himalayan belt in general and the HPG in particular, is under compressive stress regime due to the northward movement of the Indian plate and net resistive forces at the Himalayan collision zone. Thus, the central and northern India including Nepal, the Greater Himalayas and Pakistan fall under this stress province characterized by NNE-ENE oriented $S_{\text{max}}$ (Chandrasekharam, 2001b; 2002). Investigation carried out around Zanskar (north of HPG) by Pierre Dèzes (1999) also shows compressive regime in
this region. Compressional stress regime is favourable to create several sub-horizontal reservoirs in granites by hydro fracturing, interconnected by boreholes (Baria et al., 1999; Wyborn, 2001). Thus the entire subduction tectonic regime along the Himalayan Geothermal Province appears to be similar to HDR (Hot Dry Rock) prospect of Hijiori and Kansai provinces of Japan. International HDR feasibility study can be initiated in the region falling between MBT and ITSZ with local government support and support from the independent power producers to develop a geothermal power project.

5 Geothermal energy utilization in HPG

HPG, being a region with high altitudes and rugged mountain topography, it is not possible to transmit power to remote villages by conventional coal or hydropower grid. Though local government has installed transmission cables to remote villages, power supply has not been commissioned even after several years and the rural population are still using conventional lanterns to meet their power requirement. With the existing geothermal resources and available technology, it should be possible to generate power, which can provide at least one electric bulb in every home in these villages! In regions like Puga, which is covered by snow and ice throughout the year, geothermal heat will benefit to a large extent to the army personal. Thus besides power, direct utilization of geothermal energy (e.g. space-heating and greenhouse; Lund, 2002) will be more beneficial and economical in these regions.

HPG have varied agro-climatic conditions suitable for growing different varieties of fruits. This region is successfully growing apple, pear, peach, plum, almond, walnut, citrus, mango, raisin grapes etc. The total area under fruit cultivation in Himachal Pradesh (HP) alone is about 2000 km$^2$ with a production of about 5000 MT of all kinds of fruits annually. Apple is the major fruit accounting for more than 40% of total area under fruit cultivation and about 88% of total fruit production in HP. The present two fruit processing plants in HP has a combined capacity to process about 20,000 MT of fruit every year. But, then the region has to import other food products from other parts of the country. If local geothermal resources are put to use, this region can be one of the major food producing and processing regions in the country (Chandrasekharam, 2001a; 2002).

Greenhouses, dehydration of fruits and vegetables and aquaculture (fish farming) are the three primary uses of geothermal energy in the agribusiness industry (Lund, 2002), which are most suited under the existing Indian conditions. The relatively rural location of most geothermal resources in India also offers advantages, including clean air, few disease problems, clean water, a stable workforce, and low taxes. The HGP is best suited to initiate state-of art technology in food processing (dehydration and greenhouse cultivation) using geothermal energy. Beside the agro-based industry, large cold storage facilities can be commissioned along the west coast geothermal province where fishing is a major business.

6 Conclusions

The existing data on the geothermal resources on HPG indicates that both power and direct applications are possible over the entire area of the Himalaya Geothermal Province. Using locally available geothermal resources enable to adopt Clean Development Mechanism and reduce dependency on conventional power sources and also mitigate global climate change. When Yangbajing geothermal field in China, located north of ITSZ and east of HPG is able to produce 25MW of power (Chandrasekharlaram, 2000), considering similar tectonic setting, the HPG should also
be in a position to produce similar amount of power thereby improving the socio-economic status of the local hill population.

7 References


Hydrogeochemical study of the Resadiye (Tokat) geothermal field, Turkey

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Abstract

Resadiye Cermik travertine area is one of the main natural heritages located within the Kelkit valley in the Middle of the Black Sea geographical region of Turkey. It is covered by the widespread natural, white travertines, which are acquired immediately on deposition from hot spring waters. Definition of the physico-chemical characteristics of the hot waters, factors affecting the travertine deposition, sources of pollution and protection were the main objectives of this study. Thermal water emanates from a N25W-N65W oriented tension fracture which is located within the North Anatolian Fault Zone. The composition of waters in Resadiye is governed by water-rock interactions. They are bicarbonate waters but do not reflect a peripheral or steam-heated origin. The silica geothermometer gives temperature ranging from 51 to 96°C. These hot waters are of meteoric origin and circulation in the systems is closely related to tectonic activity.

Keywords: hydrogeochemistry, thermal waters, Resadiye, Turkey.

1 Introduction

The study area is within the Tokat-Resadiye town boundaries and encompasses 2 km². Resadiye spa is immediately west of Resadiye town (see Figure 1). The town was established within the Kelkit Valley. The North Anatolian Fault Zone (NAFZ) passes through the Kelkit Valley and has prime importance for our study. The hot waters of the Resadiye discharge from the branches of the NAFZ in this area. These waters emerge from more than 10 different places around the spa. Their temperatures are between 38-49°C and the discharge rate is 3 l/s. One well is situated northwest of Resadiye spa. The temperature of the water at the wellhead is 50°C and the discharge rate is 30 l/s. The discharge mechanism of the thermal springs and their relationship with meteoric waters are important since the groundwater circulation system in the area is not known in detail. Hydrogeochemical and isotopic investigations have been carried out not only to provide information on the origin of the Resadiye thermal springs and their position in the ground water circulation system, but also to lead to the development of new groundwater wells in the area for domestic purposes.

2 Geological outlook

Upper Jurassic-lower Cretaceous Zinav Limestone exposed on the western bank of the Kelkit River is the oldest unit in the area. It is composed of whitish micritic, biomicritic, sparitic and detritic limestone and has a thickness of 150-200 m (Seymen, 1975). Limestone is extremely laminated, brecciated and fractured, and open spaces are filled with calcite and silica cement. The upper part of the unit is unconformably overlain by the Nebiseyh formation (Kocak and Erzenoglu, 1987). The Nebiseyh formation is of Turonian to early Campanian age is made of clayey limestone and marl that are interlayered with tuffaceous levels. It is thickly fractured and has a thickness of 150-200 m. Nebiseyh formation sits conformably on the Kapakli Formation.
Figure 1: Geological map and conservation area of Resadiye Spa and adjacent areas.

Figure 2: Geological cross section of the Resadiye Spa area.

LEGEND

- Traverse line and alluvium (Qal) Plio-Quaternary
- Alluvium (PQ)
- Thick lava tuff, Ammonites and fossiliferous limestone (Kürek)
- Nallı, fragments of limestone and sandstone alternation (Kapaklı)
- Nebisya formation (Král) Mesozoic (Cretaceous)
- Trilobite formation (Král) Mesozoic (Jurassic)
- Carnivorous, sandstone, mudstone (n1) Karstic formation
- Conservation area of first degree
- Conservation area of second degree
- Fault (probable etc.)
- Ground water flow direction
- Spa
- Line of cross section
- Drilling localities
- Production well
- Sampling location
- North Anatolian Fault (NAF)
The Kapakli Formation is of early Maastrichtian age and consists of volcanic rocks of andesitic composition. Volcanic units widely covering the area have thickness of 200-1000 m. Alteration of volcanics have produced vast amount of bentonite occurrences. Alluvium consisting of gravel, sand and silt comprise the youngest units in the study area. Travertine deposits exposed along the Kelkit valley are associated with modern spring activity. Among them Cermik travertine, with a thickness up to 60 m, is the largest deposit in the area (Seymen, 1975).

3 General hydrogeology

The main aquifer supplying hot water to the Resadiye thermal springs is the Zinav Limestone. This unit has abundant fractures and dissolution cavities. Dissolution cavities in karstic or fractured limestones usually account for high permeability and hence allow transmitting considerable volumes of water making it an important aquifer. The Nebiseyh and Kapakli Formations have low permabilities. These units form the overburden layer, which is needed for the occurrence of the thermal springs (Figure 2). The alluvium deposits of the Kelkit Valley may also host good aquifer. Borehole S-1, about 450 m NW of the Resadiye Spa, was opened by MTA (General Directorate of Mineral Research and Exploration) for the utilization of thermal waters for bathing. The discharge of water from the permeable zone was measured as 30 l/s. The temperature of the water ranges from 48°C to 50°C. Resadiye thermal waters also emanate in E-W direction along NAFZ and also from N25W-N65W-trending fracture zone immediately west of the Resadiye town. These water springs emerge from more than 10 different places around the Resadiye spa. Their discharge rate is 3 l/s, and the temperatures range between 38°and 49°C. Travertines precipitating from thermal waters form a dome-like formation (~0.5 km²). In places, travertine deposits are translucent. Depending on the water flow, kidney stony and stalagmite type morphologies are observed. At present, most of thermal waters discharge from the lower levels of the travertine dome. Gas also emanates from near the top of the deposit. Travertine deposition blocks fluid paths causing the springs to migrate over time. The deposition rate of travertine is greatest at the rim of the terraces, where out gassing of CO₂ is enhanced by turbulent flow. However, the deposition rate is also significantly high where the water flow has high velocity and the flow thickness is small. Spring locations are also sensitive to seismic activity (Seymen, 1975).

4 Results of hydrochemical and isotopic analysis

4.1 Water samples and analytical methods

Water samples for both chemical and isotopic analyses were collected from the springs and well in February 2000 and again in June 2000. Samples were collected twice in order to assess the possible influence of precipitation on the spring water types and flow paths. All the analyses were done in the State Hydraulic Works (DSI) Laboratory of Turkey, Ankara (Table 1). Although chemical analyses of the spring waters have been published (Kocak and Erzenoglu, 1987), no previous isotopic analyses of the groundwater of the investigation area are available.

4.2 Hydrochemical evaluation

The total dissolved solids of the Resadiye water range from 3563 to 5990 mg/l. The waters are colourless and odourless but contain CO₂ gas. At the point of discharge, a deposit of iron oxide is visible. The dominant ions are Na and HCO₃. The source of
Na may be from alteration of Na-plagioclase in the volcanic rock in the area. Clay minerals also enhance exchange of Na with Ca. HCO₃ results from interaction of CO₂-rich water with limestone.

Table 1: Chemical composition of waters from the study area (in mg/l).

<table>
<thead>
<tr>
<th>Location name</th>
<th>Kelkit stream</th>
<th>Resadiye cold water</th>
<th>S-1 well</th>
<th>Resadiye thermal spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>T(°C)</td>
<td>4.56</td>
<td>14.9</td>
<td>-</td>
<td>48.2</td>
</tr>
<tr>
<td>PH(25°C)</td>
<td>7.4</td>
<td>6.9</td>
<td>6.7</td>
<td>6.6</td>
</tr>
<tr>
<td>Ca</td>
<td>51</td>
<td>208</td>
<td>180</td>
<td>260</td>
</tr>
<tr>
<td>Mg</td>
<td>15.8</td>
<td>52.8</td>
<td>89.8</td>
<td>63.7</td>
</tr>
<tr>
<td>Na</td>
<td>26.4</td>
<td>68.3</td>
<td>64.2</td>
<td>819</td>
</tr>
<tr>
<td>K</td>
<td>1.5</td>
<td>6.9</td>
<td>8.6</td>
<td>34</td>
</tr>
<tr>
<td>Cl</td>
<td>15.6</td>
<td>49.7</td>
<td>37.3</td>
<td>830.7</td>
</tr>
<tr>
<td>SO₄</td>
<td>19.8</td>
<td>292</td>
<td>275</td>
<td>140</td>
</tr>
<tr>
<td>HCO₃</td>
<td>88.4</td>
<td>640.5</td>
<td>774.7</td>
<td>1739</td>
</tr>
<tr>
<td>SiO₂</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>45</td>
</tr>
<tr>
<td>Li</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
</tr>
<tr>
<td>B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EC</td>
<td>558</td>
<td>1660</td>
<td>1710</td>
<td>5328</td>
</tr>
</tbody>
</table>

Table 2: Geothermometry results of thermal water samples from the study area.

<table>
<thead>
<tr>
<th>Geothermometer</th>
<th>S-1 well</th>
<th>Resadiye thermal water</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>T (°C)</td>
<td>50</td>
<td>46</td>
<td>Measured</td>
</tr>
<tr>
<td>SiO₂ (quartz, no steam loss)</td>
<td>94</td>
<td>82</td>
<td>Fournier et al, 1973</td>
</tr>
<tr>
<td>SiO₂ (quartz, no steam loss)</td>
<td>82</td>
<td>70</td>
<td>Arnorsson et al, 1983</td>
</tr>
<tr>
<td>SiO₂ (chalcedony, no steam loss)</td>
<td>64</td>
<td>51</td>
<td>Fournier et al, 1973</td>
</tr>
<tr>
<td>SiO₂ (chalcedony, no steam loss)</td>
<td>65</td>
<td>54</td>
<td>Arnorsson et al, 1983</td>
</tr>
</tbody>
</table>

Table 3: Saturation indices of waters from the study area

<table>
<thead>
<tr>
<th>No</th>
<th>Calcite</th>
<th>Aragonite</th>
<th>Dolomite</th>
<th>Gypsum</th>
<th>Anhydrite</th>
<th>Quartz</th>
<th>Chalcedony</th>
<th>Halite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kelkit stream</td>
<td>-0.60</td>
<td>-0.76</td>
<td>-1.70</td>
<td>-2.32</td>
<td>-2.58</td>
<td>-7.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resadiye cold</td>
<td>0.31</td>
<td>0.16</td>
<td>0.24</td>
<td>-0.93</td>
<td>-1.18</td>
<td>-7.07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-1 well</td>
<td>1.15</td>
<td>1.02</td>
<td>2.34</td>
<td>-1.30</td>
<td>-1.36</td>
<td>0.50</td>
<td>0.14</td>
<td>-4.89</td>
</tr>
<tr>
<td>Resadiye</td>
<td>1.16</td>
<td>1.03</td>
<td>2.36</td>
<td>-1.33</td>
<td>-1.43</td>
<td>0.43</td>
<td>0.06</td>
<td>-4.87</td>
</tr>
<tr>
<td>thermal water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The source of Cl may be rainwater or evaporitic deposits. The results show that the Resadiye spa water and the water from well S-1 are similar in origin. These waters are Na-Ca-HCO₃-Cl-As-B-CO₂ bearing (IAH, 1979). From Cl- SO₄- HCO₃ triangular diagram (Figure 3) Resadiye thermal and mineralised waters and well S-1 are bicarbonate-rich waters. They are near neutral pH, low in chloride and the major cation is sodium. The reservoir rocks in the Resadiye are composed of limestone. The water emerging from such a reservoir is naturally rich with calcium and bicarbonate ions as in the studied water. Also these waters contain a slightly high concentrations of sulphate, the source of which maybe the oxidation of H₂S gas escaping from magma, and/or dissolution of minerals like gypsum and celestite (SrSO₄). It is concluded that the relative abundance of SO₄ and HCO₃ in the Resadiye Turkish
geothermal water in relation to Cl, is a reflection of the sedimentary rocks in these areas but not that their abundance reflects a peripheral or steam heated origin. Based on Figure 4 all the data points plot in the area of immature waters, therefore solute geothermometry is not likely to yield meaningful equilibration temperatures. The only option is to use silica geothermometers (Table 2). Clearly, the estimated subsurface temperatures range from 51 to 94°C for the study area. The thermal waters derive from conductive heating and geothermal gradient. The recharge probably derives from higher elevation to the north and south of the Resadiye. These waters seep into the subsurface system along fault and fracture zones, get heated and discharge at the surface.

Mineral saturation indices for a number of hydrothermal minerals potentially present in the reservoir were calculated at measured surface temperatures by the PHREEQC computer code (Parkhurst and Appello, 1999). Results are presented in Table 3. Thermal waters from the well and springs of the area are undersaturated with respect to gypsum, anhydrite, and halite. They are oversaturated or nearly in equilibrium with respect to calcite, aragonite, dolomite, quartz, and chalcedony indicating that these minerals will have a thermodynamic tendency to precipitate at the point of sampling. Scaling of carbonate minerals is expected for all the thermal waters. These results coincide with the field observations. Water from the well causes scaling during extraction. Some inhibitors are used to prevent scaling in the well.

4.3 Isotopic evaluation

In the $^{18}$O-D diagram all the waters fall close to meteoric water line ($\delta D = 88^{18}O + 10$) of Craig (1961), indicating that the springs and well waters are mainly fed by meteoric water Resadiye thermal waters lie over the (+) positive side of the meteoric water line, which belongs to the Eastern Mediterranean basins ($\delta D = 80^{18}O + 22$) of Gat and Carmi (1970). Also thermal spring and well have a lighter isotopic composition than cold spring and stream. This would be an indicator of the effect of continental rains (Figure 4). As the North Anatolian Fault Zone (NAFZ) passes through the Kelkit valley, the surface water reaches Kelkit stream leaves the stream through fault, fracture and by streambed infiltration, without a significant amount of evaporation. Enrichment in $^{18}$O values would be expected had the stream water been exposed to the atmosphere for a long period. They are affected, to a great extent, by meteoric waters.
Three different groundwater circulation systems have been distinguished by the following factors: depth of groundwater circulation system, relative residence time between the samples, effect of altitude, and recharge area. The first circulation system is characterized by only shallow circulation. The stream belongs to this group. The intermediate group is characterized by continental recharge, relatively higher recharge elevation, and longer residence time. The Resadiye cold-water spring is in this group. The third group is characterized by the deepest and longest circulation system and higher recharge elevations. The Resadiye thermal water spring and S-1 drilling well are typical examples for this group (Figure 5). Based on the results of isotopic data, Resadiye thermal waters are of meteoric origin. The circulation velocity of these waters, which have hardly any tritium in the ground, is very low (Table 1) and their minimum age is 50 years. Their reservoir temperatures are not very high. Using all of this set of data along with elevation-δ¹⁸O data, the surface waters that infiltrate the aquifer system probably reach the well and springs in a long time. In addition, Resadiye thermal water spring has a higher elevation of recharge area than the S-1 well and the recharge elevation of the Resadiye thermal spring is over than 958 m, whereas the S-1 drilling well recharged at an elevation of 925 m or more.

Figure 4: ²H and δ¹⁸O compositions of Resadiye waters.

Figure 5: Plot of δ¹⁸O-tritium diagram.

5 Protection sites of thermal and mineral waters

In order to protect thermal springs from pollution and preserve their discharge rate and chemical composition, three boundaries for a protected area are suggested. For the Resadiye spa, the protected area is based on geological and hydrogeochemical data of the springs (Ministerialblatt, 1968), (Figure 1).

Boundary 1: This boundary represents the 1st degree protection site. It was determined on the basis of travertine outcrops and the fault direction from which thermal and mineral waters issue. The extremely porous and permeable character of travertine is found to be a negative factor for determining of protection site. In this respect, 1st degree protection site was drawn at 10-60 m distance from fault and fractures.

Boundary 2: This boundary, also including the 1st degree protection site, comprises an area 50-150 m distant from the spring site. The boundary of this site was drawn on the basis of the estimated 50-day’s groundwater travel time. This boundary intersects with
alluvium in the west and Resadiye-Aybasti to the east. Its northwest and southeast boundaries are drawn to include the fracture zone.

Boundary 3: This boundary, also including the 2\textsuperscript{nd} degree protection site, extends to a distance of 100 and 150 m from northern and western parts of the 2\textsuperscript{nd} protection site. 3\textsuperscript{rd} degree protection site intersects with the 2\textsuperscript{nd} degree protection site in the east while it extends to Kelkit stream in the south.

5.1 Restrictions with protection sites

Protection measurements necessary for the outer belt should also be applied to the inner belts.

\textbf{1\textsuperscript{st} degree protection Site}: entry to the zone should be restricted to authorized persons. It must be protected from any type of pollutant and other harmful materials. Except for structures for storage and capture of the thermal and mineral waters, no other facility and structure should be allowed. Whatever the reason is, no explosion can be made. No stone and material can be extracted. The area should be grassed. No fertilizer and pesticide should be used. Soil should not be cultivated. If the area is utilised for therapy, all necessary measures must be taken against pollution.

\textbf{2\textsuperscript{nd} degree protection Site}: This area should be protected from any kind of harmful human impacts. For example, an existing building and its supplementary structures in the eastern part of the field should be removed. Trash and other waste material should be demolished. No stone and material should be extracted. Camping activity, vehicle washing, establishment of cattle markets and the opening of galleries and excavation should be prohibited.

\textbf{3\textsuperscript{rd} degree protection Site}: In this site, all necessary measures must be taken against radioactive and chemical pollutants. Storage of petroleum, gas, textile and detergent products as well as production of battery, paint and explosive materials should be prohibited. New graveyard should be prohibited. If a proper sewage system is built, new settlement areas may be established. Drilling of water wells, any kind of underground works and explosions should not be allowed.

6 Increasing the discharge rate of the water

Resadiye Spa greatly contributes to the local economy of Resadiye. Thus to support the supply of increasing tourism, more thermal water must be secured, and this depends on the drilling of two new boreholes. Based on the field study two new wells (W-1, W-2) are suggested (Figure 1). Resadiye Municipality has initiated a geothermal heating project in 1992 (Orme Jeo, 1992). This project includes supply of water to 1000 new homes. Together with the S-1 borehole, these two boreholes should be sufficient. Used hot water must be re-injected to the subsurface via proposed new injection wells.

7 Results

The hydrogeological and isotopic evaluations have revealed three different ground water circulation systems in the area. A shallow zone characterized the first circulation system. The intermediate group is characterized by continental recharge, relatively higher recharge elevation, and longer residence time. The Resadiye cold-water spring is in this group. The third group is characterized by the deepest and longest circulation system with the longest residence time and higher recharge elevations. The Resadiye thermal water springs and S-1 well are typical examples for this. The springs are located on a major fault zone caused by intensive stress tectonic
movements in the Upper Jurassic- Lower Cretaceous and the Quaternary units. The thermal waters derive from conductive heating and geothermal gradient. The recharge probably derives from higher elevation to the north and south of the Resadiye. These waters get into the subsurface system along fault and fracture zones, get heated and discharge at surface. The most common ions in Resadiye thermal and mineralised water are sodium and bicarbonate. Based on the silica geothermometers, the estimated subsurface temperature range from 51 to 94°C. Thermal waters of well and springs are typically oversaturated with respect to calcite, aragonite, dolomite, and quartz minerals. Scaling of carbonate minerals is expected for thermal waters. To conserve the thermal waters, three protection areas are proposed. Two well sites are proposed for drilling to increase the water production in Resadiye.

8 References
Assessment of geothermal resources for the Qichun geothermal field, Shanxi, China

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Abstract

The current situation and features of the Qichun geothermal field, Shanxi province are introduced in the paper. LUMPFIT is used to simulate pumping test data and predict water level changes of the system under different production scenarios as well as temperature changes. Based on the simulation, suggestions are drawn to improve management of the geothermal system.

Keywords: Qichun geothermal field, simulation, prediction.

1 Introduction

The Qichun geothermal field is located in Qichun village of Shanxi Province, in the north of China where 14 sanatoriums have been constructed so far. It is a low-temperature system covering an area of 3 km\textsuperscript{2}. In all 19 geothermal wells had been drilled producing water with a temperature between 40-92°C by the end of 2002. The production rate of the system is increasing, from 4 l/s in 1972 to 23 l/s in 2002. This paper presents the features of the system on geology and geothermal water regime. LUMPFIT is used to simulate pumping test data, and change of water level and temperature are predicted under different production scenarios.

2 Features of the Qichun geothermal field

2.1 Geological settings

There are 6 thin geothermal reservoirs located in the Quaternary formation in the system, bottomed by dolomite and phyllite. Due to the presence of a deep fault, hot water moves upward, mixing with cold water in the geothermal reservoirs (Liang, 1989).

2.2 Features of geothermal water regime

The Qichun geothermal field has been developed for more than 30 years. The total production rate is increasing, particularly since 1991, which caused continual water level drop. Water level of the system dropped for 1.8 m during 1992-2002. Water level is lowest in July, and then recovers from October to March next year.

Temperature drops quickly due to cold-water intrusion. Longterm over-extraction causes regional water level drawdown, which results in cold-water intrusion in some places. Taking one well as an example, the temperature was 63°C in 1990 but dropped to 45°C in 2002. Similar cooling occurs in several wells due to over-production.
The chemical components in the geothermal water are also changing. The contents, such as of Cl, Na, and \( \text{SO}_4 \), are decreasing according to the results of analysis of samples taken from the same well at different time.

3 Geothermal resources assessment

3.1 Simulation by LUMPFIT

A LUMPFIT simulation tackles the simulation problem as an inverse problem. It automatically matches analytical response functions of the lumped model to the observed data by using non-linear iterative least-squares technique for estimation the parameters (Bodvarsson and Axelsson, 1986). Observed water level from a pumping test, which lasts about 40 hours, is applied to the simulation. Figure 1 shows the result of the simulation. Quite good agreement is obtained, and parameters produced from the simulation are similar to those obtained form the pumping test.

The purpose of carrying out the simulation is to predict water level change under different production rates. Two production rates are adopted to predict future water level variations, one with production rate remaining the same (9 l/s) as in the pumping test, while the other assumes doubling of the production. Water level drop will be 0.5 m for 10 years running under the first scenario, while 1.2 m under the second as shown in Figure 2. The upper line represents the water level simulated under the first production rate, and the lower one under the second production rate. The simulated water lever indicates that the Qichun geothermal system is an open system, which receives recharge quickly.

3.2 Prediction of temperature change

Based on the above simulation, water level is not a troublemaker for the Qichun geothermal field, but the temperature of the system might be a problem. As mentioned before, temperature drops quickly, and even worse some wells have been abandoned due to cold-water intrusion (Huang, 1992). The following formula is used to predict temperature of the system roughly:
\[ E_p = \frac{P_{cw}}{P_t} E_{cw} + \frac{P_{hw}}{P_t} E_{hw} \]  \hspace{1cm} (1)

where \( E_p \), \( E_{cw} \) and \( E_{hw} \) are enthalpies of water from production wells, cold water and hot water respectively. \( E_p \) is the enthalpy of 87°C water, which is a typical temperature of production wells in 2000, and \( E_{cw} \) is that of 17°C, which is the temperature of the cold water outside the geothermal system, and \( E_{hw} \) is the enthalpy of water at 108°C, which is the estimated unperturbed reservoir temperature based on geothermometry. If \( P_t \) is the production rate in 2000, 13 l/s, and then \( P_{hw} \) can be calculated form equation (1), and temperature prediction is performed under different production rates, assuming that the hot water (108°C) gives constant contribution, independent of the pump rate. Figure 3 shows the results, which indicates that temperature drops roughly by 2°C if the production rate increases 1 l/s.

4 Conclusions and suggestions

- The Qichun geothermal field is a low-temperature field. Based on prediction by LUMPFIT, water level drop will be 0.5m after 10-years if production rate is kept the same as at the present (13 l/s), but it will drop by 1.2 m if the production rate is doubled. Temperature drop will be roughly 2°C if the production rate is increased by 1 l/s.
- Improvement on geothermal field management is needed. Systematic monitoring is crucial for updating the exiting model, and parameters needing to be monitored include water level, production rate and temperature.
- Numerical modelling is strongly recommended to update the current rough estimation on temperature, which is a key issue of how to run the system.

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5 References


Geology and the geothermal systems of the southern segment of the Kenya Rift

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Abstract

The Kenya Rift is part of the East African Rift system, which is an active continental divergent zone. The Southern segment of the Kenya Rift Valley is a unique petrographic province comprising of at least four Quaternary to Recent volcanic complexes namely Suswa, Longonot, Olkaria, and Eburru. Although these volcanoes are located only about 40 km from each other, the eruptive products show marked compositional contrasts, requiring differences in magmatic processes. The rocks are characterised by subalkaline/peralkaline trachyte and/or peralkaline rhyolite volcanism with basalts being confined to eruption sites between individual centres. The segment of the Kenya Rift has anomalously high heat flow due to shallow intrusions. Active geothermal systems are associated with the volcanic centres. This paper summarizes the geology of the southern segment of the Kenya Rift and discusses reasons that indicate greater geothermal potential for Olkaria and Eburru and promising geothermal potential for Suswa and Longonot volcanic centres all with an estimated potential of more than 1000 MWₑ.

Keywords: Volcanism, geothermal systems, geothermal potential, Olkaria, Eburru, Suswa, Longonot, Kenya.

1 Introduction

The Kenya Rift valley (Figure 1) is part of the East African Rift system that runs from Afar triple junction in the north to Beira, Mozambique in the south. It is part of an incipient continental divergence zone, a zone where thinning of the crust is occurring and hence eruption of lavas and associated volcanic activities. The development of the rifting within Kenya started during the late Oligocene (30 Ma) and continues to present, with most of the Quaternary volcanism concentrated within the axis of the rift. The southern segment of the Kenya Rift is a unique petrographic province comprising of at least four Quaternary to Recent volcanic complexes. These are, from south to north, Suswa, Longonot, Olkaria and Eburru. The shallow lithosphere-asthenosphere boundary and Moho is responsible for the general high heat flow within the rift with a geothermal gradient of over 200°C/km (Weildon et al., 1994).

Geothermal systems are confined to these centres, with Olkaria and Eburru having a proven geothermal resource of 173 MWₑ and 20 MWₑ respectively. The former has been producing electricity since 1981. The total estimated power output from Olkaria and Eburru when both conventional and binary systems are used is over 600 MWₑ. Detailed scientific studies have been conducted in Suswa and Longonot, and the results indicate good prospects for geothermal resources exploitation with an estimated power output of over 400 MWₑ. This puts the total estimated power output
for this sector of the Kenya Rift at 1000 MW_e. Described below is the geology of the volcanic centres from south to north of the sector.

2 Geology

2.1 Suswa

Suswa is made up of two calderas; the inner (younger) and the outer caldera. The outer caldera measures about 12x10 km in diameter and has a general orientation of ENE-WSW. The inner caldera has a diameter of about 4 km and the central resurgent block measures about 3 km in diameter. The rock outcrops in Suswa and the adjacent areas can be divided into four main groups: Pre-Suswa volcanics, pre-caldera trachytes, syn-caldera trachytes, and phonolites. The Pre-Suswa volcanics, which comprise of Limuru Trachytes and Plateau Trachytes, have been dated at 2.0-1.7 Ma and 1.3-1.9 Ma respectively and they predate the rift block faulting. The pre-caldera trachytes can be divided into two groups: the faulted, shield-building group and the late non-faulted shield building lavas. The early trachytes are the oldest group dated 0.4±0.01 Ma and is the onset of volcanic activity at Suswa. The late phase, non-faulted trachytes typically overlie the faulted group. Syn-caldera rocks include ignimbrites and trachytes (Baker et al., 1988). Most of these lavas contain xenoliths of syenite and hydrothermally altered rocks most likely torn from the roof and volcanic conduits. Some of the vesicles are lined with magmatic calcite. Post-caldera (I)
Phonolites lavas were erupted in two distinct episodes, both post-dating caldera (I) formation, however, one group predates caldera (II) and the other postdates caldera (II) formation. The youngest flow in Suswa occurs within the annular trench. The lava flow has scarce vegetation cover, attesting to its youthful age. Torfason (1987) suggested that this flow may be about 200 to 400 years BP, but no dating has been done to obtain the actual age. The geothermal system in Suswa developed prior to caldera collapse as hydrothermally altered lithics with alteration minerals indicating temperatures of >250°C occur within the syn-caldera sequences. Fumarole geothermometry studies indicate temperatures ranging from of 270°C to >300°C (Arnorsson, 1989).

Detailed scientific studies were carried out by KenGen in 1992-1993 in Suswa and indicated the volcano as a good prospect, which possibly has a shallow heat source under the caldera (Omenda, 1993). Three exploration wells were sited and exploratory drilling is envisaged in the near future. Estimated power stored in Suswa geothermal field is put at approximately 200 MW_e.

### 2.2 Longonot

The activity directly associated with Longonot started 0.4 Ma BP and can be described in three main periods namely pre-caldera, syn-caldera and post-caldera. A series of arcuate ridges on the northern, western and the southern parts of the summit crater indicate existence of a caldera. Due to wide spread cover of the area by post caldera pyroclastics and lavas, pre- and syn-caldera rocks are not extensively exposed. Pre-caldera rocks, which include trachytes, have been encountered in shallow boreholes on the northern and western flanks of the Longonot volcano (Clarke et al., 1990). Syn-caldera activity includes layers of ignimbrite and pumice lapilli and ash deposits. Lower and upper mixed basalt/trachyte lavas and trachyte lavas were erupted during this period. The most recent activity is emission of trachyte lava on the north and the southwest flanks of the cone and mixed basalt/trachyte lava on the crater floor and are estimated at about 200 yrs BP (Clarke et al., 1990). Trace element of studies done on Longonot volcanics indicate that they are comagmatic, thus suggesting the presence of a large, highly evolved and long lived magmatic system under the caldera (Clarke et al., 1990). Presence of hydrothermally altered lithics indicates that the geothermal system under the volcano must have attained >250°C (Geotermica Italiana, 1989).

KenGen did detailed scientific work at Longonot volcano in 1998 and the results indicated a prospect area of about 60 km² and three exploration wells were sited in the area. Drilling of the exploration wells will be conducted in the near future when funding is secured. Estimated power output from the Longonot geothermal field is approximately 200 MW_e (KenGen, 1998).

### 2.3 Olkaria

Olkaria volcanic complex is characterized by comendite lava flows and pyroclastics on the surface and basalts, trachytes, and tuffs in the subsurface. The lithostratigraphy of the Olkaria geothermal area as revealed by data from geothermal wells and regional geology can be divided into six main groups: Proterozoic “basement” formations, Pre-Mau Volcanics, Mau Tuffs, Plateau Trachytes, Olkaria Basalt and Upper Olkaria volcanics. The Pre-Mau formation is not exposed in the area, but outcrop on the rift scarps in the parts of the Southern Kenya Rift. Mau Tuffs are Pleistocene in age and are the oldest rocks that crop out in the Olkaria area. The Upper Olkaria formation consists of comendite lavas and their pyroclastic
equivalents, ashes from Suswa and Longonot volcanoes and minor trachytes and basalts (Omenda, 1997; Clarke et al., 1990; Thompson and Dodson, 1963). The youngest of the lavas is the Ololbutot comendite, which, has been dated at 250±100 yrs BP using $^{14}$C from carbonized wood obtained from a pumice flow associated with lava (Clarke et al., 1990). The geothermal system in Olkaria is bound by the ring structure which is thought to be a caldera marked by numerous volcanic cones and domes to the east and to the south, the western edge being marked by Olkaria hill.

The geothermal system at Olkaria has been used to generate power since 1981. The proven resource is 173 MWe. The Olkaria East field is currently generating 45 MWe, Olkaria North East field has a power station of 64 MWe under construction and will be producing electricity later this year, and Olkaria West field which is being developed by an IPP and will have a capacity of 48 MWe when completed in 2004. Olkaria Domes is still under exploration and is estimated will host a 64 MWe power station and this would bring the total power for the Greater Olkaria Geothermal Area to 237 MWe. The area is capable of producing more power (>400 MWe) if the available resource is used optimally and combined cycle and binary systems are used.

2.4 Eburruru

Eburruru volcano forms the highest topography within the entire rift floor at elevation of about 2800 m while the surrounding area average 1900 m. The Eburruru massif consists of east and west volcanic centers. The volcano is made up of basalts, trachytes, rhyolites, tuffs, and pumice and has possibly been active since early Pleistocene. Cores and cuttings from wells up to 2700 m deep drilled for geothermal exploration in the area revealed more information on the volcanologic history of the volcano. The western older sector of Eburruru is composed of lower pantellerite and overlying faulted lower trachyte. The eastern sector with a caldera is composed of upper trachytes and upper pantellerite. Some of the phases might be contemporaneous but the last phase of the eruption is pantellerite. The trachytes are mainly pantelleritic. The occurrence of syenite below the volcanoes within the Kenya Rift, including the Eburruru area, has been suspected given the common occurrence of syenitic xenoliths within pyroclastic deposits. Drill cores from Eburruru confirmed the presence of a syenitic body below about 2400 m depth. The Eastern Eburruru pantellerites are the youngest rocks and are dated about 400 yrs BP (Clarke et al., 1990). The east ring structure bound by numerous volcanic cones or domes has been referred to as a caldera (Omenda 1997).

Detailed geo-scientific survey was carried out by the Kenya Electricity Generating Company, Ltd in 1989, which included geophysical survey of the Eburruru geothermal field, geologic mapping of eastern Eburruru, chemical characterization of the fumaroles, and drilling of six thermally anomalous areas. The wells drilled were EW-01, EW-02, EW-03, EW-04, EW-05, and EW-06, and have average depth of 2.5 km. From those wells, only EW-01 EW-04 and EW-06 were thermally productive with produced 2.4 MWe, 1.0 MWe and 2.9 MWe respectively. The other wells EW-02, EW-03 and EW-05 recorded maximum temperatures of 131°C, 161°C and 156°C respectively. The exploration campaign indicated that Eburruru volcanic complex has about 2 km² high enthalpy area that can support a 20 MWe power station.

3 Structures

High plateaus composed of lavas and pyroclastics flank the central south sector of the Kenya Rift. The flanking plateaus reach elevations of 3280 m and 2870 m at Mau and Loita in the west and average 2300 m to the east. The main marginal escarpments are
70 km apart and are formed by en echelon normal faults with displacements greater than 500 m. The rift floor lies at an elevation of about 2000 m in the Naivasha-Nakuru region, descending southwards to 800 m near Ololkisalie. Faults are not well exposed within the southern-central sector of the Kenya Rift due to the thick lava and pyroclastic cover blanketing the area (Figure 2). The most prominent faults and fracture patterns are N-S trending ones and are common along the floor of this sector of the rift. An extensive fault fracture network is also common and cut through mostly the Plio-Pleistocene lavas. Several volcanic alignments running roughly N-S are common in the portion of the rift floor with the prominent one being the NNW-SSE volcanic alignment that starts south of Mt. Longonot and runs all the way to the Crescent Island in Lake Naivasha. Suswa and Longonot have clear caldera structures, but Olkaria and Eburru have their calderas inferred by alignment of volcanic centres.

4 Hydrogeology

The hydrogeology of central to southern portion of the rift valley is mainly controlled by the rift flanks faults, the grid faulting and the tectono-volcanic axis along the rift floor. Fluids are recharged laterally from the high rift flanks and axially along the rift floor southwards as indicated by the piezometric map of the study area in Figure 3. Analysis of the elevation of the ground water in the boreholes in the area done by Clarke et al. (1990) shows that the water table is shallowest around Lake Naivasha getting deeper towards the south with those drilled between Longonot and Suswa never encountering water at drilled depth. The grid faulting act as channels for ground water or they provide permeable barriers to lateral flow. A microseismic study has shown that the grid faulting unlike the escarpment faulting is quite active suggesting they are open (Allen et al., 1989). Thus the faulting causes the ground water to flow from the escarpments to the center and then follow longer flow paths reaching greater depths, and aligning their flow within the rift along its axis. Due to the southward sloping of the rift floor, the axial flow from Lake Naivasha could also be an important source of recharge in the area south of the lake. The N-S normal faults could be very instrumental in channelling the fluids to the area. In Olkaria and Eburru where drilling has been carried out, the geothermal reservoirs are hosted by the faulted Plio-Pleistocene Plateau Trachytes, which are common within the floor of the southern Kenya Rift valley. It is therefore probable that the reservoirs of Suswa and Longonot are hosted in the same formation.

Figure 3. The piezometric map of Southern Kenya Rift (From Clarke et al., 1990).
5 Geothermal manifestations

Thermal surface signatures in this southern sector of the rift valley are marked by active and extinct geothermal manifestations. The active manifestations occur in form of fumaroles, altered grounds, warm grounds, and sulphur or silica deposition. Extinct manifestations are indicated by presence of altered grounds to brick red/grey clays and silica deposition. These manifestations are mainly structurally controlled, occurring along faults and fractures. Other areas with subsurface information include the boreholes drilled, which tapped low-pressure steam, and hot water. A well drilled to 55 m depth about a half a kilometer south of Longonot recorded a bottom hole temperature of 200°C (KRISP, 1985). Geotermica Italiana (1987) studied xenoliths showing high alteration temperature mineral assemblages which suggest hydromagmatic eruptions must have encountered geothermal reservoirs with temperatures of over 250°C.

6 Geothermal utilization in Kenya

The geothermal energy in Kenya is mainly used for production of electricity, however minimal direct uses are in drying of pyrethrum, soil fumigation and greenhouse heating. In 1981, a 15 MW power plant was commissioned at Olkaria East field (Olkaria I) followed by the second and third units with the same capacity in 1982 and 1985 respectively. A second 64 MW power station is being constructed at Olkaria Northeast field (Olkaria II) and will be commissioned towards end of year 2003. OrPower 4 an IPP (a subsidiary of Ormat International) is developing Olkaria Northwest field (Olkaria III) and are at the moment generating 12 MWe. When completed in 2004 Olkaria III will produce 48 MW.

Tapped steam has been used to dry pyrethrum at Eburru, but on a small scale. Well OW-101 at Olkaria Central field has been used for soil fumigation for use in horticultural farming. Steam from the well is also used to heat fresh water through heat exchangers and the water is then circulated to heat the greenhouses and hence utilizing the 1.28 MWe from the well effectively.

7 Discussion and conclusions

The Kenya Rift is part of an active continental divergent zone, the shallow lithosphere-asthenosphere boundary and Moho is responsible for the general high heat flow within the rift with a geothermal gradient of over 200°C/km. The southern Kenya Rift Valley is a unique petrographic province comprising of at least four Quaternary to Recent Volcanic complexes that host important geothermal prospects. Although these volcanoes are near apart, the eruptive products show marked compositional contrasts with subalkaline/peralkaline trachyte and/or peralkaline rhyolite volcanism with basalts being confined to eruption sites between individual centres.

Magmatic activity associated with these volcanic complexes commenced during late Pleistocene and has been continuous to very recent times. Suswa and Longonot volcanoes are clearly associated with caldera structures whereas Olkaria and Eburru have inferred caldera structures. Presence of very young lava flows indicate that the magma chambers of these volcanic complexes are still active and or hot magmatic intrusions underlie these calderas as evident by the strong thermal surface manifestations present in all the centres. Fumaroles, hot springs, altered grounds and high temperature boreholes are the common geothermal manifestations in most of these prospect areas. Xenoliths showing high mineral alteration
temperatures suggest hydromagmatic eruptions encountered geothermal aquifers with high temperatures in most of these prospect areas. In Olkaria and Eburru geothermal systems, high temperature hydrothermal alteration minerals were encountered in well drill cuttings. It is therefore possible that geothermal systems are associated with Longonot and Suswa volcanic centres because of presence of hydrothermally altered lithics with high temperature signatures in pyroclastics from these centres.

The main marginal rift escarpments are 70 km apart and are formed by en echelon normal faults with displacements of greater than 500 m. The rift floor is cut by numerous minor faults that rarely exceed 150 m in displacement. The extensive fault/fracture network evident in this part of the rift provides hydraulic connection and flow towards the rift axis. The rift floor in this central sector of the rift valley is at very low altitude relative to the rift scarps. The flanks, which are wet high altitude areas, therefore provide deep recharge into the floor of the rift due to its great hydraulic gradient between the floor and the flanks. It is therefore possible that surface waters percolate downwards through deep rift structures.

Utilization of geothermal in Kenya has been restricted mainly to production of electricity; direct uses are, however, being applied on a small scale. Direct use should however be boosted especially in farming and industry to make use of wasted energy heat.

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8 References


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Geothermal energy in Uganda, country update
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Abstract
Recent studies on the Uganda geothermal systems have focused on three geothermal prospects, Katwe, Buranga and Kibiro, all located in the tectonically active and Recent volcanic belt in the Western Rift valley along the border of Uganda and the Democratic Republic of Congo. Geothermal systems and saline and fresh water lakes characterize the Rift Valley. The three areas were chosen for study because of their volcanic and tectonic features that indicate a powerful heat source and high permeability. The objective is to develop geothermal energy as an alternative energy source to hydro and others to meet the energy demand of rural areas in sound environment. The geology and geochemistry results for the surface hot springs indicate that potential geothermal systems exist at depth. The subsurface temperatures of 160-200°C, 200°C, and above 200°C for the Katwe, Buranga and Kibiro prospects, respectively, have been inferred by geothermometry and mixing models. These temperatures are suitable for electric power production and direct use in industry and agriculture. Other areas outside the tectonically active and recent volcanic belt have typical fluid temperatures suitable for direct application to domestic use, agriculture and industrial heating. Surface exploration studies have reached advanced stages in the three areas with the execution of the ongoing geophysical survey, the results of which will be used to upgrade the current geothermal model of geology and geochemistry and develop an integrated model that will be a basis for siting the exploration wells.

Keywords: Katwe-Kikorongo, Buranga, Kibiro, geothermometry, isotopes, geophysical surveys.

1 Introduction
Uganda is situated in East Africa and has borders with the Democratic Republic of the Congo (to the West), Kenya (to the East), Rwanda and Tanzania (to the South) and Sudan (to the North). Uganda has an area of approximately 241,000 km² and a population of about 24.7 million people with an annual growth rate of 2.5%. The country’s per capita energy consumption of 0.3 tonnes of oil equivalent (TOE) or 12.72 GJ is among the lowest in the world. Few people have access to modern energy supplies such as electricity and petroleum products. The energy consumption rate stands at about 5 million toe/year of which approximately 93% is biomass (wood, charcoal and agricultural residues). The grid electricity access rate is very low: 6% for the whole country and about 2% for the rural areas. Demand for power is growing at 3-4 MW a month.

The country is well endowed with considerable hydropower resources with the potential capacity estimated to be in excess of 2,000 MW. Hydropower is the main source of Uganda’s electricity supply with a total generating capacity of 317 MW. The total demand is estimated to be around 580 MW by the year 2005. The major hydroelectric plant, the Nalubale (Owen Falls) dam on River Nile at Jinja, was rated at 180 MW by 1999. An extension to this, the Kiira plant was commissioned in 2001 and is rated at 200 MW. However, only 120 MW have been put on line, bringing the total generation capacity to the current 317 MW.

The Government of Uganda is presently rehabilitating the existing power generation and distribution installations and is studying ways to meet the increasing...
energy demand by other indigenous energy sources. As part of this effort, the Government is in the process of formulating a long term integrated least-cost “Alternative Energy Resources Development Programme (AERDP)” for the country, and defining projects that are optimal within the framework of the programme. Geothermal energy presents a high priority alternative to hydropower and therefore, findings and recommendations from the geothermal project will be an important input to the programme.

2 Geothermal potential

The country’s geothermal resources were estimated at about 450 MW (McNitt, 1982) in the Ugandan Rift System and no new estimates have been put forward. Geothermal energy cannot be left out of Uganda’s energy plans for the following reasons:

- Hydro - electricity sites are more or less concentrated in one area (along the river Nile) resulting in long transmission distances and high energy losses;
- Lack of security in case of reduction in hydropower output arising from climatic fluctuations and therefore need to diversify energy sources;
- Location of geothermal fields in isolated areas such as Buranga in Bundibugyo district; far from the national grid.
- It is environmentally benign.

3 Geothermal areas

The major areas under study are Katwe-Kikorongo (Katwe), Buranga and Kibiro. They are all situated in the Western branch of the East African Rift System that runs for most of its length along the border of Uganda with the Democratic Republic of Congo (DRC) (Figure 1). The three areas were chosen as priority areas because of their volcanic and tectonic features that are indicators of powerful heat sources and permeability. Other geothermal areas are located on the outskirts and/or close to the rift valley in SW-Uganda and Northern Uganda (Figure 1). Surface exploration in the three areas has reached advanced stages while in the other areas it is still at preliminary level (Bahati, 1996).

4 Recent studies

Recent studies have concentrated on the three geothermal prospects of Katwe, Buranga and Kibiro under two projects, Geothermal Energy Exploration I (UGA/92/002) and Isotope Hydrology for exploring Geothermal Resources (UGA/8/003).

4.1 Geothermal energy exploration I

This project was carried between 1993 and 1994. It was funded by the Government of Uganda, UNDP, the OPEC Fund and the Government of Iceland and was executed by the Department of Development Support and Management Services of United Nations (UNDDSMS) and implemented by the Geological Survey and Mines Department (GSMD) of the Ministry of Energy and Mineral Development (MEMD) of Uganda. The study employed geological and geochemical methods with the aim of selecting one of the geothermal areas for further surface geophysical analysis and exploratory drilling (Armannsson et al., 1994).
Figure 1: Location of geothermal areas of Uganda.

Main findings
- The three study areas are considered as potential geothermal targets.
- The geothermal activity is clearly related to the tectonic and volcanic activity of the rift, which has higher heat flow than the surrounding Pre-Cambrian crust.
- All three hydrothermal systems appear to be relatively old and rise from volcanic rocks rather than from the young overlying sediments.
- At Katwe, the size of the volcanic field, the high subsurface temperature of about 160-200°C, as well as various geological observations and proximity to the national grid make the prospect attractive for electricity production.
- The Buranga prospect appears to have a significant volume of water at 120 - 150°C and may be appropriate for electricity generation from a binary power plant, and drying of agricultural products.
- The Kibiro prospect has a relatively simple geologic structure and waters indicative of subsurface temperatures of above 200°C suitable for conventional electricity production.

Recommendations
- Execution of the geophysical survey followed by a drilling programme. This would provide information on reservoir size and characteristics.
- To install a small power plant to supply Bundibugyo district with electricity and to build a pilot plant for drying agricultural produce.
• To install power plants in the Katwe and Kibiro prospects to supply power to the surrounding areas and national grid.
• Uganda should pursue the development of its geothermal resources, in order to reduce the dependence on the hydropower single-source on the River Nile.

4.2 Isotope hydrology for exploring geothermal resources

Hydrological studies that were carried out as part of the geochemical investigation under the UGA/92/002 left many questions about the origin of the geothermal fluids, their age, source of salinity and recharge areas of the fields unanswered. Detailed studies of the above problems have been carried under UGA/8/003, funded by the International Atomic Energy Agency (IAEA) and the Government of Uganda (UGA/8/003 Terminal Report). This project started in 1999 and ended in 2002 (Bahati and Pang, 2003).

Main findings

• The thermal waters show isotopic composition compatible with the local meteoric water line, confirming the meteoric origin of the water circulating in the geothermal systems.
• The tritium concentration indicates some admixture of modern water close to the surface in Kibiro but not in Buranga and Katwe, where hot springs discharge tritium-free waters.
• A slight $\delta^{18}O$ enrichment of about 1‰ observed in the hot springs at Kibiro suggests high temperature water-rock interaction, old age, or low water/rock ratio. A similar enrichment in Katwe may have similar causes, and/or be due to high carbonate in the subsurface rock.
• Sulphur isotopes ($\delta^{34}S_{SO_4}$) of hot water samples show magmatic contributions of sulphate, which confirm earlier results of chemical investigations.
• Recharge water to hot springs comes from higher elevations in the nearby Rwenzori Mountains in the case of Katwe and Buranga, and Mukihani-Waisembe ridge for Kibiro.
• Subsurface temperatures predicted by sulfate-water oxygen isotope geothermometry are highest for Buranga (200°C), but 100-140°C for Kibiro and 140°C for Katwe. Mixing with cold water may have lowered the temperature estimates for Kibiro and Katwe.
• Reservoir rock types for Katwe are most likely Basalt (Leucites and Melilites) and Granitic xenoliths; Granitic gneisses for Buranga and Kibiro.
• Major source of salinity is from water-rock interaction, but some magmatic inputs in the case of Buranga and Kibiro are also evident.

5 Present geothermal programs

5.1 The Uganda alternative energy resources assessment and utilization study (UAERAUS)

The UAERAUS is a cooperative project between the African Development Bank (ADB) and the Government of Uganda whose aim is to formulate a long-term integrated least cost AERDP. The energy resources being considered include geothermal, biomass, wind, peat, solar and mini- and micro-hydro. A core activity of this study is geophysical surveys and collection of additional geological and geochemical data. The results of the geophysical surveys when completed, will be
used to upgrade the geothermal models of Katwe and Buranga to near pre-feasibility status. The study started in October 2002 and will last for 13 months.

5.2 Further surface analysis of the Kibiro geothermal area

Iceland through the Icelandic International Development Agency (ICEIDA) and the Government of Uganda have a joint project to complete surface exploration in the Kibiro geothermal prospect (Gislason, 2002). Kibiro will not be surveyed under the UAERAUS. The project will upgrade the existing geological and geochemical models by carrying out geophysical surveys and additional geological studies. The project is scheduled to start in October 2003 and will take three months to complete. Under this project the data from the other areas, Katwe and Buranga, will be evaluated and reviewed to get a second opinion and the three models will be compared, and arranged in an order based on their predicted geothermal potential.

6 Geothermal energy exploration II

In order to move ahead with geothermal exploration and development in Uganda, it is important to build on work already done and carry out further analyses which should lead to exploratory drilling at one or more sites, if successful. This activity is proposed under the Geothermal Exploration II project the funding of which has not yet been brought to be.

Project objectives

- Upgrading of geothermal models and siting of boreholes in one or more selected areas.
- Drilling at selected sites, in one or more of the identified target areas.
- Preparation of technical and financial/investment plans for the installation of an appropriately sized power plant and feasibility of direct use in industry and agriculture.
- Increasing the number of Ugandans with experience in geothermal resource testing, evaluation, project design, and financing.

Project description

The Geothermal Energy Exploration II project is divided in two phases - A and B. The purpose of the studies in Phase A is to provide additional detailed information about the size and structure of the reservoirs as well as to aid in the siting exploration wells. Phase B will depend on the results of Phase A and, if Phase A is successful, will involve drilling into one or more prospects.

Phase A: Pre-feasibility

Prospect investigation to locate drillsites within a chosen prospect area, which will include:

- Careful review of and second opinion on the previous results.
- A further exploration narrowed down to the most promising anomalies in order to further sustain siting of exploratory wells. This includes detailed structural mapping and geophysical surveys.
- Design of exploratory wells and preparing of tender documents.
- Environmental impact assessment.
- Pre-feasibility report.
Phase B: Feasibility
This will include exploratory drilling that will involve drilling of 2-3 wells, in a selected prospect, to discover a geothermal reservoir, prove sufficient production capacity for the initial generating plant and provide data for assessing the long-term production capacity, and economically determine capital and operating costs for a generating plant and to compare the costs of generating power from other available sources. The possible economic uses of the resource for purposes other than power generation will be determined and the environmental impact of development assessed. The output is a feasibility report.

7 Conclusions
- The geochemical model for the three areas is almost complete.
- Results of geophysical surveys in the three prospect areas will soon be available and the geothermal models upgraded to enable prioritization of the three areas for detailed surface analysis and exploratory drilling.
- More detailed investigations (the feasibility phase) are required to give confidence to the private sector.

8 References