

**GEOCHEMICAL EVIDENCE OF COLD FLUID
INCURSION INTO THE OLKARIA WELL RESERVOIR,
NAIVASHA, RIFT VALLEY- KENYA**

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**A dissertation submitted in partial fulfillment of the requirements for the degree of Master
of Science in Geology.**

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DECLARATION

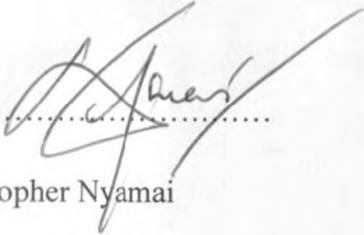
I hereby declare that this dissertation is my original work and has not been presented for a degree in any other University or any other award.

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ABBREVIATIONS AND ACRONYMS

EC	-	Electrical Conductivity
KHS	-	Kijabe Hot Spring
kJ/Kg	-	Kilo Joules per Kilogram
KS	-	Kijabe Spring
LB	-	Longonot Borehole
LN	-	Lake Naivasha
NB	-	Naivasha Borehole
OW	-	Olkaria Well
pH	-	Acidity/ Alkalinity
ppm	-	Parts per million
RM	-	River Malewa
TDS	-	Total Dissolved Solids

ABSTRACT

The study to establish the presence of cold fluid incursion into a geothermal reservoir using geochemical evidence was carried out in the greater Olkaria geothermal field. The greater Olkaria geothermal field is situated in Nakuru County, south of Lake Naivasha on the floor of the southern segment of the Great Rift Valley within the Kenyan rift. The wells in north east field, central field and Olkaria East field were monitored closely in order to establish conclusively the presence of the cold fluid into the reservoir. This was achieved through determination of fluid chemistry of geothermal fluids in Olkaria fields, geothermometry, mixing pattern and establishment of fluid origin. These were related to the geochemical characteristics of surface and subsurface neighboring fluids in the area.

This study considered geochemical data from the Olkaria geothermal fluids and the surrounding surface waters from Lake Naivasha, rivers Malewa and Gilgil, Naivasha and Longonot boreholes and springs from Kijabe. These data assisted in determination of fluid chemistry, geothermometry and mixing pattern. Samples for stable isotopes of ^2H and ^{18}O analysis were collected for determination of isotopic composition of the samples in regard to fluid origin establishment. Data interpretation was done using Aquachem software, WATCH speciation program and Microsoft Excel spread sheet and paint.

The study showed that some of the Olkaria geothermal wells had similar chemical characteristics and subsurface temperatures as the neighboring surface and subsurface fluids; this was an indication of mixing between the fluids. The main dissolved solids are Na, K, SiO_2 , Cl and HCO_3 . Sodium concentration of a high 743 ppm was recorded in OW- 202 in Olkaria Central field and a low of 24 ppm in Longonot borehole. The isotope data showed that the samples had negative $\delta^{18}\text{O}$ shift, this was due to the interaction with CO_2 enriched in ^{16}O . This was an indication that the thermal waters were mixing with cold water. The variation in δD was fairly big, between 5.5‰ in OW- 202 and 31.4‰ in Lake Naivasha; this was an indication that the samples did not originate from the same waters. The $\delta^{18}\text{O}$ varied between 0.21‰ in OW- 202 and 4.60‰ in OW- 6. Temperature values using Na/K geothermometer range from 259°C to 293°C in the East Olkaria field, 261°C to 304°C in the North-East field. Central field temperatures range from 270°C to 280°C while the surface fluids range between 32°C and 430°C.

In the North East field, lower temperatures were recorded in the central part of the field around OW -721, OW-725 and OW-727. The low temperatures were interpreted to be due to cooling, which was a result of cold fluid inflow. The Schoeller diagram showed that the thermal waters had high concentrations of Na, K, HCO_3 and SiO_2 except for the central and a few North-Eastern field wells with slightly lower values as indicated by the diagram. Surface waters had high concentrations of Mg and low concentrations of SiO_2 . The Olkaria geothermal field is experiencing both cold and warm fluid incursion from the neighboring waters and condensates due to low pressure drawdown respectively.

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CHAPTER ONE

1.0 INTRODUCTION

As elaborated in chapter three of this report, this study was carried out in the Olkaria geothermal field and its neighborhood in order to establish the presence of cold fluid incursion into the Olkaria well reservoir and the mixing trend between Olkaria wells fluids and the neighboring surface fluids in regard to well production.

The location of the study area is in the Hells gate National Park in the Kenya Rift Valley and is approximately 120 km North-West of Nairobi City, the capital City of Kenya. From Nairobi, the area can be accessed by either the road on top of the escarpment which makes a gradual descent to the rift floor near the Naivasha town or the older escarpment road which reaches the rift floor at Mai Mahiu junction. Naivasha town is the administrative and commercial centre for Naivasha district. A circum lake road which leads to the study area exists around Lake Naivasha. The water from the lake serves the Olkaria geothermal field and is used for both intensive mixed farming and horticultural enterprises.

The greater Olkaria geothermal area is situated in Nakuru County, South of Lake Naivasha on the floor of the Southern segment of the Great Rift Valley within the Kenyan rift (Figure 1.1). The Kenya rift constitutes the East African rift system that extends from the North of Afar triple junction at the Gulf of Eden to the South of Beira in Mozambique. The rift is the segment of the Eastern arm of the rift that runs from Lake Turkana to the North to Lake Natron, Northern Tanzania to the South (Figure 1.1). It is part of a continental divergent zone, where spreading occurred resulting to the thinning of the crust hence volcanic eruption of lavas and associated activities are evident.



Figure 1.1: Map of the major Quaternary volcanoes and location of Olkaria geothermal complex (after Lagat, 2004)

1.1 Study Area

1.1.1 Location and Description

1.1.2 Olkaria Geothermal Field

Olkaria Geothermal field is situated within the Hells gate National Park in the Kenya Rift Valley, 120 kilometers North-West of Nairobi City. The area is in Nakuru County, and can be approached through Naivasha town which is the administrative and commercial centre of Naivasha district. There is a circum lake road around Lake Naivasha which serves the Olkaria geothermal field and the many intensive mixed farming and horticultural enterprises.

Olkaria geothermal field covers an area of approximately 240 km². Repeated volcanic activities within the Olkaria geothermal field created elevated ground surfaces surrounding the field. These are Eburru to the North, Longonot to the West and Suswa to the South (Figure 1.1).

1.1.3 Lake Naivasha

Lake Naivasha is a freshwater lake within the County of Nakuru in Kenya. It lies to the North-Western direction of the Nairobi City, outside the Naivasha town. It is one of the formations of the Great Rift Valley. The name originates from the local Maasai community name *Nai'posha*, meaning "rough water" because of the sudden storms which can arise.

The lake is located at 04°6'6.70"S and 36°21'2.32"E coordinates of the globe, covers a surface area of approximately 139 sq km and is surrounded by a swamp whose surface area is approximately 64 km² (Figure 1.4), but this has a large variation depending on rainfall. It has an altitude of 1,884 m (6,180 ft). The average depth of the lake is 6 m (20 ft), but the deepest area is at Crescent Island, with a maximum depth of 30 m (100 ft). Ol Njorowa Gorge formed the lake's outlet, but it is currently high above the lake waters level and forms the entrance to the Hell's Gate National Park. Naivasha town lies to the North-East edge of the lake. Figure 1.2 shows a photograph taken at Lake Naivasha.

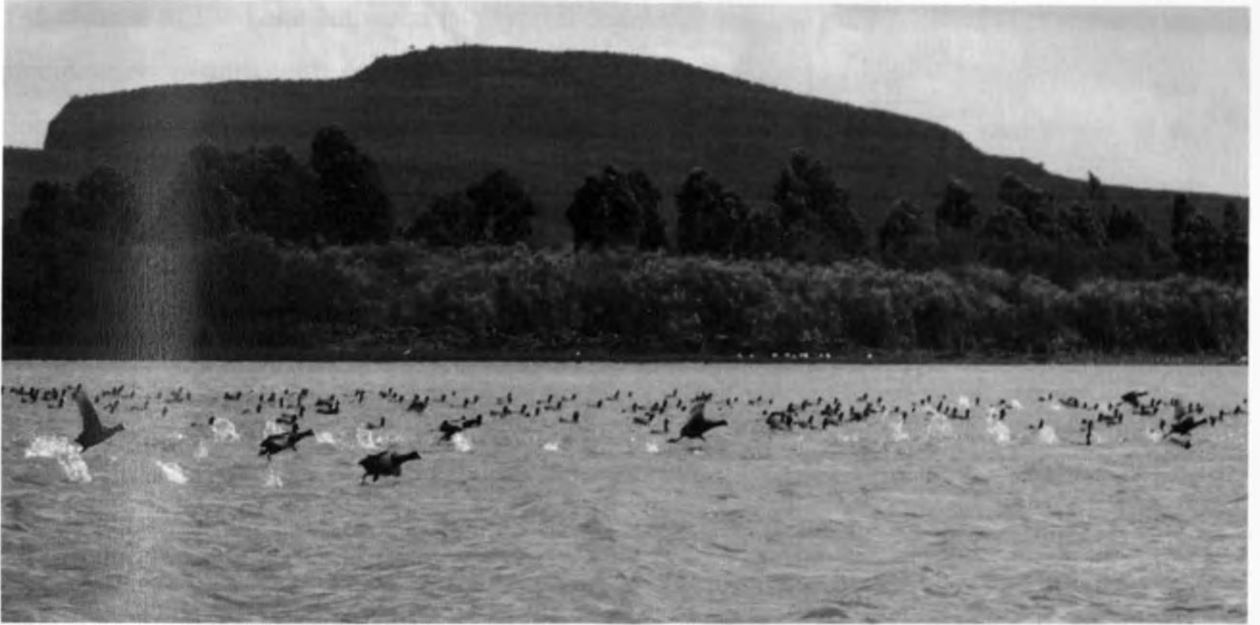


Figure 1.2: Lake Naivasha with Olkaria Hill in the background

Lake Naivasha lies at the highest elevation of the Kenyan Rift valley at 1,890 meters (6,200 ft) in a complex geological combination of volcanic rocks and sedimentary deposits from a larger Pleistocene era lake. The lake is fed chiefly by the perennial River Malewa and River Gilgil together with the transient streams. The lake has no visible outlet yet the lake water is relatively fresh, it is therefore assumed to have a subsurface outflow.

1.2 Climate

The area in which the Olkaria geothermal field is situated has two rainy seasons, the long rains which occur in March to May and the short rains in October to November. The average annual rainfall is approximately 627 mm while the average maximum and minimum daily temperatures are approximately 25°C and 9°C respectively. Relative humidity is slightly below 75% and a monthly averaged potential evaporation exceeding rainfall by a factor of 2 to 3 for every month except April when potential evaporation still exceed rainfall except for the wettest of years (Clark et al., 1990).

The climate of the Lake Naivasha is a typical equatorial tropical climate. The relief controls the precipitation pattern with much more rain in higher altitudes (M'mbui, 1999). The rift valley floor experienced an average annual rainfall of about 640mm while the wettest slopes of the mountain receive 1525mm. Due to altitudinal differences, there are diverse climatic conditions found in the basin.

1.3 Physiography and Drainage

Many recent fissures controlled by eruption resulted into uneven ground with surface covered with fresh lava rocks and pyroclastics (Mungania, 1992). Within Olkaria, the highest ground elevation is at 2400m at Olkaria Hill and slopes towards the South at Akiira Ranch at 1600m. At least 80 volcanic centers have formed within the Olkaria geothermal field. Most of these volcanic centers occur as either steep sided domes formed of lava and or pyroclastic rocks or as thick lava flow of restricted lateral extent (Clark et al., 1990).

Magnificent scenery includes two volcanic plugs namely: the Fisher's Tower and the Central Tower, and the Hell's Gate Gorge. This gorge is a narrow split in cliffs that drained lake Naivasha towards South during the period of high lake level which lasted until 5600 years ago (Clarke, et al., 1990).

Hell's Gate National Park was established in 1984 and is managed by the Kenya Wildlife Service, it hosts all the seven Olkaria geothermal fields and three camp sites which include the Maasai cultural centre that provides education on the Maasai community culture and traditions. In regard to population and settlement, this park is inhabited by wild game while some parts are occupied by Maasai community.

The area hosts the freshwater Lake Naivasha whose level fluctuates depending on the amount of rainfall. The lake feeders collect runoff from the Nyandarua Mountains and their foothills to the North-East of the lake and discharge in a papyrus swamp forming part of the lake.

1.4 Land Use and Land Resources

Lake Naivasha is a home to a range of types of wildlife including over 400 diverse species of bird and a sizeable population of hippos. This makes the Lake a tourist attraction place

Two smaller lakes are visible in the vicinity of Lake Naivasha; these are Lake Oloiden and Lake Sonachi which is also referred to as 'a green crater lake'. The Crater Lake Game Sanctuary lies adjacent to the Lake Naivasha, while the lake shore is known for its population of foreign immigrants and settlers. Multiple use of Lake Naivasha includes agricultural irrigation, domestic, municipal, wildlife and generating geothermal power.

Floriculture is the main industry around the lake; this is evident by the many greenhouses in the area. On the other hand, the lack of regulation on the use of lake water for irrigation is constantly reducing the lake water levels and is of great concern to the Kenyan economy. Fishing in the lake is another source of employment and income for the local population.

The existence of the features mentioned under Physiography (1.3), within the Olkaria geothermal field has attracted a large number of tourists both domestic and foreign. This has benefited both the local community and the nation in terms of revenue earned. Swimming, sailing and boat riding are part of the lake activities.

1.5 Geology and Structures

1.5.1 Geology

The Kenya Rift is a fraction of the East African Rift Valley with a well renowned structure of continental scale. Active crustal extension and asthenospheric upwelling characterized by severe fracturing of the crust, recent volcanoes and high heat flows are evident (Mungania, 1992).

Rift related activities have been dated to have commenced in the early Miocene. The Northern part of the rift and the Eastern rift shoulder are characterized by the out crop of early volcanic rocks.

These rocks superimpose Proterozoic schists and gneiss of the Mozambican mobile belt that occur greater depths of more than 5 km within the vital part of the Kenya rift graben (Omenda, 1998).

Late Miocene rift faulting began with the eruption of huge ignimbritic volcanism and major rift-bounding faults developed in this era. Subsequent fissure eruptions of trachytes and basalts took place on the graben floor in the early Pleistocene followed by extensive rift-floor faulting event. As a result, horsts and graben structures, open fractures and conduits for subsequent volcanism formed on the rift floor (Clarke et al., 1990 and Omenda, 1998).

Quaternary volcanoes which are potential geothermal resources are evident within the axial region of the rift (Omenda, 1998). These volcanoes are Suswa, Longonot, Eburru, Menengai, Korosi, Paka, Silali, Emuruagogolack, Namarunu and Barrier volcanoes.

The Olkaria geothermal field is sited within the Greater Olkaria Volcanic Complex which consists of a series of lava domes/flows and ashes; the youngest is Ololbutot which was dated at 180 ± 50 yr BP (Clarke et al., 1990) in Figure 1.4. The high heat flow in the field is believed to be as a result of intrusive portions of these magmas. Rhyolitic volcanism in the Olkaria area was dated to have commenced about 400,000 years ago, it is very prominent in this area.

The main surface rocks of the Olkaria geothermal field are the brownish grey porphyritic and siliceous comendites, pumice fall and ash deposits. The pumice and ash deposits have their origin from Olkaria, Longonot and perhaps Suswa volcanoes. The activities of the three centres were active over the same period, though it has not been possible to quantify contribution from each centre (Clarke et al., 1990).

Rare Lacustrine sediments occur close to Lake Naivasha. The rough morphology pragmatic in the area is due to commenditic flows which are short with steep flow fronts.

There are four lithostratigraphic subsurface geological groups based on age, tectono-stratigraphy and lithology. The group formations are the Mau Tuffs, Plateau Trachytes, Olkaria Basalts and upper Olkaria volcanics. There exists a distinct lithostratigraphy through the Olkaria Hill. The West sector has plenty of Mau Tuffs while plateau trachytes and the Basalts are unique to the East sector (Omenda, 1998).

1.5.2 Conceptualized Geological Model of Olkaria Geothermal Field

Permeability sources in the Olkaria geothermal field are considered to be both primary and secondary. The identified sources of permeability include; fractures and joints due to intrusion and along edges of plugs and domes, lithological contacts, joints, clast matrix or fragment contacts in some breccias as indicated on Figure 1.3. The main feeders of geothermal fluids is believed to be fissured zones associated with subsurface faults and contact zones between formations. The feeders intercepted have been identified by the loss zones, quick recovery in temperature profiles, sheared rocks and abundant calcite and pyrite in veins (Lagat et al., 2005).

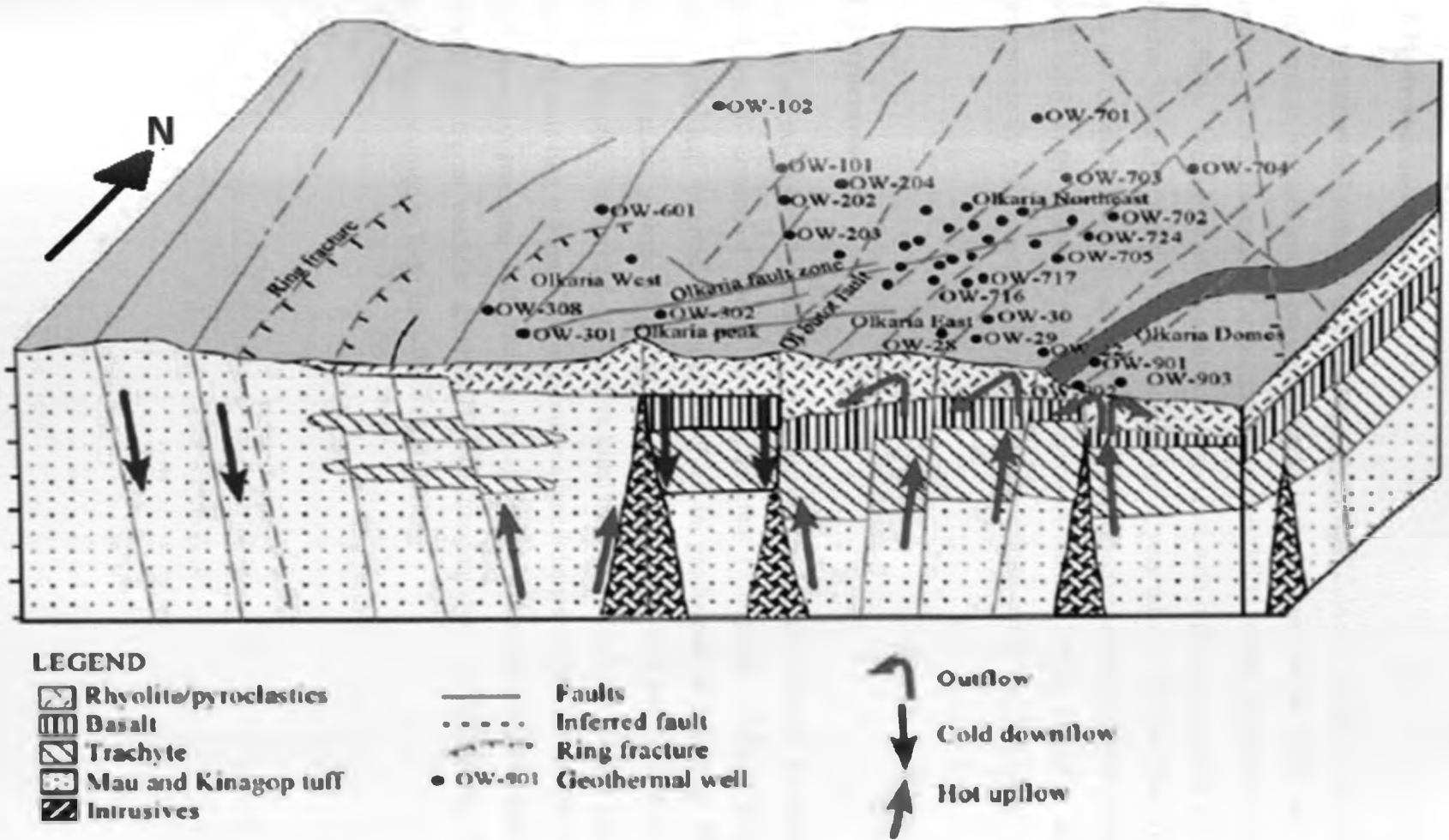


Figure 1.3: Conceptualized geological model of the greater Olkaria geothermal area showing generalized geology and locations of the field with respect to downflow, upflow and the outflow zones (after Lagat et al., 2005)

1.6 Hydrothermal Minerals

The hydrothermal minerals in the Olkaria geothermal field are mainly found within the vein lets, vugs and as replacement of primary minerals in the volcanic rocks. These are; chlorite, epidote, titanite, biotite, chalcedony, amphibole, secondary Fe-Ti oxides, anhydrite and quartz (Lagat et al., 2005). Most of these minerals are associated with high temperatures and occur at various depths. Wairakite and prehnite are present but at very minor portions. The Western field which was not covered in this report has Hematite and smectite minerals whose presence is associated with cold water incursion into the reservoir (Omenda, 1993). Common secondary minerals present are the clay minerals, fluorite, anhydrite, calcite, pyrite and iron oxides.

1.7 Structures

There are no standard surface faults observed within the Olkaria geothermal field though evidence of concealed intense faulting is great (Mungania, 1992). Figure 1.4 shows the observable and inferred structures involved in geothermal activities of Olkaria field. The structure pattern is characterized by N-S, NW- SE, NNW-SSE and ENE-WSW orienting faults. A ring structure interpreted as a caldera filled by later volcanics is evident in the Eastern part of the field, this ring is formed by the Arcuate aligned domes of the Eastern field, (Muchemi, 1998). The near N-S trending faults and the rim of the inferred caldera are interpreted to have formed due to the recent volcanic activity. The N-S trending dykes which outcrop along Ol Njorowa gorge are assumed to form East-West fluid barriers.

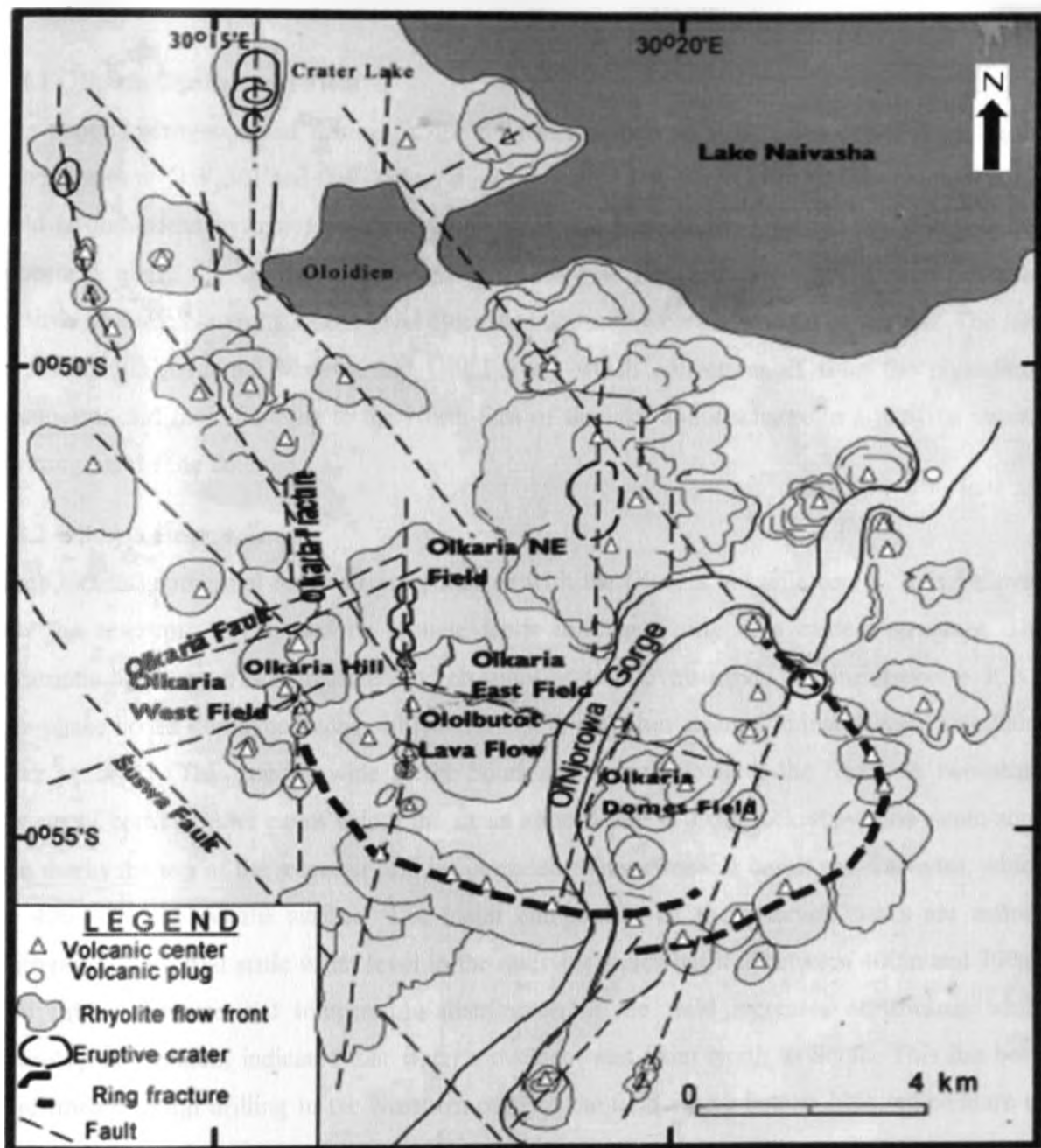


Figure 1.4: Geological and structural map of the Olkaria Geothermal Field (after Omenda, 1998)

1.8 Surface and Groundwater Resources

1.8.1 Olkaria Geothermal Field

The major hydrogeological features of the field include two up flow zones of hot fluids in the general area of OW-301 and OW-716 as shown in Figure 1.3. Large scale fluid movement in the field is dominated by major faults, fracture zones and large steam losses at the reservoir top, especially along the Ololbutot fault between wells OW-201 and OW-01. The area hosts the freshwater Lake Naivasha whose level fluctuates depending on the amount of rainfall. The lake is fed by the perennial Malewa and Gilgil rivers which collect runoff from the Nyandarua Mountains and their foothills to the North-East of the lake and discharge in a papyrus swamp forming part of the lake.

1.8.2 Olkaria Reservoir

The Olkaria geothermal reservoir is connected with the Olkaria volcanic centre. It is believed that the reservoir is enclosed by arcuate faults forming a ring or a caldera structure. The magmatic heat source is represented by intrusions at deep levels inside the ring structure. It is a two-phase liquid dominated zone, which is overlain by a thin steam dominated zone 100-200m thick at 240°C. This zone is wide in the South and reduces towards the North. A two-phase system of boiling water exists below the steam zone. There is a cap rock above the steam zone that marks the top of the reservoir and is composed of impermeable basalt and trachytes, which lie 400-700m below the surface. The major components of the reservoir rocks are mainly trachytic. The initial static water level in the reservoir varies but it is between 400m and 700m. The initial pressure and temperature distribution in the field increases northwards while hydrological gradient indicated that water movement was from North to South. This has been confirmed through drilling in the Northern parts of the field where bottom-hole temperature in most wells exceed 310°C (Ambusso and Ouma, 1991).

1.8.3 Lake Naivasha

Lake Naivasha is the only fresh water lake within the East African rift valley. Since there is no surface outlet to the basin, the quality of the lake is maintained by ground water flow. Multiple use of Lake Naivasha includes agricultural irrigation, domestic, municipal, wildlife and generating geothermal power. Olkaria geothermal power plant, located south of the lake generates about 12% of the country's electricity demand.

These geothermal wells are recharged with water from the lake (M'mbui, 1999). Past studies show that the lake evaporation is higher than the rainfall (Farah, 2001), so the lake solely depends on discharge from the basin. Therefore the changes in the upper areas of the basin greatly influence the lake waters quality and quantity.

The greatest threats to Lake Naivasha result from an increased water demand throughout the region. Basin altitude varies from 1900m at the bottom of the valley to 3200m in Nyandarua Mountains found on the Eastern boundary of the basin.

The annual temperature range of the lake is approximately from 8°C to 30°C (Farah, 2001). River Malewa is the major river that drains into the lake, contributing about 90% of the discharge within the basin. Gilgil and Karati rivers contribute the remaining 10% of discharge into the lake (Lukman, 2003).

CHAPTER TWO

2.0 LITERATURE REVIEW

Exploration for geothermal energy in Olkaria started in 1956 with the drilling of two geothermal wells sited within the area with extensive geothermal manifestations. A maximum temperature of 245°C at a depth of 940 m was recorded in one of the wells; however the well did not have significant discharge and produced low enthalpy at low wellhead pressures (Karingithi, 2002). The vertical extent of the reservoir has not been established but it is believed to be several hundred meters approximately (Bodvarsson and Pruess, 1984).

After geological and geochemical surveys carried out in 1970's, drilling of deep exploratory wells at Olkaria geothermal field started in 1973 aided financially by UNDP. Olkaria geothermal field is large in size hence it was found practical to segment Olkaria geothermal field into seven sectors so as to ease development. These seven sectors are; Olkaria North-East, Olkaria East, Olkaria South-East, Olkaria Central, Olkaria South West, Olkaria North-West and Olkaria Domes. A two-phase mixture of steam and water is produced by the Olkaria well reservoir in general proportions of 85% steam and 15% water and thus the resource is appropriate for generation of electrical power. Since exploitation commenced in Olkaria geothermal field, the power plants performance has been encouraging and that has lead to consideration of additional installations for the various sectors. Olkaria well reservoir has been monitored for thermodynamic and chemical changes as part of reservoir management and assessment. This has been achieved through geochemical sampling and regular output metering of the production wells. The data collected during the sampling survey was used to prepare the field bi-annual status reports on steam production.

It has been noted that the output from the production wells has been on the decline and this is confirmed with the predictions of the numerical simulation studies that were carried out for the Olkaria well reservoir (Bodvarsson and Pruess, 1981). To counter the decline in output of the wells, drilling and connection of make-up wells and in-field re-injection of effluent from the production wells has been implemented. In addition, routine down-hole temperature and pressure logs have been jointly carried out in production wells during well outages or plant shutdowns.

High steam demand has limited the availability of wells for down-hole logs thus inadequate data information has been availed on the changes in reservoir temperature and pressure across the seven fields. Nevertheless, from the available data, pressure decline is the most significant change in this field that has been observed over the last twenty-six (26) years of production. Incursion of cold fluid into the Olkaria well reservoir has been suspected as a result of the down-hole temperature and pressure logs that have been carried out in the field. These log results show that the central field wells and Western field wells of Olkaria East field are nearly dry while temperature inversion at the bottom has been indicated by those wells in the Southern part. Pressure drawdown which causes decline in production output from the wells has led to decline in steam supply for Olkaria I plant. The persistent pressure drawdown has caused severe fluid cyclicity in some of the wells in Olkaria East field (Ouma, 1992).

Steam decline has been observed within the Olkaria geothermal field at various regimes and the annual steam decline is from an initial of 5-6% decline to the current near zero. For the period between 1981 and 1988, the mean steam decline was approximately 5.5 % per annum (Ambusso and Karingithi, 1993), this decreased to about 4% per annum between 1988 and 1992 and less than 4% between 1993 and 1998 with some wells experiencing nearly no decline while others experiencing an increase (Ouma and Karingithi, 1998). In 1998, there was steam increase to about 4.6% (Ofwona and Wambugu, 1999) and a further steam increase of about 1% was experienced between 1999 and 2000 in the Olkaria East field (Kariuki and Opondo, 2001). The tendency of steam increase continued with a percentage of 3.7 increases observed in 2001. The Olkaria East field had constant steam available at approximately 707 t/hr between 2002 and 2004 (Karingithi and Mburu, 2005) except for the predicament with well OW-34 (Ofwona and Opondo, 2003). In general it has been observed that the Olkaria East field has a reduced rate in steam deliverability compared to what was predicted by the numerical simulation models. From 1992 to 2004, discharge enthalpy has increased in the centrally located wells in Olkaria East field to as high as 600kJ/kg. This has led to drying up of wells due to large reservoir pressure drawdown.

The Central field wells and the North-East field wells were monitored closely during this study so as to establish the incursion of the cold fluid into the reservoir which could be coming from the South-East into the reservoir.

2.1 Fluid Chemistry of Olkaria Geothermal Fields

The fluid chemistry of Olkaria fields have been continuously reported by earlier researchers, these are shown in reports from various personnel who include; Olkaria West (Kenya Power Company (KPC) 1984, 1990, Muna 1990, Wambugu 1995), Olkaria North-East (KPC 1988, Wambugu 1996), Olkaria East (KPC 1984, 1988, Karingithi 1992, 1993, 1996, Karingithi et al, 1997), Olkaria Domes (Karingithi, 1999). The fluid chemistry in Olkaria West field has sharp contrasts with that in the Olkaria East field and Olkaria North-East field. The Olkaria West field discharges fluids with high bicarbonate contents of about 10,000 ppm but low Chloride content of about 50-200 ppm. The Olkaria North-East field comparatively has a chemistry of bicarbonates-carbonate concentration of <1000 ppm and Chloride content of 400- 600 ppm. The Olkaria East field fluid discharges have similar bicarbonates-carbonate concentration of <200 ppm as those in the Olkaria North-East and lower Chloride concentrations of 200-350 ppm as compared to Olkaria North-East field concentrations. Olkaria Central wells give deep reservoir Chloride concentrations of 200-300 ppm except for well OW-201, which gives higher values of approximately 700 ppm.

These central field wells produce waters with relatively high reservoir CO₂ concentrations similar to those of Olkaria West field wells. Olkaria Domes wells discharge mixed sodium bicarbonate-chloride-sulphate type with low mean chloride concentrations of 181.5-269.9 ppm. Reservoir temperatures had been calculated using chemical geothermometers indicated that the K/Na ratio function by Arnorsson et al (1983) provide aquifer temperature values for the Olkaria East field ranging between 199-275°C with an average value of 230-260°C.

In the Olkaria North-East, the temperatures range between 215-302°C with an average value of 260-290°C. For the Olkaria West field, minimum temperatures values of 180-264°C were recorded with an average value of 230-260°C. This is quite similar to those recorded in the Olkaria East wells.

Reservoir temperatures calculated using the quartz geothermometry function by Fournier et al (1982) show Olkaria East wells give aquifer temperatures ranging from 172-272°C with an average value of 230-260°C. The Olkaria North East wells have values ranging from 195-304°C with an average value of 265-270°C whereas Olkaria Central field give values ranging from 186-259°C.

From the calculated aquifer temperatures, some wells indicate that high temperature values are associated with hot geothermal fluid up-flow and these wells are considered to be located within this up-flow zone, which is mainly within the Olkaria fault zone as indicated by Figure 1.3. Reduction in geothermometric temperatures is quite significant towards the fields' edges around wells OW-304D and OW-307 in Olkaria West field and towards wells OW-708, OW-704 and OW-724 in Olkaria North-East field. These wells were considered to mark the margins of the Olkaria geothermal system and definite recharge zones of the system.

2.2 Stable Isotopes

Samples for stable isotope studies for Naivasha area were first collected by Bwire and others between 1971 and 1972 so as to establish stable isotope relationship between rain water, rivers, lake and geothermal fluids of the Rift Valley region. Results from the analyzed data showed that fluids on the flanks of the Rift Valley had undergone depletion in stable isotopes. Lake waters and Olkaria geothermal fluids were enriched with respect to ^{18}O and ^2H isotopes. Initially collected data showed that there was a flow of water towards lake Naivasha with isotopic composition increasing towards the lake.

Due to the great evaporation potential, Bwire (1984) demonstrated that Lakes Elementaita and Nakuru which are salty water lakes are highly enriched in heavy isotopes as compared to Lake Naivasha which is a fresh water lake. Lakes Elementaita and Nakuru are discharge lakes with a closed drainage while Lake Naivasha is a recharge lake and provides a very effective tracer for axial groundwater movement. Stable isotope composition of representative Rift wall was given as $-28\text{‰ } \delta^2\text{H}$ and $-4.8\text{‰ } \delta^{18}\text{O}$ and typical Lake Naivasha composition as $+35\text{‰ } \delta^2\text{H}$ and $+6.6\text{‰ } \delta^{18}\text{O}$ by Clark et al.,(1990). The ground water composition sampled in this portion of the Rift is discussed in relation to unmodified rainwater or rainfall mixed with Lake Naivasha water.

The total fluid composition and steam condensates collected from fumarole discharges on Suswa, Longonot, Olkaria Domes and Eburru volcanoes plotted on a $\delta^{18}\text{O}$ and $\delta^2\text{H}$ graph, formed an elongate group parallel to the Rift Valley meteoric line covering a range of -1 to -15‰ $\delta^{18}\text{O}$ (Clark, et al., 1990).

The study demonstrated that most fumarole isotopes could be explained by production of steam from a mixing series between Rift wall meteoric water and evaporated water from Lake Naivasha. Olkaria is considered to be a part of this general hydrothermal system. A Southward flow from Lake Naivasha largely confined in width to the East Olkaria and Domes area had been established by Bwire in 1984.

A study carried out by Karingithi in the Olkaria geothermal field on ^2H and ^{18}O isotopes in Olkaria field water samples indicated that, though the samples lay close to the Kenya Rift Valley meteoric line, the fluid source for every individual field was different (Karingithi, 2002). Water samples taken from East of Ol Olbutot fault were enriched in both ^2H and ^{18}O relative to local precipitation. The samples plotted close to the meteoric water line implying that, the water evaporated before infiltrating into the bedrock of the geothermal system. This study was carried out in this study in order to compare the origin of the thermal waters and surface waters in the Olkaria geothermal area. From this study, the variation in δD was fairly big, between 5.5‰ in OW- 202 and 31.4‰ in Lake Naivasha; this was an indication that the samples did not originate from the same waters.

2.3 The Proposed Research

2.3.1 Problem Statement

According to the previous work, there is evidence that Olkaria geothermal power project experiences the challenges of wells collapsing and cold fluid incursion into the reservoir which subsequently hinders the rate of power production which is later experienced in the country's economy. Subsequently, the neighboring lake Naivasha also experiences variation in its static water level due to rainfall and suspected underground fluid outflow into the Olkaria reservoir. As a result, it was necessary to establish the relationship between the Reservoir and the neighbouring fluids so as to determine the effects of underground fluid flows.

2.3.2 Aim and Objectives

Main Objective

This study was carried out in order to establish the presence of cold fluid incursion into the Olkaria well reservoir, and the mixing trend between Olkaria wells fluids and the neighboring surface fluids in regard to well production. This was achieved through the investigation of flowpaths of the regional groundwater flow using stable isotope analysis.

Specific Objectives

1. Determine the origin and direction of fluid migration using isotopic composition of surface and well discharges.
2. Relate the chemical characteristics of Olkaria geothermal fluids and its neighborhood so as to determine their mixing pattern using fluid chemistry and fluid constituents.
3. Compare the variation in the prevailing Reservoir temperatures and neighboring fluids using chemical geothermometry.

2.3.3 Justification and Significance of Research

- Some of the Olkaria wells have been reported to dry up at some point; this could be due to the imbalance between the extraction rate and the natural replenishment rate and by the fact that some wells also reject the re-injected waters which results in the depletion of the reservoir.
- The East field and the Central field tend to exhibit surface geochemical characteristics unexpected of the subsurface geochemical characteristics.
- There is variation of the subsurface temperatures, in that some wells do produce cold fluids with very low temperatures and at times hot fluids with very high temperatures. This could be due to underground mixing between well fluids and surface fluids.

2.3.4 Output

- Hydrogeological investigations in the central sector of the Rift showed that faulting had significant effect on regional flows (Allen and Burges 1989). The faults act as conduits if they are permeable or they hinder lateral flow if they are of low permeability. The stable isotope analysis assisted in the determination of the direction of fluid migration within the study area.
- By relating the geochemical characteristics of the Olkaria fluids and the neighborhood, it was possible to infer the fluid compositional changes during the wet and dry season. Additional analysis of the trace elements like Cl, B and Li which when added to a fluid phase, the fluid remains unchanged allowing their origin to be traced to their source component.
- Geothermometry enables the estimation of Reservoir temperatures. The comparison between the reservoir temperatures and the surface temperatures indicated the inflow of cold and warm fluids into the reservoir.

CHAPTER THREE

3.0 METHODOLOGY AND RESULTS

The presence or absence of a geothermal resource and about the resource itself can be studied well by taking appropriate samples of fluids from surface springs, lakes, rivers, boreholes and well discharges (Wright 1991). Samples for the study in the Olkaria geothermal field and its neighborhood were thus collected from three fields of the seven geothermal fields from Olkaria, namely Central, East and North East fields, two boreholes one from Naivasha and the other from Longonot areas, two springs from Kijabe on the Eastern wall of the rift, and a sample each from River Malewa and Lake Naivasha. The various results of the study were obtained in the following areas:

- Reservoir fluid types: Various fluid types evolve from distinctive geothermal systems and discovery of the fluid type helped understand the important implications on the existence of other fluid types in the vicinity of the geothermal resource and thus facilitated exploration.
- Reservoir fluid processes: These processes assisted in the determination of the extent of mixing of thermal and non- thermal waters and boiling aspects in the sub-surface.
- Well Production monitoring: In a producing geothermal resource, monitoring of the concentrations of the chemical species over a period offered substantial information on the nature of the recharge to the system and to the prediction of adverse temperature changes prior to their manifestation in the well.
- Geothermometry: With the use of chemical data from the geothermal resource area, maximum subsurface fluid temperatures were estimated in the study area.

3.1 Sample Collection

The Olkaria geothermal field has been subdivided into seven sectors; these are Olkaria East, Olkaria South-East, Olkaria North-East, Olkaria North-West, Olkaria South- West, Olkaria Central, and Olkaria Domes as shown in Figure 3.1.

Water samples were collected using the simple random sampling method from 16 wells of three fields of the seven geothermal fields from Olkaria, namely Central, East and North East fields, two boreholes one from Naivasha and the other from Longonot areas, two springs from Kijabe on the Eastern wall of the rift, and a sample each from River Malewa and Lake Naivasha. This took place between October, 2011 and April, 2012.

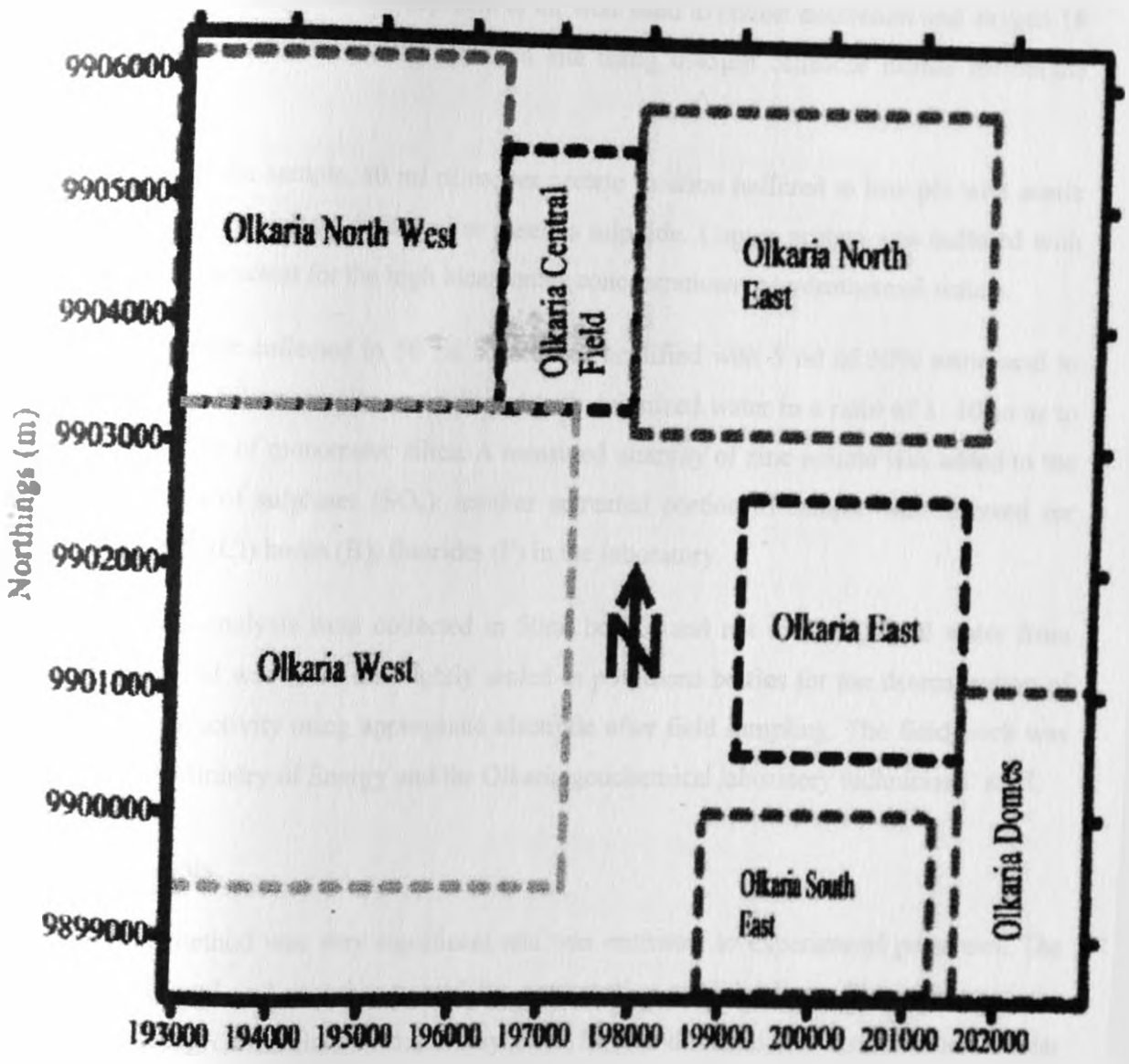


Figure 3.1: Geothermal fields in the Olkaria geothermal area (after Opondo, 2009)

From the wells water samples were collected from weirboxes at atmospheric pressure while where the separated water was unavailable in the weirbox due to reinjection, samples were collected from the valve near the wellhead and the sampling pressure recorded. From the springs, boreholes, lake and river, water samples were collected using a collecting jar and kept in the sampling bottles. Isotope sampling was a challenge due to inadequate facilities and limited experience, thus an alternative method was used. Thirty milliliters McCartney bottles with neoprene lined caps that prevent entrapment of air were used to collect deuterium and oxygen 18 water samples. The samples were filtered on site using 0.45µm cellulose nitrate membrane filters.

For a litre bottle of the sample, 80 ml of copper acetate solution buffered to low pH with acetic acid were added to precipitate dissolved or gaseous sulphide. Copper acetate was buffered with extra acetic acid to account for the high bicarbonate concentrations in hydrothermal waters.

Cations samples were collected in 50 ml bottles and acidified with 5 ml of 50% nitric acid to avoid precipitation. Silica samples were diluted with deionized water in a ratio of 1: 10 so as to avoid polymerization of monomeric silica. A measured quantity of zinc acetate was added to the sample for fixation of sulphates (SO₄); another untreated portion of sample was reserved for analysis of chloride (Cl) boron (B), fluorides (F) in the laboratory.

Samples for anion analysis were collected in 50ml bottles and not treated. 50 ml water from every sampling point was taken and tightly sealed in polythene bottles for the determination of pH, TDS and conductivity using appropriate electrode after field sampling. The field work was facilitated by the Ministry of Energy and the Olkaria geochemical laboratory technicians' staff.

3.2 Sample Analysis

Proper sampling method was very significant and was entrusted to experienced personnel. The samples were filtered and properly treated for preservation until analysis. This prevented the samples from being contaminated which may have further distorted the results. The sampler designed a sampling program with a chemist at the laboratory where the analysis was performed; this was to ensure that the sample analysis was done on time before the collected samples expired (Wright 1991).

Fluid sampling was repeated at intervals of hours for accuracy and precision purposes. The water samples collected were taken to Olkaria geochemical laboratory for full chemical analysis with the assistance of the laboratory staff. Electrical conductivity and TDS of the discharge were measured using a portable TDS/conductivity meter, pH by a pH meter and surface temperature by a thermistor. The different chemical analytical methods adopted for the collected samples were as listed in Table 3.1.

TABLE 3.1: Chemical analytical methods that were used for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

Composition	Method of Analysis
K	Atomic absorption spectrometry
Na	Atomic absorption spectrometry
Ca	Atomic absorption spectrometry
Mg	Atomic absorption spectrometry
Li	Atomic absorption spectrometry
SiO ₂	Spectrophotometry
SO ₄	Ion Chromatography
CO ₂	Titration
H ₂ S	Titration
Cl	Ion Chromatography
F	Ion selective method
B	Spectrophotometry
¹⁸ O	Mass spectrometry
D	Mass spectrometry

3.3 Analytical Results

Sample analysis was done in reference to various standards of the reagents marked by the Olkaria geochemical laboratory. The standards assisted in the estimation of error margins of the samples. Mercury acetate used in titration had a reference standard of 9.57g/kg; the atomic absorption spectrophotometer was standardized between a range of 110ppm. With the use of the various analytical methods mentioned (Table 3.1), the results of the physical parameters, chemical analysis and the isotopic composition of water samples from the geothermal wells, neighboring boreholes, springs, river and lake in the study area are presented in Tables 3.2, 3.3 and 3.4 respectively.

TABLE 3.2: Physical parameters of the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

Sample Name	Easting (m)	Northing (m)	Elevation (m.a.s.l)	Temp (°C)	PH	Cond (µS)	TDS (ppm)
OW -2	200080	9901150	1941	93.0	9.10	3201	1590
OW- 6	200390	9901040	1930	97.0	9.10	2480	1230
OW -15	200610	9901300	1926	95.0	8.50	3815	1902
OW-22	201110	9901136	1924	83.4	9.56	2326	1167
OW-23	201118	9901665	1942	83.0	9.58	1933	970
OW-26	201125	9902432	2006	95.0	9.31	2087	1043
OW-202	196530	9903784	2026	65.0	9.30	4287	2150
OW-204	196528	9903762	2022	68.0	8.25	3860	1920
OW-710	198530	9904319	2079	90.0	9.60	3258	1610
OW-712	198885	9904321	2081	87.0	9.72	2990	1487
OW-715	199451	9904454	2011	85.0	8.97	4870	2430
OW-716	200753	9904719	2169	92.0	8.77	5170	2590
OW-719	199646	9903813	2044	92.0	9.50	4305	2160
OW-721	198757	9903381	2163	75.0	10.0	2688	1344
OW-725	200253	9904223	2137	90.0	9.65	3945	1990
OW-727	200259	9904230	2140	93.1	8.54	4025	2010
KHS	-	-	-	37.8	8.99	274.4	137.0
KS	-	-	-	18.9	7.81	252.5	126.3
LB	-	-	-	56.9	6.29	855.0	423.0
LN	-	-	-	19.0	7.86	292.4	146.2
NB	-	-	-	28.6	7.47	420.7	209.0
RM	-	-	-	18.7	7.24	137.2	68.6

The total dissolved solids in geothermal fluids are dependent on temperature and the local geology. Lower temperature resources usually have smaller amounts of dissolved solids than do higher temperature resources although there are exceptions to this rule. Many of the high temperature resources contain from 6000 to 10,000 ppm TDS (Wright 1991).

From the Table 3.2 above, the fluids from the three fields sampled for this study in Olkaria geothermal field and its neighborhoods had the highest TDS content of 2590 ppm recorded in OW- 716 in the North-East field and the lowest was 970 ppm recorded in OW- 23 in the Olkaria East field. The surface waters had the highest TDS of 423 ppm recorded at Longonot borehole and the lowest was 68.6 ppm recorded at River Malewa.

The pH of geothermal resources ranges from moderately alkaline to acidic in a range of 8.5-5.5 (Wright 1991). The pH range from the sampled fluids range from 6.29 recorded in Longonot borehole to 10.0 in OW- 721 of the North-East field. The high pH values in the wells were attributed to the fact that since the measurements were made at ambient temperatures the acidic gases H₂S and CO₂ were lost on cooling of the samples. Moreover, where amorphous silica is over-saturated in waters, unionized aqueous in excess of saturation tends to polymerize and polymerization causes the removal of unionized silica (weak acid) from solution which tends to raise the pH value (Karingithi 2000). This contributed to the high pH values.

The lowest temperature recorded was 18.7°C at River Malewa and the highest was 97.0°C at OW- 6 in the East field.

TABLE 3.3: Analytical results for major chemical components of the selected Olkaria geothermal waters and its neighborhood (Naivasha area) (ppm)

Sample	Li	Na	K	Ca	Mg	SiO ₂	CO ₃	H ₂ S	B	F	Cl	SO ₄
OW-2	0.93	625	100.00	0.71	0.018	813	11.8	2.0	10.000	78.0	935	18.0
OW-6	1.07	430	75.00	0.45	0.044	675	9.8	4.0	6.000	54.0	610	29.0
OW-15	1.69	530	105.00	1.67	0.040	795	14.4	2.0	10.000	52.0	880	43.0
OW-22	0.61	407	56.00	0.49	0.015	631	163.8	24.0	1.000	155.0	228	10.0
OW-23	0.73	324	54.00	0.90	0.051	229	23.2	8.0	2.000	175.0	257	9.0
OW-26	0.70	195	29.00	0.28	0.088	239	53.1	3.1	1.000	72.0	164	29.0
OW-202	3.00	743	128.00	0.79	0.040	320	1485	2.4	2.500	53.4	354	75.7
OW-204	2.85	709	110.10	0.67	0.038	308	1240	2.1	2.150	50.3	302	68.1
OW-710	1.41	448	98.00	0.58	0.017	396	269.0	7.1	1.700	40.0	517	22.0
OW-712	1.69	510	82.00	0.47	0.012	796	278.6	5.5	4.400	46.0	590	63.0
OW-715	1.51	557	108.00	0.88	0.056	739	310.6	3.6	3.630	66.4	682	35.2
OW-716	1.67	535	110.00	0.20	0.330	438	25.9	1.3	6.900	28.0	797	90.0
OW-719	1.02	540	87.00	1.09	0.042	753	327.8	50.0	3.300	46.0	507	39.0
OW-721	1.14	550	77.00	0.35	0.010	845	235.8	32.0	3.000	62.0	468	71.0
OW-725	1.77	500	88.00	0.43	0.010	677	276.3	18.0	5.000	58.0	588	34.0
OW-727	1.58	473	67.00	0.39	0.012	818	111.6	45.0	4.200	37.0	576	77.0
KHS	0.04	78	0.12	0.58	0.178	47	193.1	45.0	0.074	3.5	9.0	3.1
KS	0.09	62	7.13	11.34	2.985	53	198.6	43.0	0.062	1.1	11.4	13.7
LB	0.01	174	27.01	32.15	6.087	152	530.9	2.0	0.078	3.8	29.6	17.8
LN	0.08	24	14.24	12.69	3.467	25	120.8	3.1	0.256	1.7	13.9	1.0
NB	0.08	280	35.15	35.43	3.005	81	591.8	2.0	0.226	8.6	110	74.5
RM	0.08	152	2.16	25.75	2.234	27	520.3	1.0	0.111	0.5	8.0	0.7

From the fluid chemistry results for the samples presented in Table 3.3 above, the main dissolved solids are Na, K, SiO₂, Cl and HCO₃. Sodium concentration of a high 743 ppm was recorded in OW- 202 in Olkaria Central field and a low of 24 ppm in Longonot borehole. Similarly, potassium recorded the highest concentration of 128 ppm in Central Olkaria field while the lowest concentration of 0.121 ppm was in the Kijabe hot spring.

High silica content of 845 ppm was recorded in OW- 721 in Olkaria North-East field and a low of 25 ppm in Longonot borehole. Chloride was high in OW- 2 of the East field with a concentration of 935 ppm and a low of 8.04 ppm in River Malewa. OW- 202 in the Central field had the highest bicarbonate concentration of 1485.20 ppm while OW- 6 of the East field had the lowest concentration of 9.80ppm.

Sample ID	Na (ppm)	K (ppm)	SiO ₂ (ppm)	Cl (ppm)	HCO ₃ (ppm)
OW- 202	743	128	845	935	1485.20
Longonot borehole	24	0.121	25	8.04	9.80
OW- 721			845		
OW- 2				935	
River Malewa				8.04	
OW- 6				9.80	

TABLE 3.4: Enthalpy and Isotopic composition of the selected Olkaria geothermal waters

Sample Name	Enthalpy (kJ/Kg)	ΔD_{SMOW} (‰)	$\Delta^{18}O_{SMOW}$ (‰)
OW-2	2168	18.7	3.02
OW-6	2383	22.0	4.60
OW-15	2634	19.7	4.37
OW-22	2169	20.3	4.05
OW-23	2150	21.7	4.59
OW-26	1856	27.4	3.81
OW-202	1104	5.50	0.21
OW-204	920	5.80	0.52
OW-710	1082	28.6	4.18
OW-712	2036	30.6	4.53
OW-715	940	20.4	3.71
OW-716	2645	23.7	3.09
OW-719	1259	22.3	3.43
OW-721	1706	22.0	3.40
OW-725	1380	24.2	3.72
OW-727	1720	26.7	3.80
LN	—	31.4	1.95

CHAPTER FOUR

4.0 GEOCHEMICAL INTERPRETATION AND DISCUSSION

4.1 Ionic Charge Balance

For the purposes of determination of accuracy and precision of the analytical results, the ionic charge balance was calculated for the samples from the study area. The ion balance or the charge balance of a solution is used to check on the comprehensiveness and accuracy of an analysis and takes into account charged species. The check is dependent on major charged species like Na, K, and Cl, SO₄ and HCO₃ and errors of uncharged species like SiO₂, NH₃ and B are not indicated by the ionic balance. Ideally the sum of the cations must be equal to the sum of anions in any sample. This should range between -10% to +10% for a well analyzed sample. The charge unbalance in percentage deviation (% DEV) is calculated using the following equation:-

$$\% \text{ DEV} = \{[\text{SUM ANION} + \text{SUM CATION}] / [(\text{SUM ANION} + \text{SUM CATION})/2]\} \times 100 \dots (1)$$

The ionic charge balance for the collected samples was calculated using the WATCH Speciation Program and the results of charge balance calculations are presented in Table 4.1.

TABLE 4.1: Ionic Charge Balance for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

Sample Name	Sum Cations	Sum Anions	Charge Balance
OW-2	29.92	31.05	-2%
OW-6	20.8	20.82	0%
OW-15	26.07	28.69	-5%
OW-22	19.25	17.48	5%
OW-23	15.63	17.03	-4%
OW-26	9.35	9.89	-3%
OW-202	36.07	38.7	-4%
OW-204	34.11	32.91	2%
OW-710	22.23	21.56	2%
OW-712	24.55	24.94	-1%
OW-715	27.26	28.56	-2%
OW-716	26.36	26.26	0%
OW-719	25.92	22.91	6%
OW-721	26.08	21.81	9%
OW-725	24.28	24.88	-1%
OW-727	22.54	21.63	2%
KHS	3.45	3.67	-3%
KS	3.7	3.92	-3%
LB	10.37	10.11	1%
LN	2.34	2.49	-3%
NB	15.11	14.81	1%
RM	8.17	8.8	-4%

From the collected fluid samples in Table 4.1 above, ionic charge balance ranges between -4% to +9% with the lowest indicated by the surface water sample and the highest indicated by the well water sample. This was due to loss of volatiles through the container walls or through the cap seal caused by cooling geothermal well samples and the long storage before analysis. The standard deviation from the surface water samples were indications of surface water mixing which was experienced in some wells.

4.2 Fluid Chemistry

4.2.1 Classification of thermal waters

The geochemical characteristics of thermal water depend not only on the characteristics of deep-seated geothermal water, but also on the Lithology of the geothermal reservoir, movement of thermal water and replenishment of cold water. The persistence of groundwater in the reservoir for a long period changes the intrinsic chemical characteristics of the geothermal water. This is experienced as a result of interaction between the groundwater and the country rocks. The water chemistry was used to determine subsurface temperatures as well as boiling and mixing relationships during the study (Tonani 1980). The chemical composition of the thermal fluids was used to identify the nature of the geothermal system. The samples collected from the Olkaria geothermal field and its neighborhood were thus classified using the various ternary diagrams described below.

4.2.2 Cl-SO₄-HCO₃ triangular diagram

In order to classify the Olkaria thermal waters and the neighboring fluids, the Cl-SO₄-HCO₃ triangular diagram (Giggenbach, 1991) was used. This diagram was used to discern immature unstable waters and give an initial indication of mixing relationships or geographical groupings. The diagram showed several types of thermal waters (including immature waters, peripheral waters, volcanic waters and steam heated waters). It gave a preliminary statistical evaluation of groupings and trends. The position of a sample point was ascertained by obtaining the sum (S) of the concentrations (C) of the three constituents considered (Giggenbach, 1991):

$$S=C_{Cl} + C_{SO4} + C_{HCO3} \dots\dots\dots (2)$$

And then calculating the % of the three anions (Cl, SO₄ and HCO₃):

$$Cl (\%) = 100C_{Cl}/S; \quad SO_4 (\%) = 100C_{SO_4}/S; \quad HCO_3 (\%) = 100C_{HCO_3}/S \dots \dots \dots (3)$$

The relative concentration of Cl, SO₄ and HCO₃ of the discharge from Olkaria wells and surface and near surface samples collected from Naivasha and walls of the rift near Kijabe are plotted in Figure 4.1.

Cl-SO₄-HCO₃ Ternary diagram for selected wells

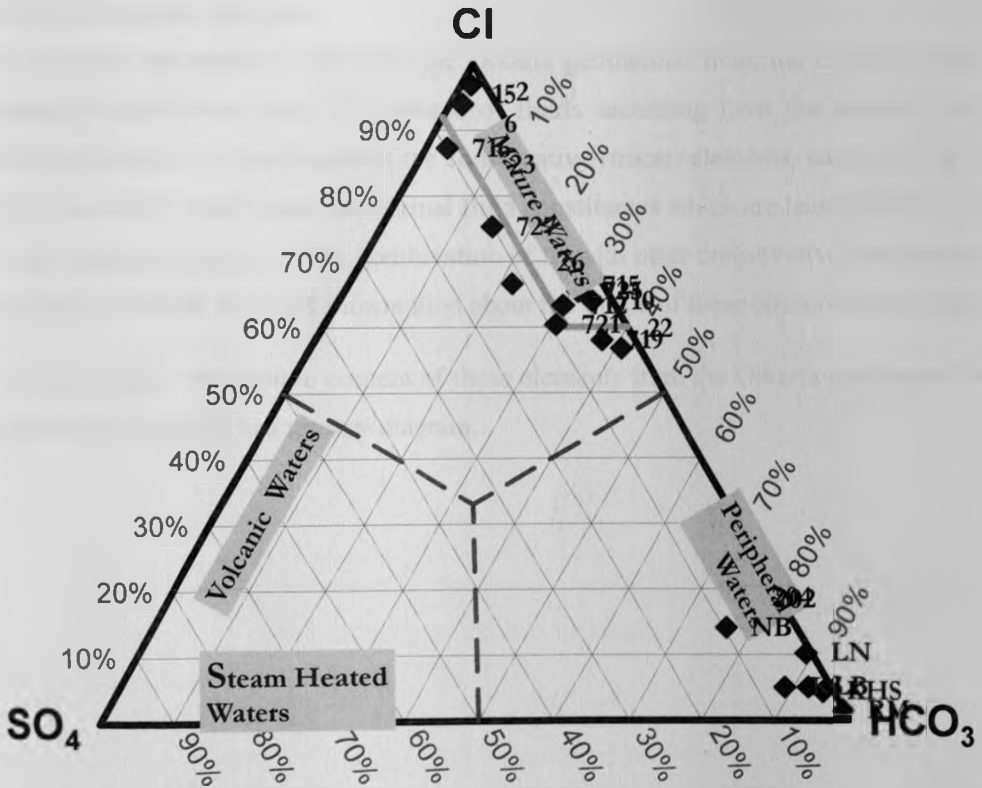


Figure 4.1: Cl-SO₄-HCO₃ Ternary diagram for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

From the above Figure 4.1, eight samples were positioned in the mature water region while another eight samples were in the peripheral water region. The geothermal wells plotted on the mature region except for two wells, OW-202 and OW-204 which lay in the HCO_3 apex or in the peripheral region same as the near surface and surface waters. These two wells recorded the highest HCO_3 concentrations accompanied by low chloride concentrations. This made them poor candidates for geothermometry.

4.2.3 Cl- B- Li triangular diagram

In order to ascertain the source of fluids in the Olkaria geothermal field, the Chloride- Boron- Lithium ternary diagram was used. The source of fluids ascending from the reservoir to the surface was determined from the aspect of the conservative (tracer) elements, namely, Cl, B and Li. Cl, B and the alkali metal Li are the thermal fluid constituents which are least affected by the shallow water transport processes. The combination of Li with other conservative constituents of the thermal fluid, Cl and B provided information about the origin of these conservative elements.

Figure 4.2 below shows the relative content of these elements from the Olkaria geothermal field and its neighborhood plotted in a ternary diagram.

Cl-Li-B Ternary diagram

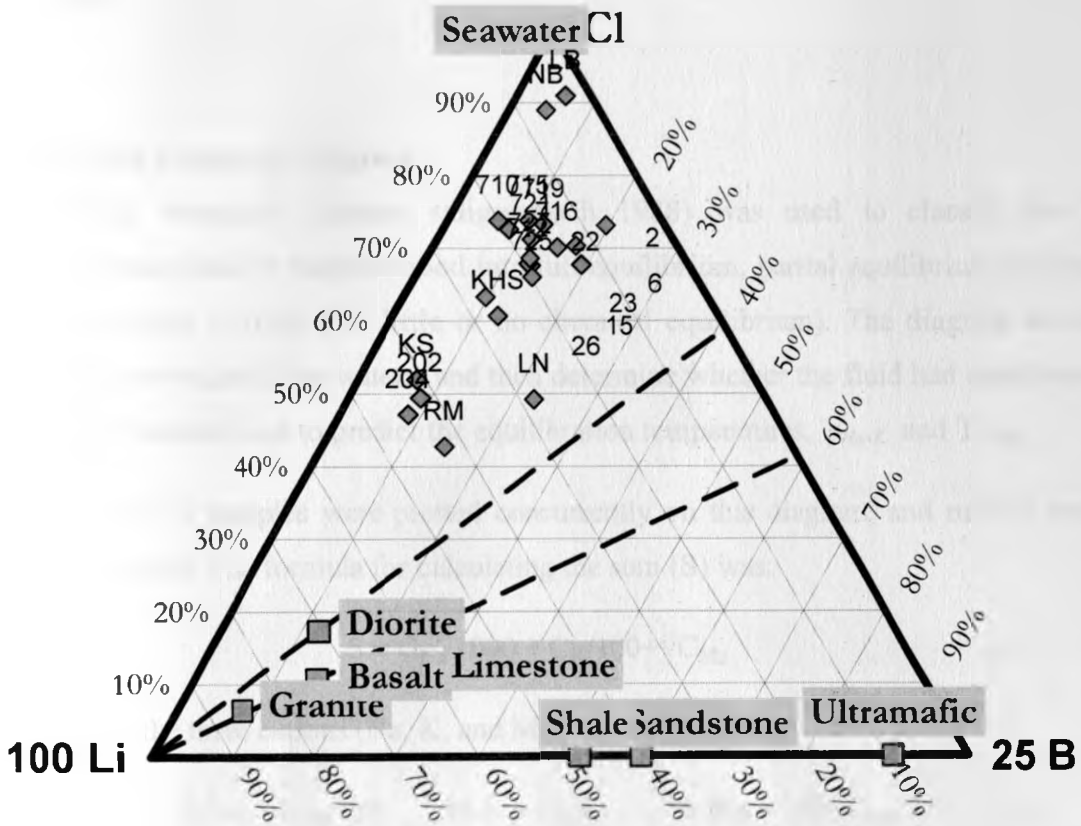


Figure 4.2: Cl- Li-B Ternary diagram for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

From the Cl, B, Li ternary diagram in Figure 4.2 above, the surface waters appeared scattered and mixed with the well waters. Four cold samples, namely, LN, OW-202, OW-204 and RM and one warm sample KS plotted close to the composition of crustal rocks. It seemed that their composition was derived from simple rock leaching process. Samples, OW-26, OW-710 and KHS plotted in the region of absorption of low B/Cl steam. These samples were relatively high in B and Cl and belong to a mature geothermal system. Samples OW-2, OW-6, OW-23, and OW-15 seemed to have absorbed high B/Cl steam.

These samples were considered as fairly young compared to the samples in the older hydrothermal system region. Most of the fluid discharges plotted in the older hydrothermal system region.

4.2.4 Na-K-Mg triangular diagram

The Na-K-Mg triangular diagram (Giggenbach 1988) was used to classify the Olkaria geothermal waters and its neighborhood into full equilibrium, partial equilibrium and immature waters (dissolution of rock with little or no chemical equilibrium). The diagram was used to better clarify the origin of the waters, and then determine whether the fluid had equilibrated with hydrothermal minerals and to predict the equilibration temperatures, T_{Na-K} and T_{K-Mg} .

A large number of samples were plotted concurrently on this diagram, and mixing trends and grouping predicted. The formula for calculating the sum (S) was:

$$S = C_{Na}/1000 + C_K/100 + \sqrt{C_{Mg}} \dots \dots \dots (4)$$

Then the % of the three cations (Na, K, and Mg) was calculated as;

$$\% Na = C_{Na}/10S; \quad \% K = C_K/S; \quad \% Mg = 100\sqrt{C_{Mg}}/S. \dots \dots (5)$$

where C is concentration in mg/l.

Well discharges, surface and near surface waters were plotted in this diagram as shown in Figure 4.3. The diagram determined which waters were suitable for use in geothermometry by the position on which the fluids plotted on the ternary diagram.

Na-K-Mg Ternary diagram

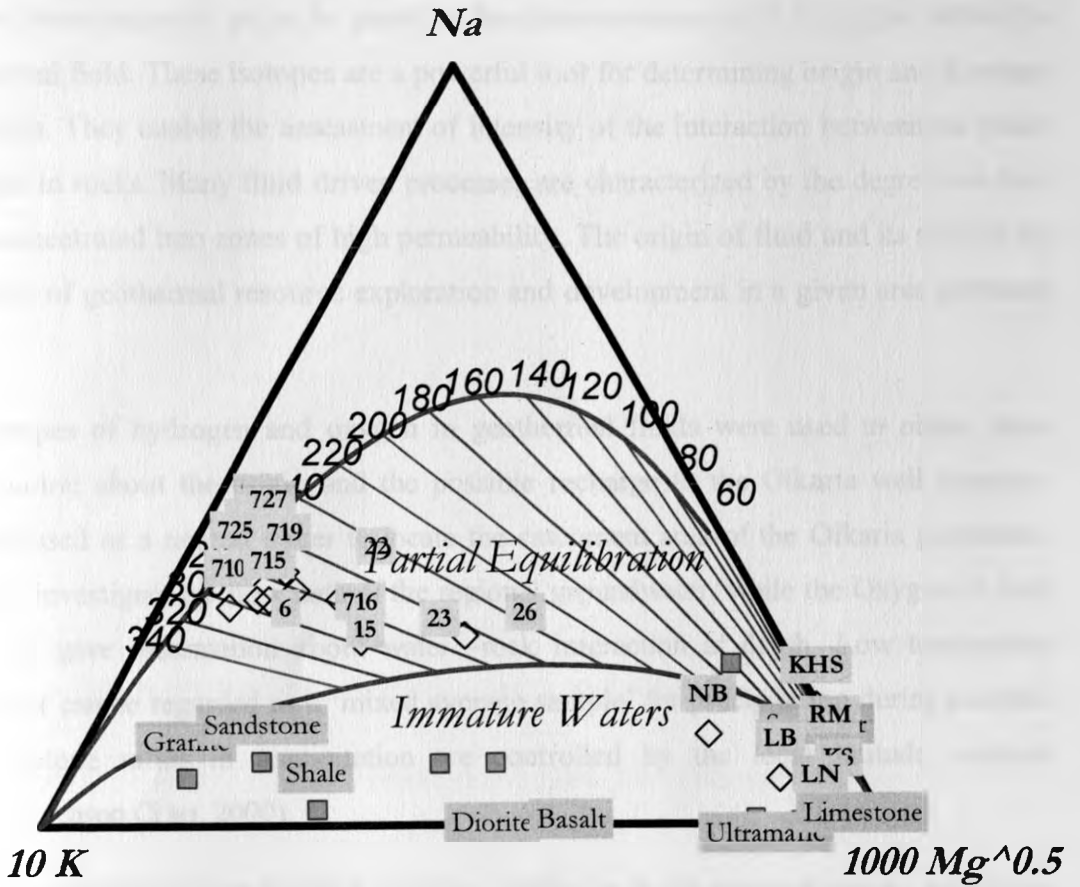


Figure 4.3: Na-K-Mg Ternary diagram for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

From the Na-K-Mg ternary diagram in Figure 4.3, the geothermal waters plotted in the fully equilibrated and the partially equilibrated regions or mixed waters. This was an indication that the waters could be safely used for geothermometry calculations. The East field wells plotted in the partially equilibrated region together with OW- 716 and Kijabe hot spring. The surface and near surface waters plotted in the immature water sector, this meant that the waters had not attained equilibrium with the host rocks.

4.3 ORIGIN OF THE FLUIDS

4.3.1 Isotopic Composition

Stable isotopes were analyzed so as to assist in the determination of fluid origin within the Olkaria geothermal field. These isotopes are a powerful tool for determining origin and direction of fluid migration. They enable the assessment of intensity of the interaction between the fluids and the minerals in rocks. Many fluid driven processes are characterized by the degree to which fluid flow is concentrated into zones of high permeability. The origin of fluid and its salinity are fundamental part of geothermal resource exploration and development in a given area (Arnason 1976).

The stable isotopes of hydrogen and oxygen in geothermal fluids were used to obtain more reliable information about the origin and the possible recharge to the Olkaria well reservoir. Deuterium was used as a natural tracer to locate the catchment area of the Olkaria geothermal reservoir and to investigate the flow path of the regional groundwater, while the Oxygen-18 shift for each system gave information about water –rock interaction at depth. Low temperature geothermal water can be regarded as a ‘mixed average sample’ for precipitation during a certain period. The isotope ratios in precipitation are controlled by the local latitude, altitude, temperature and season (Yao, 2000).

The Global Meteoric Water Line (GMWL) (Craig, 1996) plot is the standard way to depict data on stable isotopes from water in a given area. It is defined by the equation $\delta D = 8 \times \delta^{18}O + 10$. Sample fluids for stable isotopes in the Olkaria geothermal field and its neighborhood are plotted in the isotopic concentration plot diagram as shown in Figure 4.4.

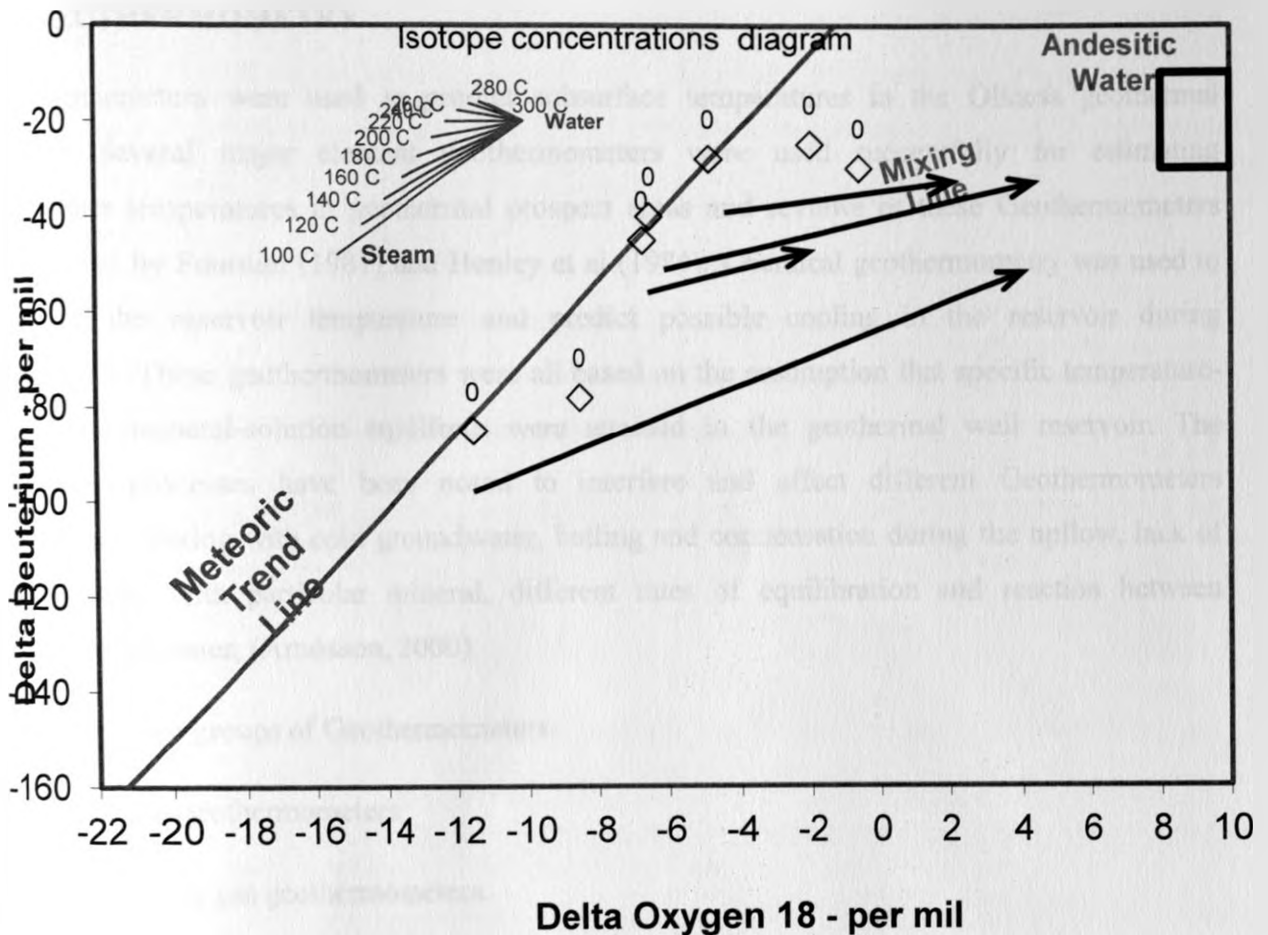


Figure 4.4: Isotopic Concentration Plot for the Olkaria geothermal waters and its neighborhood (Naivasha area)

From the Isotopic Concentration plot in Figure 4.4 above, the samples plotted close to the Kenya Rift Valley meteoric line (Kenya rain line- Clarke et al., 1990). The variation in δD was fairly big, between 5.5‰ in OW- 202 and 31.4‰ in Lake Naivasha; this was an indication that the samples did not originate from the same waters. The $\delta^{18}O$ varied between 0.21‰ in OW- 202 and 4.60‰ in OW- 6. Most of the samples showed negative $\delta^{18}O$ shift, this was due to the interaction with CO_2 enriched in ^{16}O . The negative shift was as a result of mixing between cold water and thermal waters.

4.4 GEOTHERMOMETRY

Geothermometers were used to predict subsurface temperatures in the Olkaria geothermal system. Several major element geothermometers were used successfully for estimating subsurface temperatures in geothermal prospect areas and reviews of these Geothermometers were given by Fournier (1981) and Henley et al (1984). Chemical geothermometry was used to evaluate the reservoir temperature and predict possible cooling in the reservoir during production. These geothermometers were all based on the assumption that specific temperature-dependent mineral-solution equilibria were attained in the geothermal well reservoir. The following processes have been noted to interfere and affect different Geothermometers differently: mixing with cold groundwater, boiling and condensation during the upflow, lack of equilibration with particular mineral, different rates of equilibration and reaction between minerals and water, (Arnósson, 2000).

There are three groups of Geothermometers:

- Solute geothermometers
- Steam or gas geothermometers
- Isotope geothermometers.

The reliability and accuracy of geothermometers at high or low temperatures is a function of the temperature dependence of the reactions and the rate of the reaction at different temperatures. In effect, silica temperature is more reliable at low temperatures than Na-K temperature hence different geothermometers are applied in different geothermal areas (Arnósson 1975).

4.4.1 Silica Geothermometers

The silica geothermometer was based on the solubility of Quartz and was used to estimate subsurface temperatures in the Olkaria geothermal system. Temperature calculation using silica geothermometers was based on the fact that the concentration of silica in water solutions was determined by the solubility of silica at the temperature of water-rock interaction (Fournier and Rowe 1966). Since precipitation reduces with decrease in temperature, the silica concentration value found in surface water is a good estimation of the subsurface reservoir temperature.

Different mathematical equations have been suggested for the approximation of this functional dependence, obtained on the basis of mathematical processing of laboratory experimental data, data on measurements of temperature and silica concentrations in water from wells in various geothermal systems.

The high solubility of quartz at high temperatures has been used extensively as an indicator of geothermal temperatures (Fournier and Potter, 1982). In areas where systems have temperatures above 180-190°C, quartz equilibration has controlled the silica concentration, whereas at lower temperatures, chalcedony controls the concentration phase.

Temperature values can be derived from the following relationships for equilibrium with these silica polymorphs from 0-250°C:

Quartz temperature (Fournier and Potter, 1982);

$$T^{\circ}\text{C} = -42.198 + 0.28831\text{SiO}_2 - 3.6686 \times 10^{-7}\text{SiO}_2^3 + 77.034\log\text{SiO}_2 \dots (6)$$

Quartz- no steam loss (Fournier, 1977);

$$T^{\circ}\text{C} = \frac{1309}{5.19 - \log\text{SiO}_2} - 273.15 \dots (7)$$

Quartz -max steam loss at 100°C (Fournier, 1977);

$$T^{\circ}\text{C} = \frac{1522}{5.75 - \log \text{SiO}_2} - 273.15 \dots (8)$$

Where SiO₂ concentrations are in ppm.

4.4.2 Cations Geothermometer

The Sodium (Na)-Potassium (K)-Calcium (Ca) geothermometer was developed by (Fournier and Truesdell 1973), using an empirical relation between relative concentrations of these elements in surface water and deep reservoir fluids. The assumption that the Base Exchange reaction was at a temperatures of above 100°C was applied. The silicate reactions and the amounts of dissolved Na and K were thus influenced by the dissolved Ca, even though the final amount of aqueous Calcium may be controlled largely by carbonate and carbon dioxide solubility (Nicholson, 1988).

The Na-K-Ca geothermometer was calculated using the temperature formula in the following equation,

Na-K-Ca temperature (Fournier and Truesdell, 1973):

$$T^{\circ}\text{C} = \frac{1647}{\text{Log}(C_{\text{Na}}/C_{\text{K}}) + \mu (\log(\sqrt{C_{\text{Ca}}/C_{\text{Na}}}) + 2.06) + 2.47} - 273.15 \dots \dots \dots (9)$$

Where;

$C_{\text{Na}}, C_{\text{K}}, C_{\text{Ca}}$ are concentrations of sodium, potassium, and calcium Cations, expressed in mole/l,

μ is a coefficient with the following values:

$$\mu = 1/3, \text{ if the value of } (\mu \log(\sqrt{C_{\text{Ca}}/C_{\text{Na}}}) + 2.0) \text{ is negative, or } T > 100^{\circ}\text{C}. \dots \dots (10)$$

$$\mu = 4/3, \text{ if the value of } (\mu \log(\sqrt{C_{\text{Ca}}/C_{\text{Na}}}) + 2.0) \text{ is positive, or } T < 100^{\circ}\text{C}. \dots \dots (11)$$

The Na-K geothermometer is dependent on theoretical thermodynamic considerations. It provides information on the thermal history of the geothermal fluid during an extended period of upflow. The Quartz geothermometer responds fairly fast to changes in temperatures. The Na-K geothermometer, on the other hand, is much slower to respond and often keeps a record of old temperatures. Many Na-K temperature functions have been presented by different authors. The following mathematical equations are some of the applied formulae. The concentrations of *Na* and *K* are in ppm.

Na-K temperature (Arnórsson et al., 1983):

$$T^{\circ}\text{C} = \frac{933}{0.993 - \log(\text{Na/K})} - 273.15 \dots (12)$$

Na-K temperature (Giggenbach, 1988):

$$T^{\circ}\text{C} = \frac{1390}{1.75 - \log(\text{Na/K})} - 273.15 \dots (13)$$

Na-K temperature (Truesdell, 1976):

$$T^{\circ}\text{C} = \frac{856}{0.857 - \log(\text{Na/K})} - 273.15 \dots (14)$$

Na-K temperature (Tonani, 1980):

$$T^{\circ}\text{C} = \frac{833}{0.780 - \log(\text{Na/K})} - 273.15 \dots (15)$$

The K-Mg geothermometer responds much faster to a change in temperature, so it was used to estimate the most recent temperature in a geothermal well reservoir. It was based on the equilibrium between water and the mineral assemblage K-feldspar, K-mica and chlorite in rock.

K-Mg temperature (Giggenbach, 1988):

$$T^{\circ}\text{C} = \frac{4410}{14.0 - \log(K^2/\text{Mg})} - 273.15 \dots \dots \dots (16)$$

In addition to the Na-K, K-Mg and Na-K-Ca geothermometers, the ratios Li/Mg and Li/Na and the $^{34}\text{S}/^{32}\text{S}$ isotopes are among those that have been applied as geothermometers to geothermal waters.

The geothermometer results calculated using the WATCH Speciation program (Arnórsson et al., 1982, 1983; Bjarnason, 1994) for the thermal waters in the Olkaria geothermal field and its neighborhood were presented in Table 4.2.

TABLE 4.2: Geothermometers for the selected Olkaria geothermal waters and its neighborhood (Naivasha area) (Temperatures in °C)

Sample Name	Quartz cond	Quartz adiabatic	Na-K-Ca	Na-K-Ca- Mg corr	Na/K Fournier	Na/K Truesdell	Na/K (Giggenbach)	K/Mg (Giggenbach)
OW-2	344	263	277	276	261	244	273	264
OW-6	301	248	280	279	270	256	281	226
OW-15	338	261	278	278	284	275	293	245
OW-22	289	243	259	258	246	225	259	238
OW-23	190	176	260	260	265	250	277	207
OW-26	193	178	253	253	254	235	266	169
OW-202	216	196	286	286	269	255	280	256
OW-204	213	194	278	278	258	240	270	249
OW-710	234	210	296	296	295	291	304	265
OW-712	338	261	277	277	261	245	273	265
OW-715	319	255	286	286	281	272	291	238
OW-716	244	216	311	311	288	281	297	197
OW-719	324	257	268	268	262	245	273	234
OW-721	356	266	272	272	248	227	261	266
OW-725	301	248	285	285	271	258	282	274
OW-727	346	263	267	267	249	228	262	253
KHS	99	100	35	-49	10	-40	32	20
KS	105	105	95	-36	229	203	244	74
LB	162	153	202	24	258	240	270	98
LN	72	77	257	2	439	516	430	89
NB	126	123	197	118	237	213	251	116
RM	76	79	61	61	111	64	132	58

From the geothermometer results in Table 4.2 above, comparison was done between the Na/K (Giggenbach) geothermometer and Quartz geothermometer. Temperature values using Na/K geothermometer range from 259°C to 293°C in the East Olkaria field, 261°C to 304°C in the North-East field. Central field temperatures range from 270°C to 280°C while the surface fluids range between 32°C and 430°C. Silica temperatures range between 176-344°C for Olkaria East, 210-356°C for Olkaria North-East, 194-216°C for Olkaria Central and 72-162°C for the surface fluids. In Olkaria North-East temperatures were highest in the West, North and North East at OW- 710, OW- 715 and OW- 716. In the North East field, lower temperatures were recorded in the central part of the field around OW -721, OW-725 and OW-727. The low temperatures were interpreted to be due to cooling, which was a result of cold fluid inflow.

Silica geothermometer is based on absolute concentrations and is influenced by boiling and mixing, while Na/K geothermometer is not, because it is based on atomic ratios. By comparing calculated temperatures from different geothermometers, wells that had undergone boiling and mixing were identified. Wells OW -23, OW -715, OW -716, OW- 721 and OW -727 had undergone the conductive cooling without steam loss process, while wells OW- 2, OW- 22, OW -202, OW- 710 and OW -725 had undergone boiling with steam loss. This indicated mixing for the wells with cooler groundwater depressing the fluid geothermometry.

Results for different chemical geothermometers sometimes compare well for a particular discharge although sometimes, large differences are seen. The assumption of equilibrium is valid and faith was thus put into the results. Discrepancy in results was indicative of dis-equilibrium. A discrepancy may, however, be utilized to quantify various processes in geothermal systems such as boiling and mixing with cooler water in the upflow zones. Therefore, differences in the results of individual geothermometers need not be a negative outcome for their interpretation. The geothermometers were estimated to have an error margin, of 10°-20°C, depending on the time of the day when the sampling was done. Fairly low temperatures were experienced during the daytime while slightly high temperatures were experienced during the late evenings.

4.4.3 Quartz geothermometers vs. Chloride concentration plot

The correlation between quartz geothermometer enthalpy and chloride concentration was plotted using the WATCH Speciation program speciation and presented in Figure 4.5. The surface waters and the central field wells plotted on the low steam region. A strong correlation was evident in the wells from the East and North Eastern field as they plotted towards the high steam region. Low chloride concentration values were evident in the surface and near surface waters.

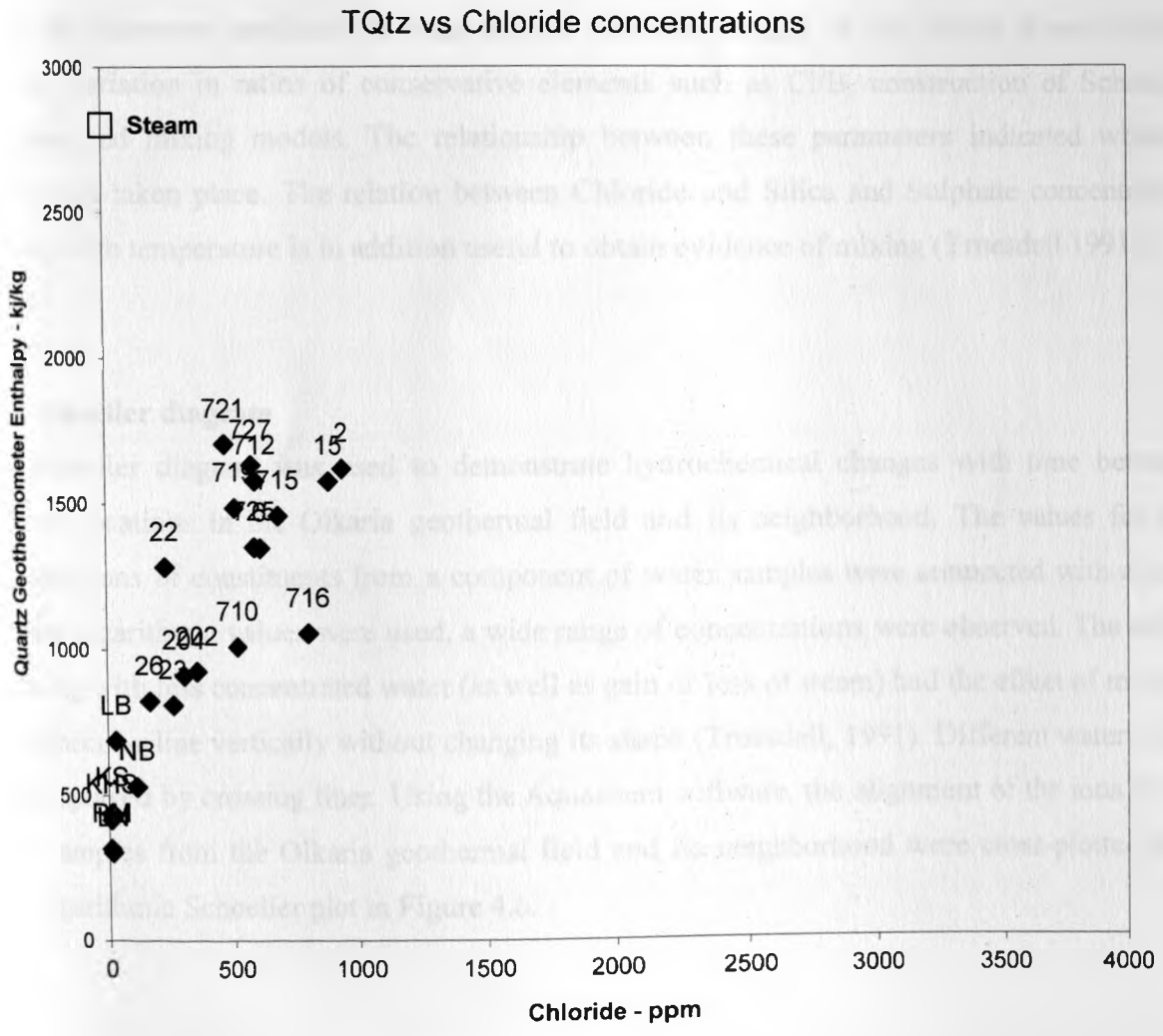


Figure 4.5: TQtz vs. Chloride concentration plot for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

4.5 MIXING PROCESSES

It has been recorded that ascending hot waters could either cool by conduction, or by mixing with shallow cold water and perhaps by a combination of these two processes. Chemical analysis of spring waters could provide information about which of these processes is taking place in geothermal systems. Ascending water at high speed with little conductive cooling will have a chemical composition that resembles rock- water equilibrium at depth. Springs with different temperatures have different chemical compositions when ascending thermal waters cool by mixing with cooler surface water (Fournier 1977).

There are numerous methods that were used to infer the mixing of two waters from different sources: variation in ratios of conservative elements such as Cl/B, construction of Schoeller diagrams and mixing models. The relationship between these parameters indicated whether mixing had taken place. The relation between Chloride and Silica and Sulphate concentration together with temperature is in addition useful to obtain evidence of mixing (Truesdell 1991).

4.5.1 Schoeller diagram

The Schoeller diagram was used to demonstrate hydrochemical changes with time between different locations in the Olkaria geothermal field and its neighborhood. The values for log concentrations of constituents from a component of water samples were connected with a line. Because logarithmic values were used, a wide range of concentrations were observed. The effect of mixing with less concentrated water (as well as gain or loss of steam) had the effect of moving the connecting line vertically without changing its shape (Truesdell, 1991). Different water types were displayed by crossing lines. Using the Aquachem software, the alignment of the ions in the water samples from the Olkaria geothermal field and its neighborhood were cross-plotted in a semi logarithmic Schoeller plot in Figure 4.6.

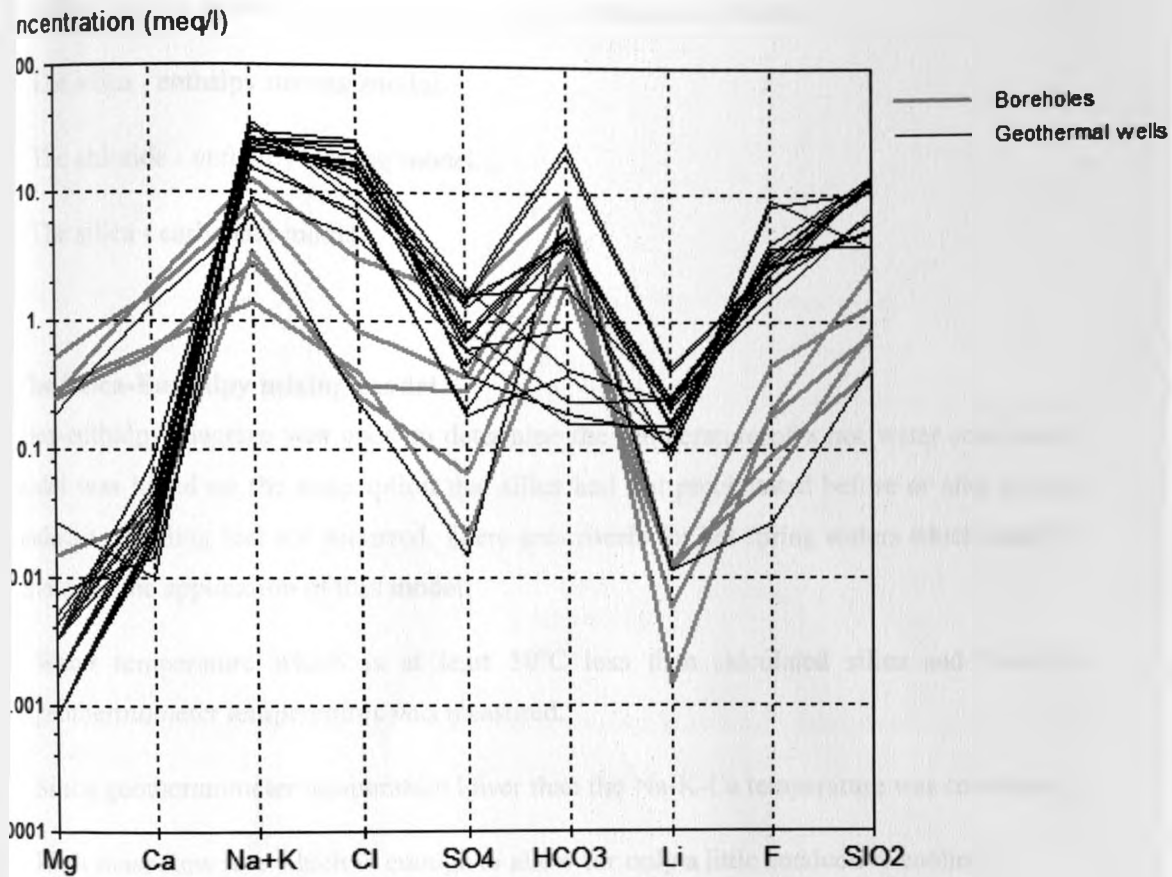


Figure 4.6 Schoeller diagram for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

In the Schoeller diagram in Figure 4.6 above, the thermal waters had high concentrations of Na+K, HCO₃ and SiO₂ except for the central and a few North-Eastern field wells with slightly lower values as indicated by the diagram. Surface waters had high concentrations of Mg and low concentrations of SiO₂. Relatively high concentrations of Mg showed that cold water was mixed with the geothermal water.

Various models were developed to allow the estimation of the hot water component in mixed waters in springs or discharged waters from wells from the Olkaria geothermal field and its neighborhood.

Three kinds of mixing models have been described by Arnorsson (2000b):

- The silica - enthalpy mixing model.
- The chloride - enthalpy mixing model.
- The silica - carbonate model.

4.5.2 The Silica-Enthalpy mixing model

The silica-enthalpy diagram was used to determine the temperature of a hot water component. The model was based on the assumption that silica had not precipitated before or after mixing and conductive cooling had not occurred. There are criteria for hot spring waters which could be appropriate for the application of this model:

- Water temperature which is at least 50°C less than calculated silica and Na-K-Ca geothermometer temperatures was measured.
- Silica geothermometer temperature lower than the Na-K-Ca temperature was considered.
- High mass flow rate which is enough to allow for only a little conductive cooling.

This model is not applicable to boiling springs because heat is carried away in the steam after mixing. Silica –enthalpy mixing model for the Olkaria geothermal field and its neighborhood is plotted in Figure 4.7.

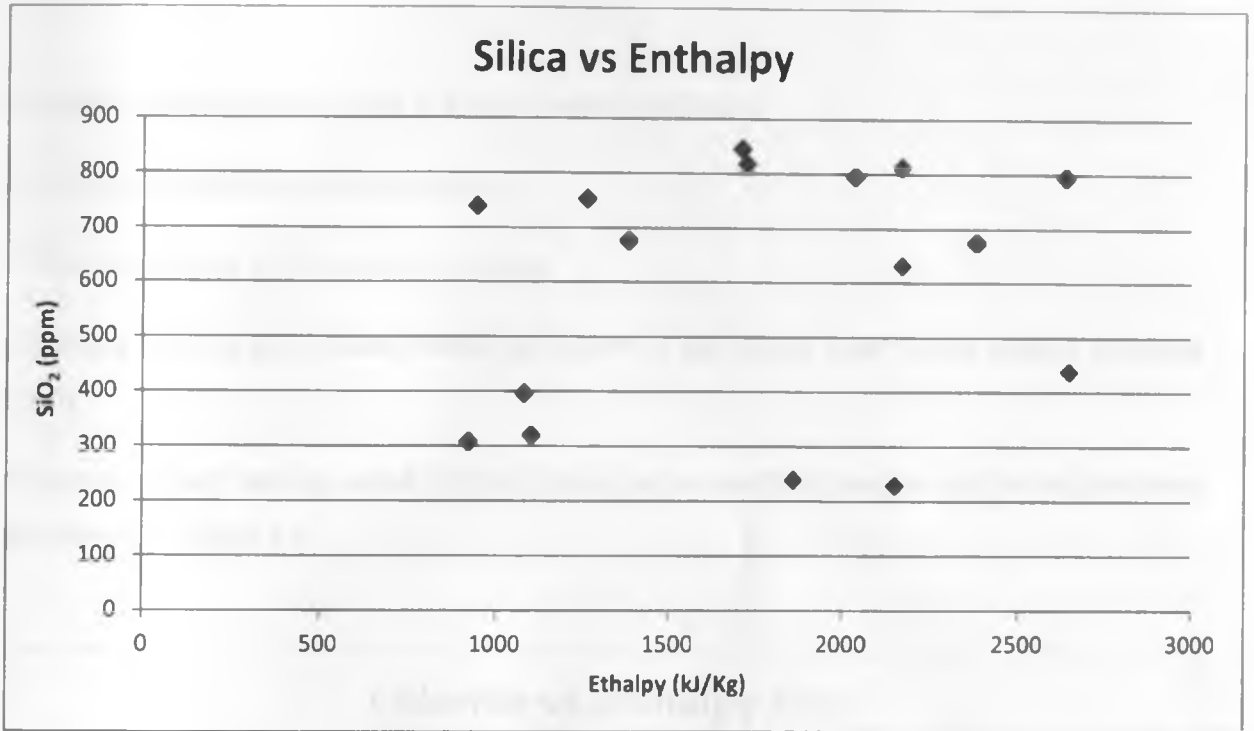


Figure 4.7: Silica-Enthalpy mixing model for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

From the Silica-Enthalpy mixing model (Figure 4.7) above, a possible mixing trend was evident with samples plotting in a scattered manner. This was an indication that samples had ample time for conductive cooling; hence, the thermal fluids from the wells had time to mix with the surface meteoric waters during their upflow.

4.5.3 The Chloride- Enthalpy mixing model

The chloride–enthalpy mixing model was applied to the Olkaria geothermal field and its neighborhood so as to predict surface temperature. It accounted for both mixing and boiling processes. This model is best applicable where the initial temperature of the hot water is above 200°C.

Necessary assumptions in using this model were listed below.

- (1) No heat loss before or after mixing.
- (2) Re-equilibrium with quartz after mixing.
- (3) Silica was not precipitated during the ascent of the mixed water to the surface (Fournier 1977).

Chloride-enthalpy mixing model for the Olkaria geothermal field samples and its neighborhood are plotted in Figure 4.8.

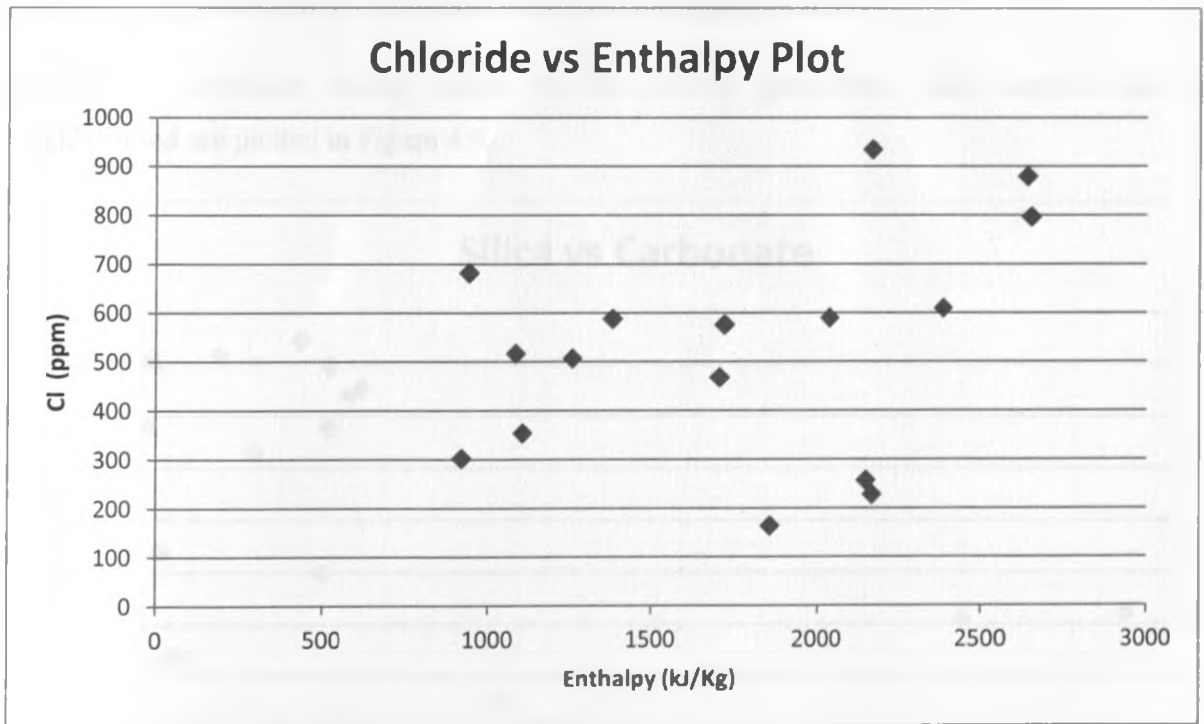


Figure 4.8: Chloride-enthalpy mixing model for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

From the chloride-enthalpy mixing model in Figure 4.8 above, the relationship between chloride concentrations and discharge enthalpies were explained by the mixing between re- injected water and fluids discharged from the wells, assuming that the re-injected water or the mixed fluid had been conductively heated by the surrounding rocks. The diagram indicated that steam had been added to a few wells namely wells, OW-202, OW-204, OW-715 and OW-716. It was also supported by the fact that fluids from these wells have higher non- condensable gas concentration than the rest of the wells.

4.5.4 The Silica-Carbonate model

This mixing model was based on the relationship between silica and total carbonate. It was based on the assumption that practically all silica in Olkaria geothermal water occurs as H_4SiO_4 and all carbonate as HCO_3 . This model was used to estimate the temperature of the hot water component in mixed waters and also to distinguish boiled and non-boiled waters.

The Silica- Carbonate mixing model for the Olkaria geothermal field samples and its neighborhood are plotted in Figure 4.9.

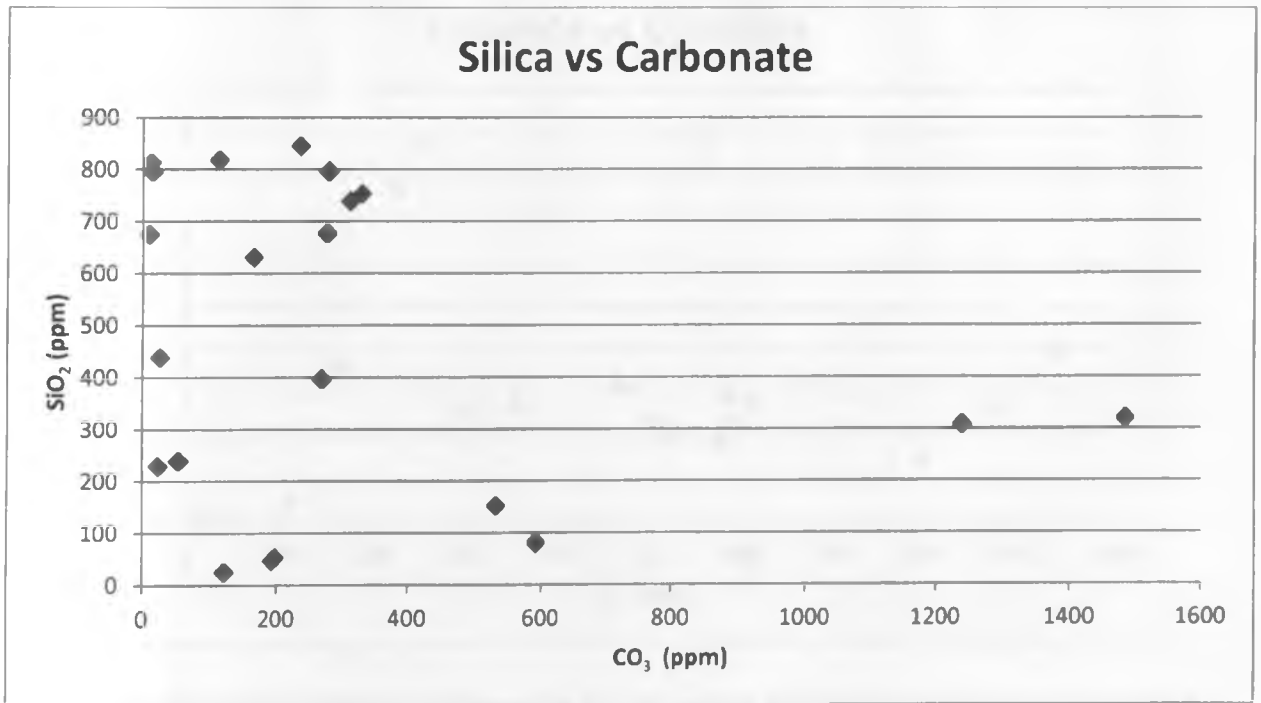


Figure 4.9: Silica-Carbonate mixing model for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

From the Silica-Carbonate mixing model in Figure 4.9 above, it was evident that most of the samples plotted in the boiled waters with a few plotting in the non-boiled waters. Water mixing was indicated by samples which are high in silica and some which are high in carbonates. Four samples plot on average in both boiled and non boiled waters. This was an indication of mixing.

4.5.5 Fluoride – Chloride - Temperature relationship

The relationship of Chloride to Fluoride concentration was used for evaluation of mixing processes. The correlation between the concentrations of chloride and fluoride indicates whether geothermal water is being diluted by cold groundwater or not. The relationship between chloride and temperature on the other hand, indicates whether or not, the geothermal water is being diluted by water warmer than the cold groundwater which could probably be condensates.

Diagrams showing Cl-F relationship and Temperature-Chloride relationship are plotted in Figures 5.0 and 5.1 respectively.

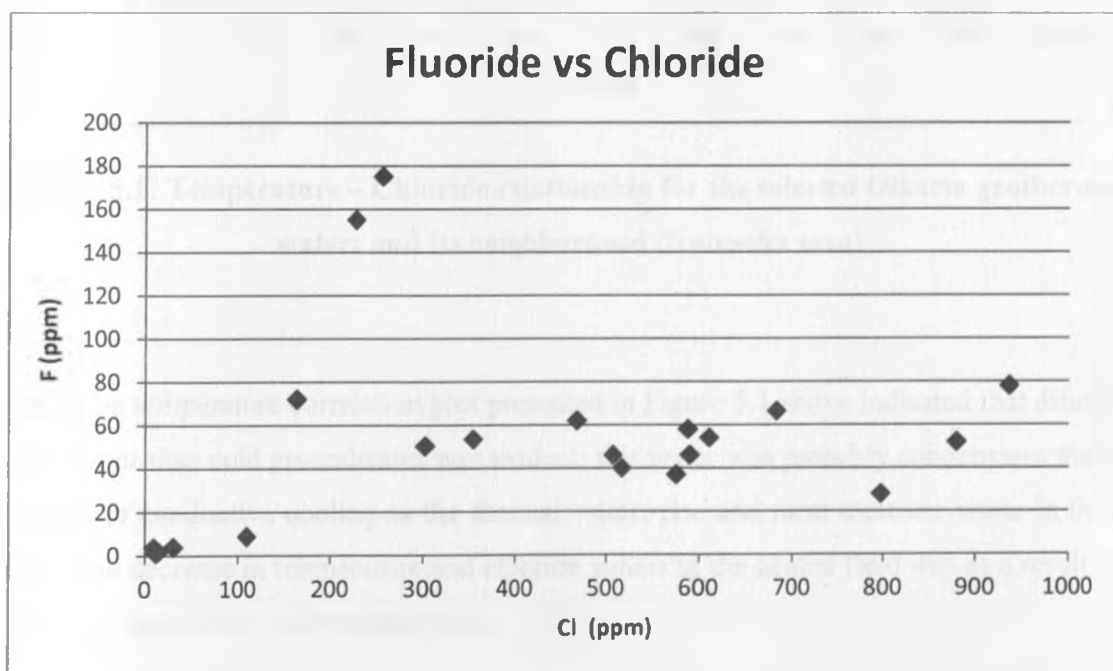


Figure 5.0: Fluoride-Chloride relationship for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

The Fluoride-Chloride correlation plot (Figure 5.0) above, depicts strong correlation between the concentrations of chloride and fluoride in the entire wells. Three samples plot in the cold water region, two samples plot in the hot water region and the rest of the samples plot in the warm water or mixed region, this suggested that the geothermal water was being diluted by cold groundwater.

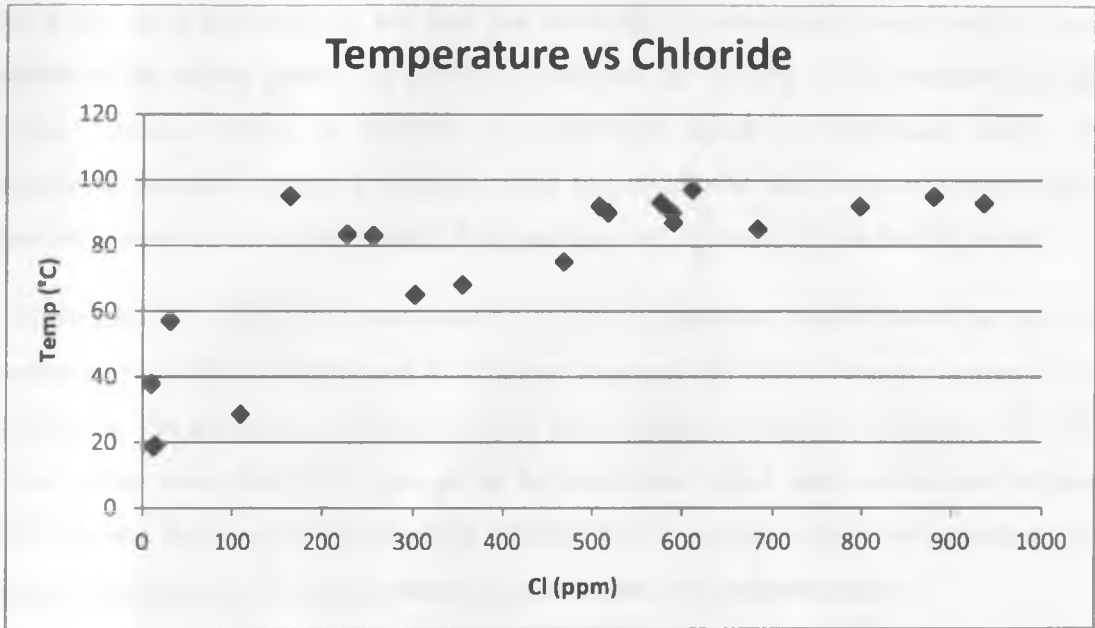


Figure 5.1: Temperature – Chloride relationship for the selected Olkaria geothermal waters and its neighborhood (Naivasha area)

The chloride temperature correlation plot presented in Figure 5.1 above indicated that dilution by water warmer than cold groundwater was evident; this water was probably condensates that form as a result of conductive cooling as the thermal waters rise and meet meteoric water in the near surface. The decrease in temperature and chloride values in the central field was as a result of the fluids losing heat to the surrounding rocks.

4.6 DISCUSSION

There are simple concentrations of dissolved constituents quoted to characterize geothermal fluids. The TDS gives a measure of the amount of chemical salts dissolved in the waters while the pH is a measure of the alkalinity or acidity of the fluid. The electrical conductivity senses the dissolved salts and the higher the dissolved salts the higher the conductivity. The high pH values in the wells were attributed to the fact that since the measurements were made at ambient temperatures the acidic gases H_2S and CO_2 were lost on cooling of the samples through the sampling container walls. In addition, in amorphous silica over-saturated waters, excess saturation of unionized aqueous solution tends to polymerize and polymerization causes the removal of unionized silica (weak acid) from solution which tends to raise the pH value.

The $Cl-SO_4-HCO_3$ ternary plot was used to classify geothermal waters based on the relative proportions of chloride, sulphate and bicarbonate ions and can also give some degree of genetic interpretation. The geothermal wells plot on the mature region except for two wells, OW-202 and OW-204 which lie in the HCO_3 apex or in the peripheral region same as the near surface and surface waters. Both wells recorded the highest HCO_3 concentrations accompanied by low chloride concentrations. This made them poor candidates for geothermometry.

The $Cl-Li - B$ Ternary plot uses relative contents of the conservative components to provide information on possible links among subsystems. From the diagram it was evident that the well samples plotted in clusters of individual fields which showed that most of the waters for wells from the individual fields were related.

The $Na-K-Mg$ ternary diagram determines which waters are suitable for geothermometry by the position on which the fluids plot on the ternary diagram. The samples collected from the Olkaria geothermal field waters proved important for use in geothermometry.

Keith (1983) pointed out that the temperature and compositions at which the full equilibrium is attained vary significantly with the form of Na/K geothermometer equation which is taken as correct and the mineralogy of the reservoir rocks.

Schoeller diagram indicated the difference in composition amongst the collected samples showing that they had passed through different rock types during the upflow (Connolly et al., 1990).

In order to estimate reservoir temperature, the silica enthalpy mixing model (Fournier, 1977) was used for comparison and further classification. The cold water point was assumed to represent the hypothetical cold water (e.g. temperature, $T = 10^{\circ}\text{C}$, and silica, $\text{SiO}_2 = 20\text{ppm}$) in the study area (Stanasel and Ludovic, 2003).

The chloride-enthalpy mixing model indicated that the cold groundwater started flowing into these wells when pumping began in the adjacent fields mainly the Olkaria domes field.

The chloride temperature correlation plot indicated dilution by waters warmer than cold groundwater, this water was established to be condensates that form as a result of conductive cooling as the thermal waters rise and meet meteoric water in the near surface. The decrease in temperature and chloride values in the central field was as a result of the fluids losing heat to the surrounding rocks.

These geochemical studies together with the conceptualized geological model were a proof that the subsurface fluid flow in the Olkaria geothermal field is through faults and conduits.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The first objective of the study was to determine the origin and direction of fluid migration using isotopic composition of surface and well discharges. From the stable isotope analysis, it was established that, fluid migration within the reservoir is from North to South. As indicated by the geology and structural map in Figure 1.4, Lake Naivasha proved to be the origin of the cold fluids into the reservoir which flows through a possible N – S striking fracture which exists in the vicinity of wells OW-15, OW-22 and OW-26.

The second objective of this study was to relate the chemical characteristics of Olkaria geothermal fluids and its neighborhood so as to determine their mixing pattern using fluid chemistry and fluid constituents. The fluid chemistry indicated that the waters in OW- 202 and OW-204 were a product of some water from the deep reservoir which has been mixed with dilute meteoric water accompanied by condensation of steam rich in carbon dioxide. The other fourteen wells, OW-2, OW-16, OW-22, OW-23, OW-26, OW-709, OW- 710, OW-712, OW-715, OW-716, OW-719, OW-721, OW-725, and OW-727 draw their waters from the deep geothermal fluids. The waters are of Na-Cl type and were used in geothermometry with confidence as they did not appear diluted from the original reservoir fluid concentration.

The last objective of this study was to compare the variation in the prevailing Reservoir temperatures and neighboring fluids using chemical geothermometry. This study showed that decrease in temperature and chloride values was evident in the central field; this was caused by well pumping in the adjacent wells namely, the East field and the Olkaria domes field. Well pumping at the Olkaria domes field also caused reduction in temperature in the North-East field; this was as a result of fluid migration from the North to South along a fault. This was proved by the geothermometer temperatures.

Conclusively, it was found that the Olkaria geothermal field experienced both cold and warm fluid incursion into the reservoir. This originated from the neighboring waters and condensates due underground fluid flow and low pressure drawdown respectively.

5.2 RECOMMENDATIONS

A study on the determination of the rate of fluid circulation using the Strontium isotope ratios should be carried out in the Olkaria geothermal field so as to determine the rate of circulation between the thermal waters, meteoric waters and surface waters.

The static water level in Lake Naivasha should be monitored so as to establish its contribution in the underground fluid flow into the Olkaria geothermal reservoir.

Construction of a potentiometric map would assist in determination of regional fluid flow direction within Olkaria and its neighborhood.

Reservoir model to monitor the pumping and re-injection rates between the Olkaria wells, OW-202, OW-204, OW-715 and OW-716 should be constructed.

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