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HYDROCHEMISTRY OF OLKARIA AND EBURRU GEOTHERMAL FIELDS, KENYAN RIFT VALLEY

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ABSTRACT

The chemical composition of waters from cold and warm boreholes, springs, Lake Naivasha, River Morendati and geothermal waters from the Olkaria and Eburru fields is presented. The study of the chemistry of the waters has been used to suggest movement and processes affecting the groundwater in the Rift Valley.

The study has shown that Lake Naivasha, which is the only fresh water lake in the Kenyan Rift Valley, recharges most of the nearby boreholes. The chemical characteristics of the geothermal waters in Olkaria and Eburru geothermal fields are similar. Eburru and Olkaria geothermal reservoirs get some of their recharge from the rift groundwater. The waters from some boreholes to the north of Eburru and Elementeita spring are outflows from Eburru geothermal field and there seems to be no other geothermal resource in the Elementeita area. The escarpment warm spring waters are shallow escarpment waters that have been heated by shallow hot rock, probably below the location of the springs. They may not be related to the geothermal systems at Olkaria and Eburru.

Monitoring of water levels around the lake is recommended to determine the possible effect of geothermal exploitation at Olkaria on Lake Naivasha. Further work to estimate the outflow of water from the lake and inflow into it is also recommended.

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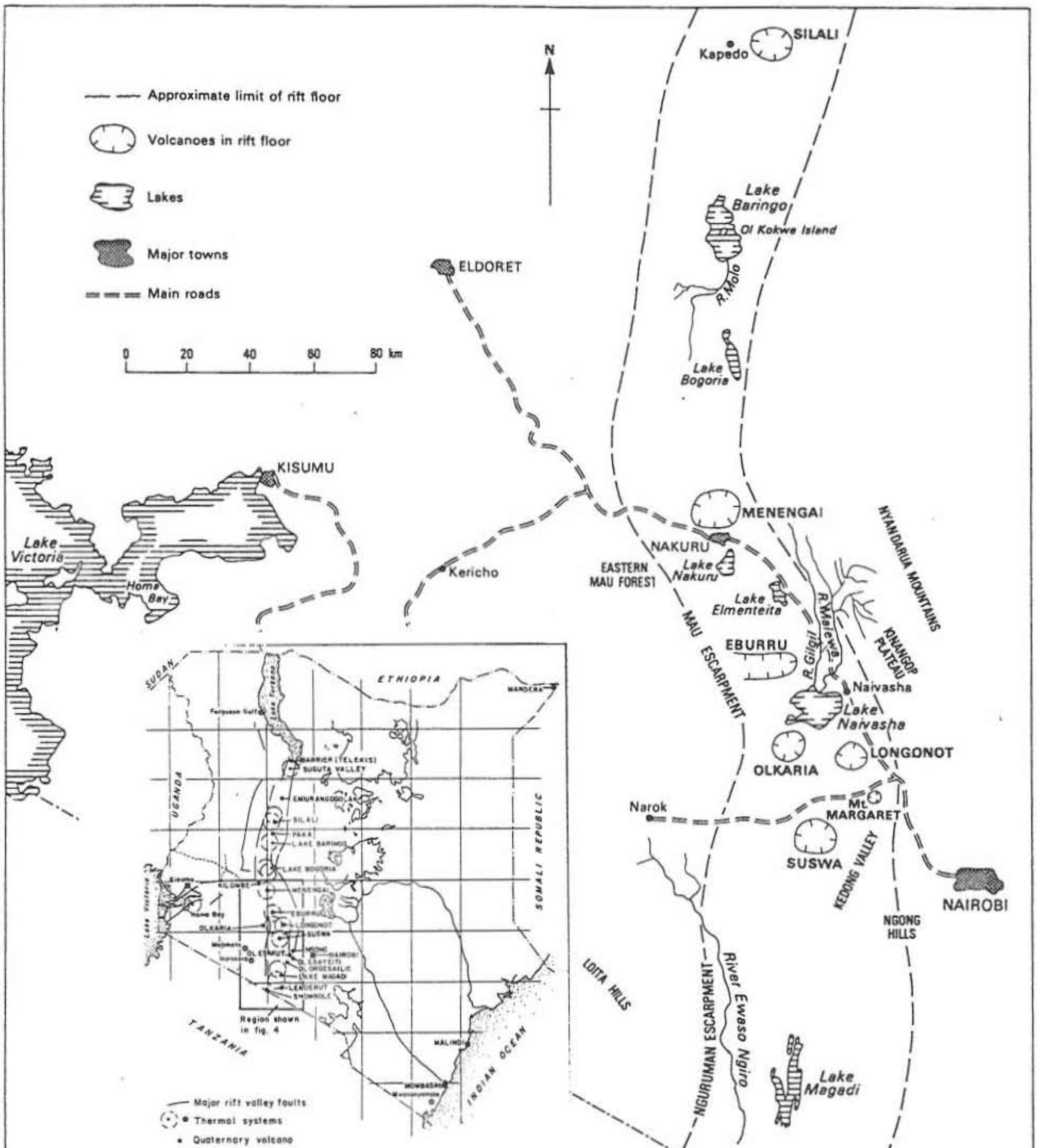


FIGURE 1: Map showing the Rift Valley and thermal areas in Kenya

1. INTRODUCTION

A number of geothermal fields lie in the Kenyan Rift Valley (Figure 1). Preliminary surface investigations have been carried out in Suswa, Longonot, Olkaria, Eburru, Menengai, Bogoria, Baringo, Korosi, Silali, and Emurangogolak geothermal fields (Clarke et al., 1990), but drilling in just two, Eburru and Olkaria, the only ones exploited (KPC, 1986). The present power station is in Olkaria East. Lake Naivasha lies between Olkaria and Eburru fields and its contribution to the hydrological regime of the area has given rise to a considerable amount of speculation. McCann (1972) carried out a comprehensive hydrogeological study of the Rift Valley catchment and quantified groundwater flows of the Naivasha area. He calculated the total precipitation in the Naivasha catchment area to be 2761×10^6 m^3/yr and estimated evaporation from the lake swamps and surrounding catchment to be 2506×10^6 m^3/yr, leaving 254×10^6 m^3/yr as outflow from the catchment. Using the same approach, he was able to estimate the water inflow from direct precipitation to be 132×10^6 m^3/yr and gauged stream flow of 248×10^6 m^3/yr. He estimated the water taken by evaporation and evapotranspiration to be 346×10^6 m^3/yr leaving 34×10^6 m^3/yr as groundwater outflow from the lake. From the piezometric levels, he was able to suggest that the water from the lake was flowing in both northerly and southerly directions.

Glover (1972) did geochemical work in the area and estimated the goundwater outflow from Lake Naivasha using chloride balance. By estimating the total annual chloride input to the lake from the rivers and the run-offs that feed it, he was able to calculate the necessary outflow from the lake to keep the concentration almost constant. Panichi and Tongiorgi (1974) used data on the stable isotopes of oxygen of the influent water and the lake water to model the groundwater outflow from the lake.

Allen et al. (1989) reviewed all the work done in the area and improved the model by using more data. They used more stable isotope analysis and calculated the groundwater outflow from the lake, and their results agreed with McCann's estimate. They also had more piezometric levels from the boreholes in the area and suggested that the lake water was outflowing in both northerly and southerly directions (Figure 2). They took the mean estimate of subsurface recharge from Lake Naivasha to be 50×10^6 m^3/yr with an error of $\pm 40 \times 10^6$. Using the mixing series of stable isotopes of oxygen and hydrogen between lake water and groundwater, they were able to infer the composition of groundwaters beneath the thermal centre at Olkaria. They suggested a 30% lake water contribution to Lake Elementeita and showed an influence of the lake in the south to southeast direction, up to 6 km away, and no flow to the west (Figure 3).

Other workers have done some studies on the falling of the lake water level, which has been falling gradually since 1917. Depth measurements were first carried out by Sikes (1935) and in 1983 by Ase et al. (1986). Sikes (1935) reported furrows in the bottom of the lake which were detected by Ase et al. (1986) after 48 years of sedimentation from the inflow to the lake. They suggested that the furrows could be underwater springs or steam jets.

The poor quality data in piezometric maps on water tables and the few assessments of hydraulic properties of the aquifer rocks of the boreholes in the Rift Valley have made the hydrology of the area difficult to understand. There are no boreholes south of Longonot nor in most of the rift margins east of Suswa. Therefore, it is difficult to draw piezometric maps and the water table fluctuations in boreholes have not been monitored regularly. The only well known rock properties are those in the Olkaria wells, which may not be typical of the whole Rift Valley. It is known that the rift groundwater is being recharged from the rift escarpments, where rainfall is substantial.

However, the movement of and the chemical processes taking place in the water from the escarpment to the rift floor are complicated by geological structures and the existence of sediments from extinct lakes. Lake Naivasha is the only freshwater lake in the Rift Valley although it has no surface outlet. It gets its recharge from direct precipitation and the two rivers, Gilgil and Malewa. The lake water, therefore, recharges some of the boreholes around it.

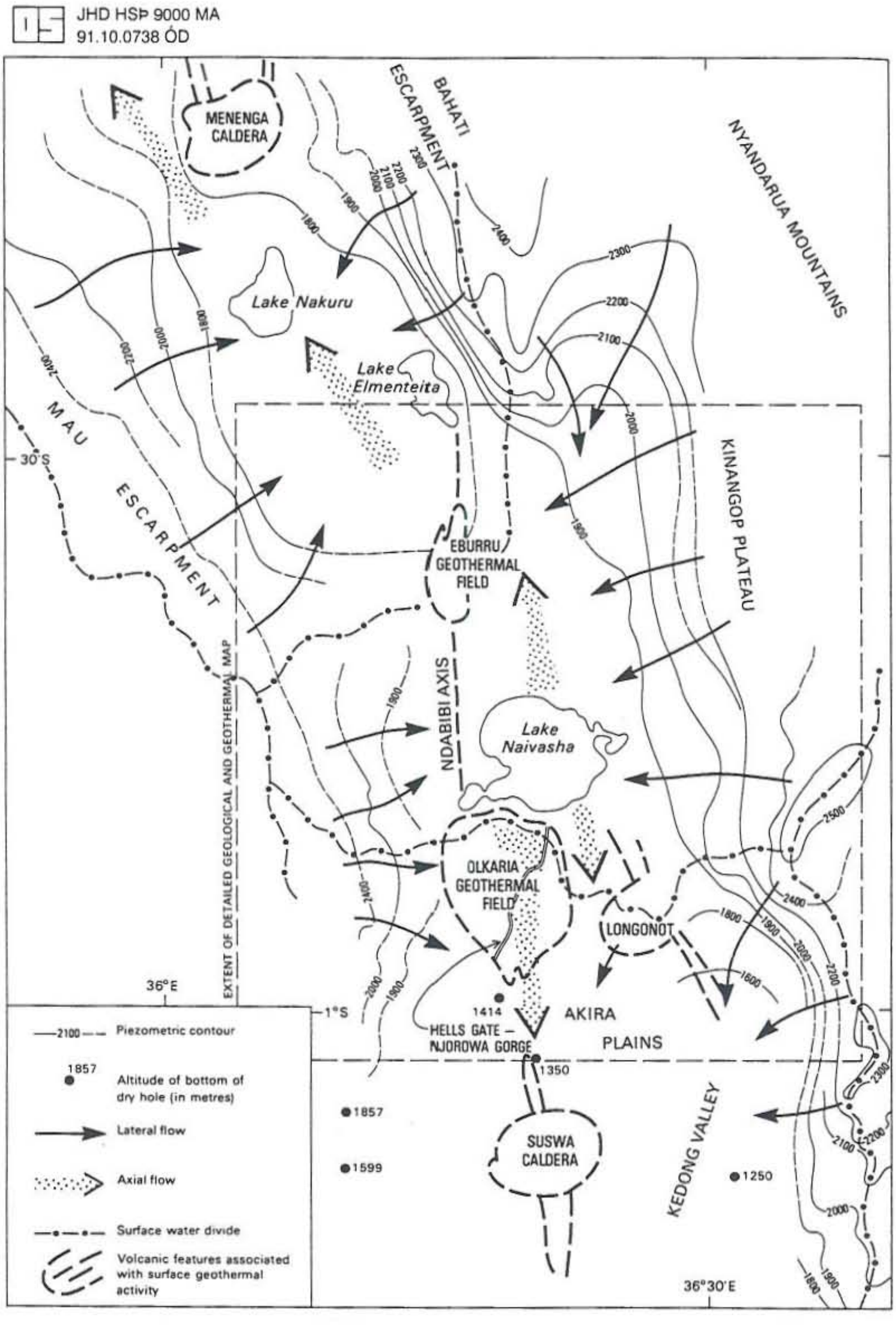


FIGURE 2: Piezometric map of the study area (Allen et al., 1989)

Olkaria geothermal field produces 45 MW_e and a 60 MW_e station is planned for Northeast Olkaria. It is speculated that the field is being recharged both by lake water and escarpment waters. Eburru field is still under exploration with only one successful well. It may support a small power station (Ambusso, 1990).

The long term success of any geothermal energy exploitation, depends on the understanding of groundwater movement and the recharge areas. The present study is designed to obtain a fuller picture of the hydrological regime in the vicinity of Lake Naivasha (Figure 4) and the Olkaria (Figure 5) and Eburru geothermal areas. Its aims are the following:

1) To try to suggest the movement and the extent of groundwater flow in the area of study.

2) To try to find out whether Lake Naivasha is the main recharging reservoir for the two geothermal fields.

3) To try to find out whether Lake Naivasha is an exposed groundwater table as suggested by other writers (Thompson and Dodson, 1963).

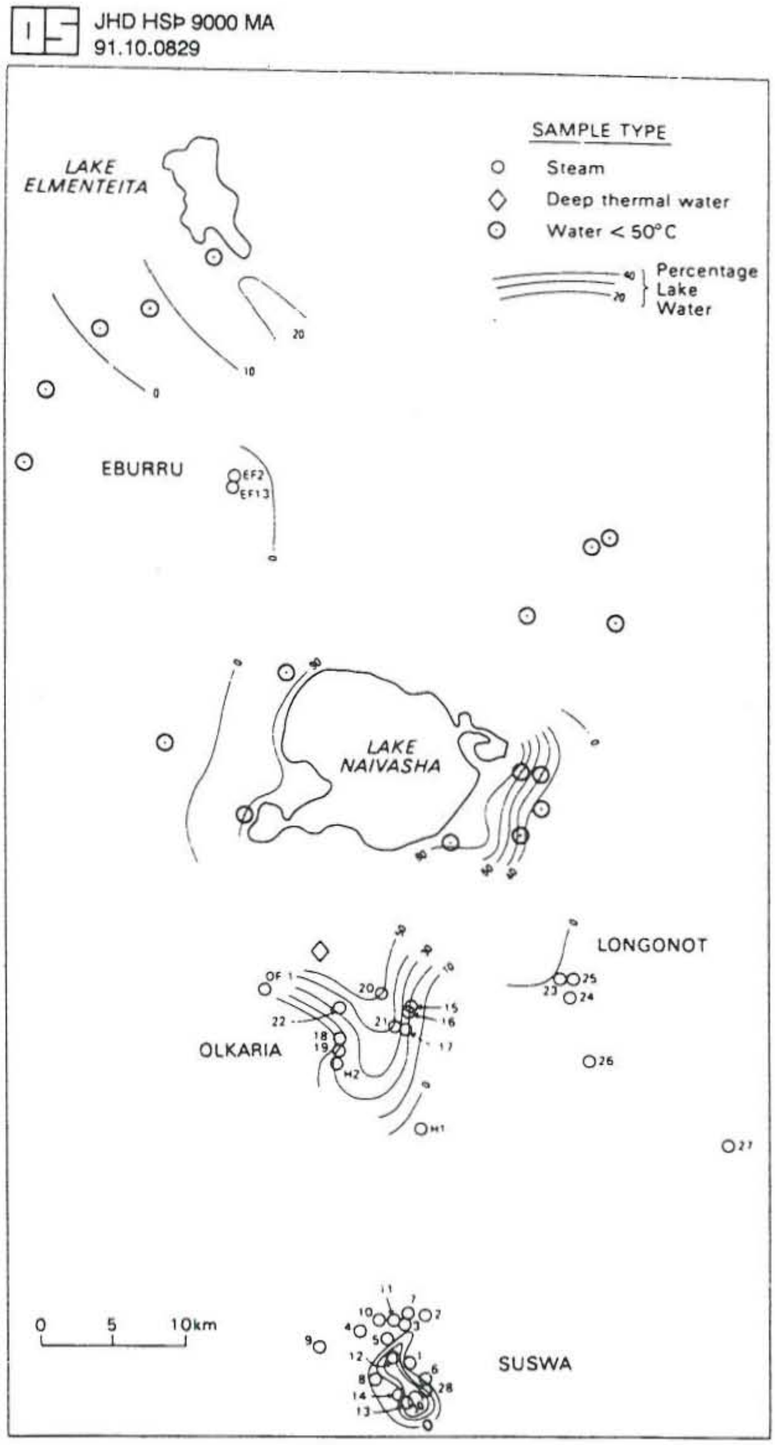


FIGURE 3: Contour map showing the contribution of Naivasha lakewater to groundwater (Allen et al., 1989)

4) To try to obtain evidence as to whether Elementeita warm spring and some of the warm water boreholes in the Elementeita area are placed on the outflow from Eburru geothermal field.

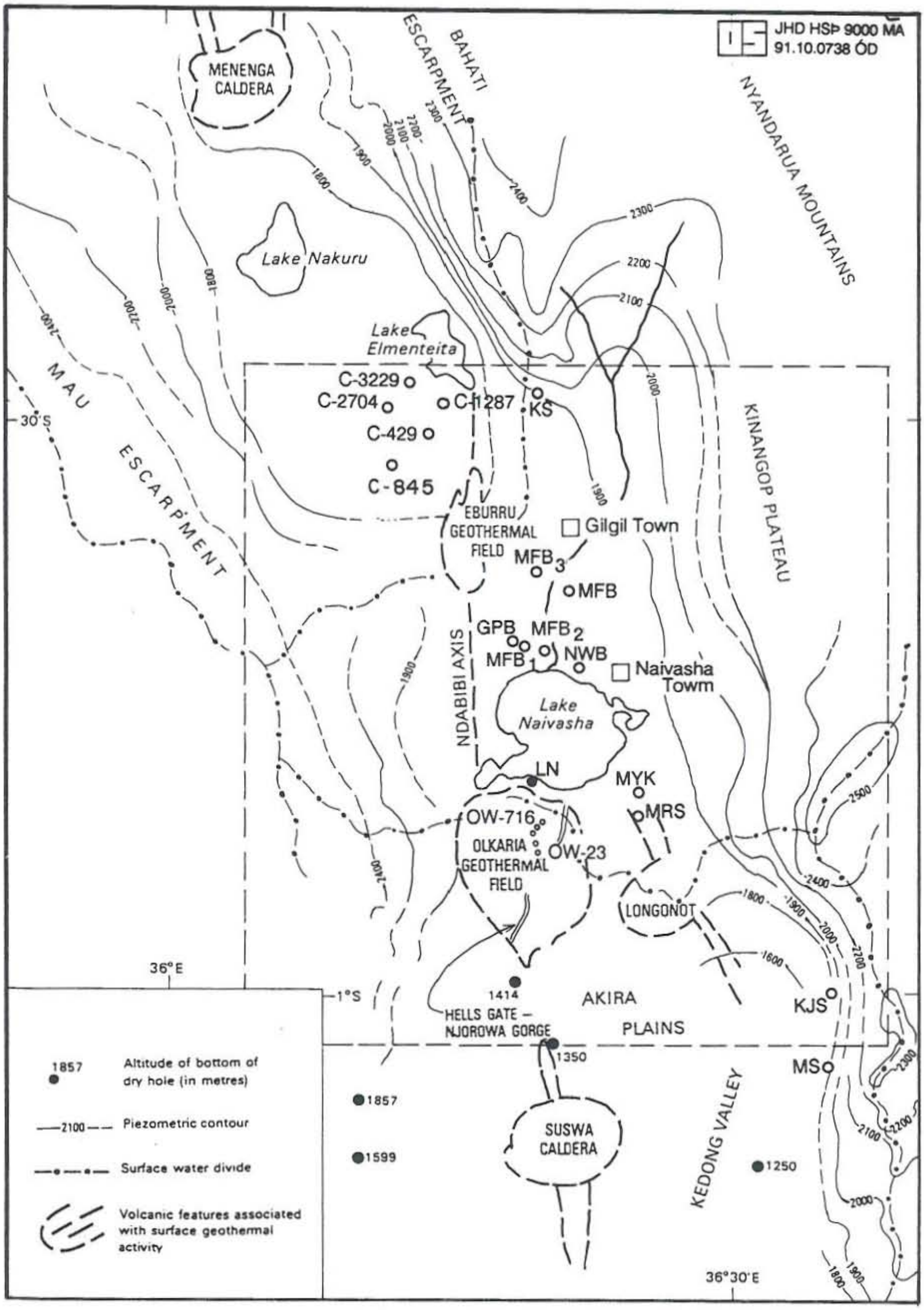


FIGURE 4: Map showing the sampling locations in the study area

This report covers work done in areas in the vicinity of Lake Naivasha extending to the Olkaria and Eburru geothermal fields. Water samples were collected from the following locations (see Figures 4 and 5):

Olkaria East wells	OW-23, OW-29
Northeast Olkaria	OW-714, OW-715, OW-716
Eburru wells	EW-01, EW-04
Lake Naivasha	Southern shore (LN)
Between Lake Naivasha and Mt. Longonot	Munyua Railway Station borehole (MRS) Musyokas borehole (MYK)
Between Lake Naivasha and Eburru field	Naivasha Town Water borehole (NWB) Marula borehole 1 (MFB1) Marula borehole 2 (MFB2) Marula borehole 3 (MFB3) Marula borehole 4 (MFB4) Green Park borehole (GPB)
Gilgil water supply	Morendati River (MR)
Elementeita area	Elementaita warm spring C-2704 borehole C-1287 borehole C-3229 borehole C-845 borehole C-429 borehole
The Rift escarpment springs	Kariandusi warm spring (KS) Kijabe warm spring (KJS) Mayer's Farm spring (MS)

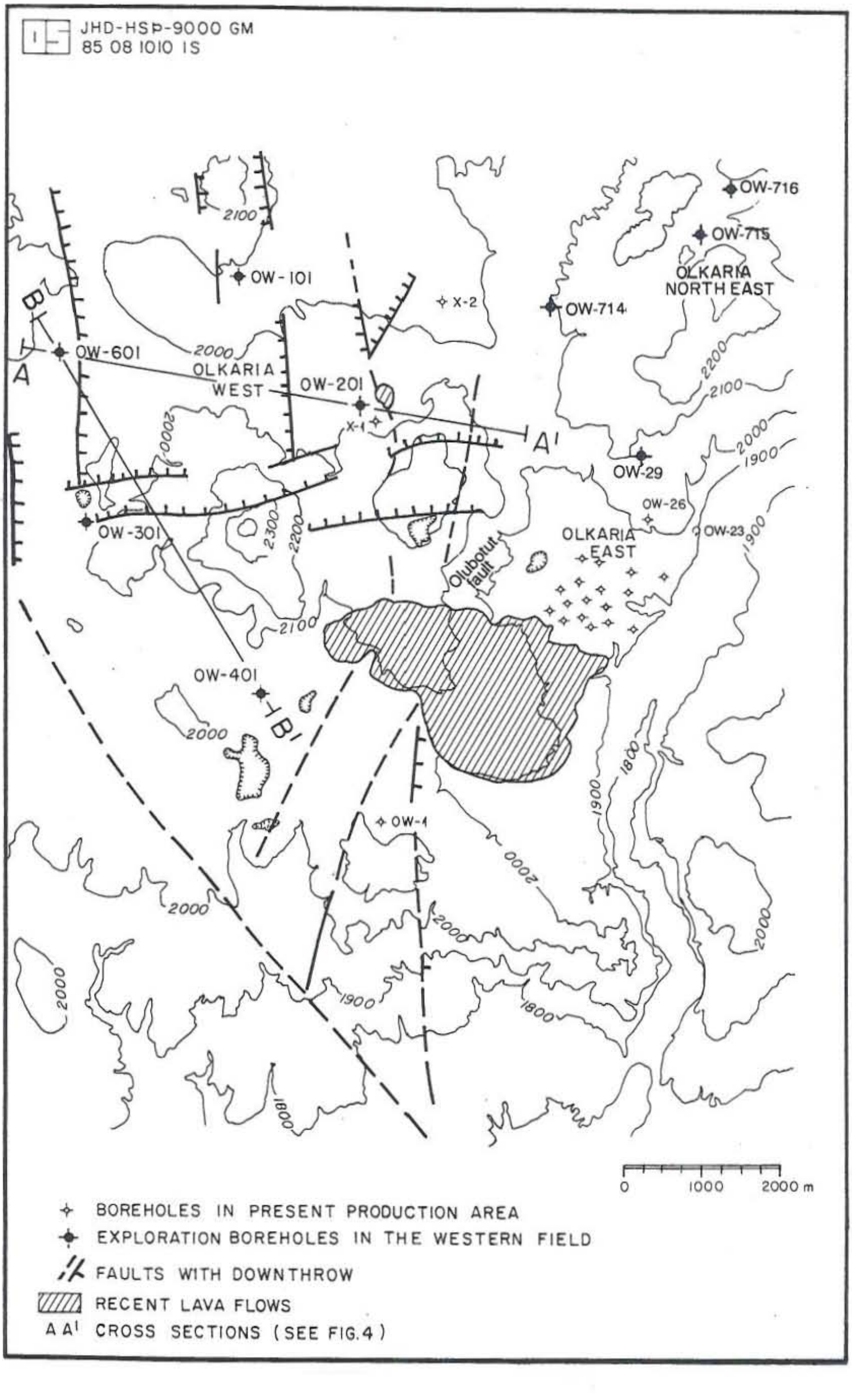


FIGURE 5: Map showing the locations of some Olkaria wells

2. STUDY AREA AND GEOLOGY

The rift is defined by the major Pliocene boundary faults of the Nguruman and Mau Escarpments in the west, and the Kikuyu, Nyandarua and Bahati Escarpments in the east. A dense system of Middle and Upper Pleistocene grid faulting within the rift dissects the graben floor and step-fault platforms (Allen et al., 1989). The oldest rocks found in this part of the Rift, according to the same authors, are the Archean Basement gneisses which outcrop near the summit of the Nguruman Escarpment in the south-east. The formation of the Rift Valley began during the Miocene period with several phases of major faulting interspersed with longer periods of relative quiescence. The major faulting occurred after the extrusion of the Gilgil trachytes (Naylor, 1972). According to Naylor (1972), Upper Middle Pleistocene and younger faulting is directly related to the volcanicity which is directly responsible for the geothermal field in Eburru. The latest major movement in Olkaria was the reactivation of the line along which the Olobutot lava was extruded and may be an earlier line of weakness (Naylor, 1972)

The Olkaria geothermal field is located about 40 km southwest of Naivasha town and about 10 km south of Lake Naivasha (Figure 4), which is the largest fresh water and the second largest lake in the Kenyan Rift Valley. The field is about 50-80 km^2 in area, based on resistivity data (Virkir, 1987) and more wells have been drilled in Northeast Olkaria where it is planned to produce 60 MW_e of electricity (Figure 5).

The Eburru geothermal field is situated about 30 km northwest of Lake Naivasha (Figure 4). The field has not been exploited yet. Lake Elementaita is located about 20 km north of Eburru. The area covered by the study is bounded by longitude 36° 00' and 36° 30' E and latitude 0° 30' and 1° 00' S (Figure 4).

The chemistry of groundwater depends on the geochemical thermodynamics of various constituents and the type of rocks the water interacts with. It is, therefore, important to know the geology to be able to understand the chemistry of groundwater. The main rock units in Olkaria are basalts, which act as caprocks for the reservoir, and volcanic lavas and tuffs which form the reservoir rocks (Muchemi, 1985). The main rocks in the area are the basalts, trachytes/rhyolites, comendites, tuffs and pyroclastics. The trachytes are the most abundant by volume and the comendites (sodic-rhyolite) are the main outcrops in the area, found in the cliffs of Hell's Gate (Ol Njorowa Gorge) (Muchemi, 1985). According to Scott (1980), Olkaria is covered with peralkaline trachytes and comendites.

The main rock units in the Eburru geothermal field are pyroclastics, rhyolites, obsidian lavas, trachytes, basalts and phonolites. The trachytes and the basalts are found to the southeast of the area. The downhole rocks in well EW-01 are pyroclastics, tuffs, rhyolites, basalts and intrusives (granitic) at the bottom (Muchemi, 1990). Generally, the Eburru area is covered with pantellerites (Scott, 1980) and trachytes (Naylor, 1972). Sediments are found around Lake Elementeita and the Kariandusi diatomite plant. The main structures in the Olkaria geothermal field are the Olkaria fracture and the Ololbutot fault which act as conduits for geothermal water (Figure 5).

The grid faulting in the Rift Valley is likely to control the flow of groundwater. The faults act as channels for groundwater because they are either open and act as conduits, or they provide permeable barriers to lateral flow. A microseismic study of the Rift Valley 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 groundwater from the Escarpments to flow towards the centre and then follow longer flowpaths reaching greater depths, and aligning their flow within the Rift along its axis.

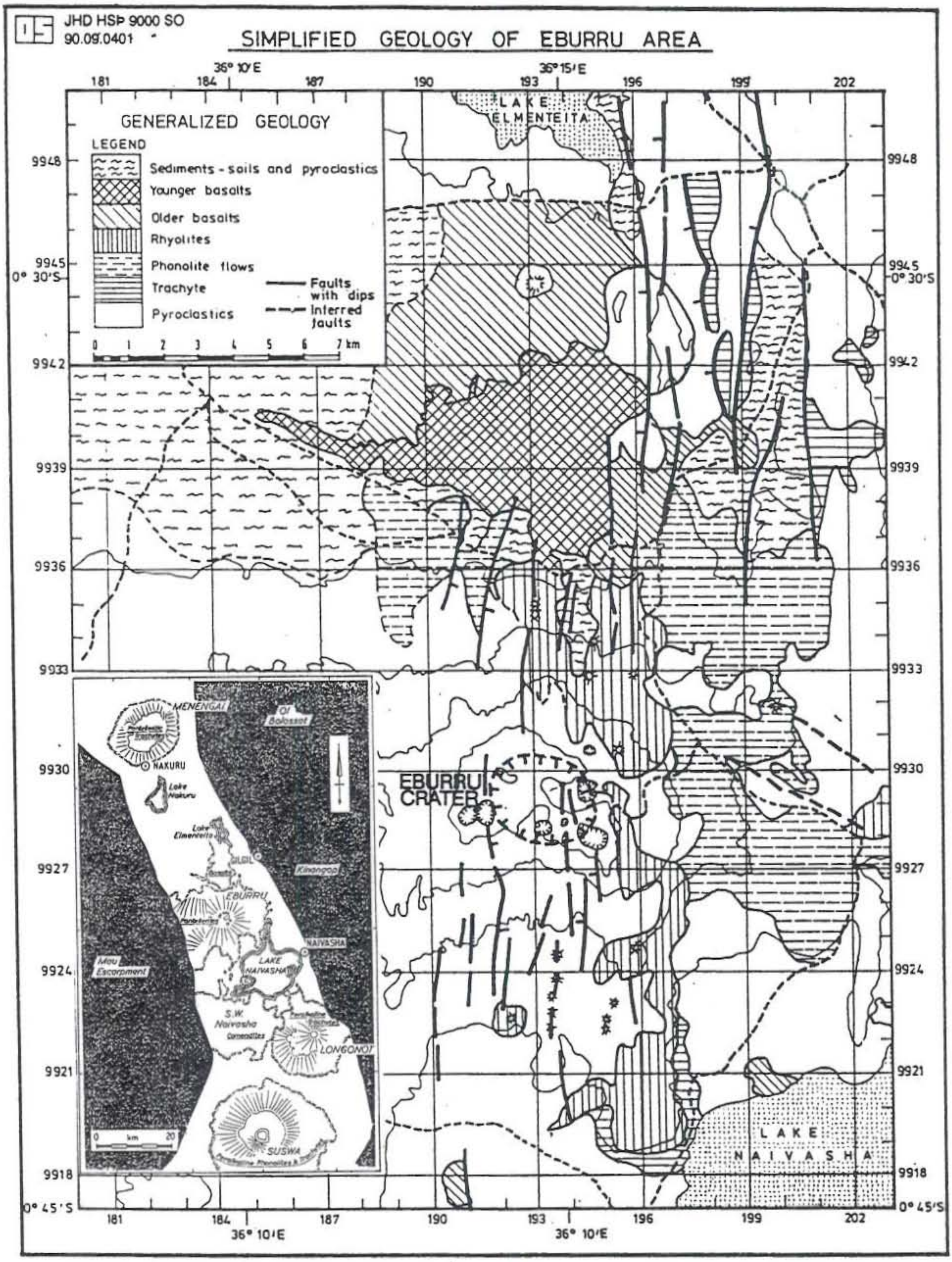


FIGURE 6: Simplified geological map of the northern part of the study area (Eburru)

3. SAMPLING AND ANALYSIS

3.1 Field sampling

Water samples were collected from the selected boreholes, springs, river, geothermal wells and Lake Naivasha in March 1991, when the rains had just started. The water was filtered through a 0.45μ millipore filter paper with the help of a hand-pump. Four 150 ml plastic sampling bottles were filled with water at each sampling site, two of them acidified with a drop of concentrated hydrochloric acid, to a pH of about 2 and the other two left untreated. The acidified samples were used for the determination of the major and trace cations while the untreated ones were used for the analysis of major and trace anions.

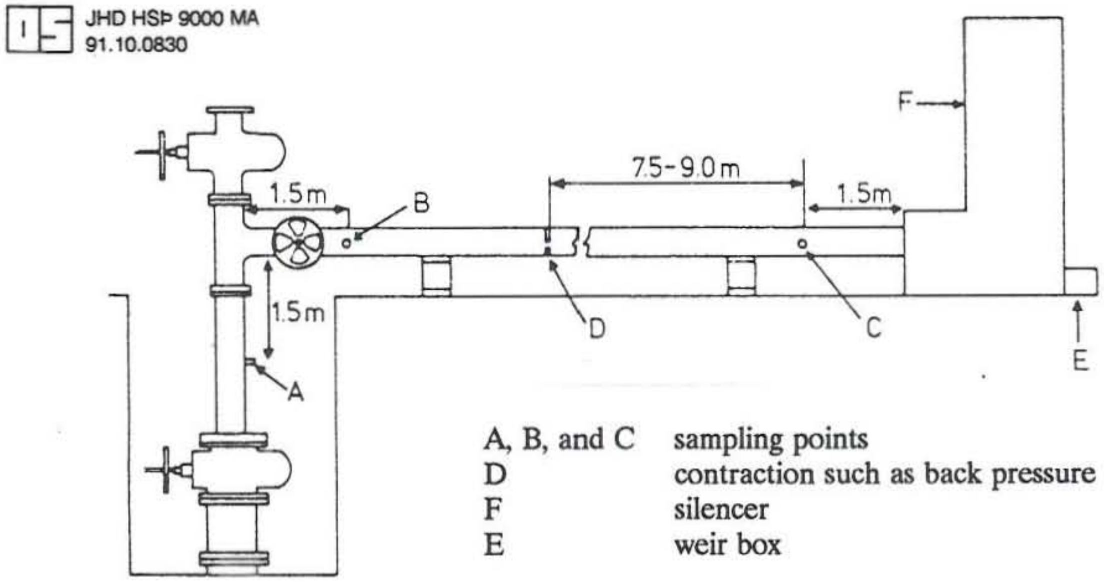
The temperature of the water was measured using a thermocouple thermometer before sample collection. The samples were then cooled to 20°C before the pH was measured, using a glass electrode pH meter. Carbon dioxide and hydrogen sulfide were determined in the field by titration methods.

A sketch of a wellhead equipment is shown in Figure 7. Liquid water from geothermal wells was collected from the weirbox, i.e from the outflow of a separator operating at atmospheric pressure. Steam samples were collected from the delivery pipe using a 2" cyclone separator which was situated about one meter from the master valve (B in Figure 7). Lip pressure and diameter of delivery pipe were used to evaluate discharge enthalpy using the following equation (James, 1962):

$$\frac{W}{783AP^{0.96}} = \frac{2673-h}{h^{1.102}} \tag{1}$$

where,

W = water flow rate (kg/s)
A = cross-section area of pipe (m^2)
P = critical lip pressure of pipe (bar abs.)
h = discharge enthalpy (kJ/kg)



A, B, and C	sampling points
D	contraction such as back pressure plate
F	silencer
E	weir box

FIGURE 7: The position of sampling points on the surface piping of a geothermal well

3.2 Laboratory analysis

The major constituents were analysed in Olkaria before coming to Iceland but the minor constituents were analysed in the Orkustofnun laboratory; analysis for some of the major ones was also repeated. The analytical methods used are listed in Table 1:

TABLE 1: Olkaria and Eburru samples, methods of chemical analysis

Constituent	Sample fraction	Method (where analysed)	Precision	References
pH	Ru	Glass electrode pH-meter (Olk)	±0.01pH	Schott, 1977
SiO_2	Fu	Spectrophotometric on yellow ammonuium molybdate ß-complex (Olk, Orkus)	1.6%	Elisson, 1969; Govett, 1961; Strickland, 1952
Na	Fa	Atomic absorption spectrometry with lithium as inhibitor (Olk, Orkus)	1.4%	Perkin-Elmer, 1976;
K	Fa	Atomic absorption spectrometry with lithium as inhibitor (Olk, Orkus)	1.4%	Perkin-Elmer, 1976
Li	Fa	Atomic absorption spetrometry (Olk, Orkus)		Perkin-Elmer, 1976
Ca	Fa	Atomic absorption spectrometry on solution containing 2% La (Olk, Orkus)	4.3%	Perkin-Elmer, 1976
Mg	Fa	Atomic absorption spectrometry on solution containing 2% La (Olk, Orkus)	13.8%	Perkin-Elmer, 1976
CO_2	Ru	pH adjusted to 8.20 titration with 0.1N HCl to pH 3.80 (Olk)	3.8%	Ellis and Mahon, 1977
SO_4	Fu	Titration with barium perchlorate with thorin as indicator (Olk) Ion chromatography (Orkus)	2.6%	Henriksen and Bergmann-Paulsen, 1974; Weiss, 1986
H_2S	Ru	Titration with $HgAc_2$ using dithizone as indicator (Olk)	13.7%	Arnorsson, 1969
Cl	Fu	Selective ion electrode ORION (Olk) Ion chromatography (Orkus)	0.5%	Orion, 1977; Weiss, 1986
F	Fu	Selective ion electrode ORION (Olk, Orkus)	3.8%	Orion, 1977
Br	Fu	Ion chromatography (Orkus)	5.1%	Weiss, 1986
I	Fu	Ion chromatography (Orkus)	6.3%	Weiss, 1986
B	Fa	UV/VIS spectophotometry with methylene blue complex (Olk)	21.7%	Staunton and McDonald, 1966
TDS	Fu	Evaporation (Olk)	3.2%	

NB: Ru stands for raw untreated water sample
Fu stands for filtered untreated water sample
Fa stands for filtered acidified water sample

3.3 Analytical results

The analytical results are presented in Tables 2 and 3. Table 2 shows the results from the Orkustofnun laboratory, and Table 3 shows those from the Olkaria laboratory. Comparison of the results for major elements from both laboratories showed a good agreement for sodium and potassium analysis. Chloride and fluoride results showed no correlation at all. Chloride concentrations obtained in the Olkaria laboratory were excessive and fluoride concentrations deficient. At very high concentrations (Elementeita spring) there was some agreement, although not very good, for both of these anions. Sulfate concentrations generally showed good agreement for concentrations above 20 ppm, but concentrations below that were reported as nil in the Olkaria laboratory and in some cases the comparison was poor e.g C-2704. Calcium and magnesium results did not compare well between the two laboratories. The Olkaria results showed lower concentrations of silica for all samples analysed compared to the results from Orkustofnun.

Ionic balances for the two sets of results were calculated and most of the Olkaria ones were above |10 %|. All the results from Orkustofnun laboratory were below |10 %| (Table 4). The results have shown that the data from Olkaria were poor and, therefore, the procedures and equipment have to be checked and attempts made to improve them. The results from the Orkustofnun laboratory showed better ionic balances and, therefore, they are used in this report.

TABLE 2: Results of analysis from Orkustofnun laboratory

Loc.	Temp	pH	SiO_2	Na	K	Li	Ca	Mg	CO_2	SO_4	H_2S	Cl	F	I (x1000)	Br (x100)	B	TDS	COND
MFB1	Amb	7.95	70	113	19.9	Nil	19.1	3.6	290	12.3	.13	11	6.1	15	7	.61	542	650
MFB2	Amb	6.9	81	60	27.3	Nil	56.4	5.1	308	21.4	.13	7.7	2.9	3	5	Nil	492	650
MFB3	Amb	8.06	75.3	115	21.4	Nil	21.5	3.9	264	26.3	.3	16.7	4.7	11	13	.04	432	660
MFB4	Amb	7.51	87	182	27	.08	24.2	2.3	408	37	.5	36.5	6	5	24	.5	636	910
LN	Amb	8.0	30.5	49	20	Nil	15.1	.05	136.4	11.4	.2	11.5	1.5	2	7	.06	282	363
MRS	Amb	7.65	64.7	250	15.1	Nil	12.7	1.4	398	42.1	.26	54.1	.9	74	44	.01	874	1210
GPB	Amb	8.13	68.8	185	13	.06	6.1	.8	378	7.97	.2	13.1	10.8	4	10	.54	640	913
MYK	Amb	8.1	72.3	227	30	Nil	39.1	5.6	448	68.7	.3	33	5.4	7	28	.04	828	1221
NWB	Amb	6.67	84	50	10.7	Nil	18.5	2.4	202	5.4	.13	7.7	2	8	7	Nil	382	890
MR	Amb	7.67	72.9	33	5	Nil	5.3	.6	84	2.6	.3	2.3	.9	4	2	.66	128	160
C-2704	31.5	8.34	84.7	453	37	.13	5.5	1.1	871	13	.4	30	18.5	5	9	.55	1443	1800
C-1287	Amb	7.33	90.4	580	28	.16	16.1	4.4	915	42.4	.4	193.5	16.9	5	42	.6	1874	2500
C-3229	35	7.93	52.9	207	3.1	Nil	6.4	2.1	378	8.3	.4	7.9	10.7	4	7	.49	468	750
C-845	Amb	7.39	104.3	200	24	.21	37.3	3	519	9.7	.13	14.1	5	2	6	.51	898	1000
C-429	Amb	7.8	114.3	433	57	.34	53.9	5.8	950	18.9	.26	57.7	10.9	7	16	.64	1318	1900
ELM	45.5	9.15	135.8	1025	30	.18	.9	.05	1074	80.3	.7	463	150	6	102	1.3	2906	4000
KS	41.0	6.6	74	45	8.2	.05	6	1.3	123	7.5	.4	2.7	7.5	12	2	1.9	165	290
KJS	45	9.08	37.4	90	1.5	Nil	.6	.05	158	2.2	.3	5.03	2.8	7	7	.04	292	330
MS	Amb	6.34	66.7	32	3.7	Nil	6.9	2.5	114	5.7	.26	21.9	.6	2	16	.03		
EW-01	85	9.70	919	2085	365	2.8	Nil	Nil	1804	160	4.08	978	279	32	2	2.1	6718	10307
EW-04	82	10.00	325	810	77	.74	Nil	Nil	455	172	23.5	778	102	195	234	2.2	2637	4015
OW-23	88	9.44	749	350	43	2.3	1	.02	226	46.8	1.63	22.5	112	65	195	4	1530	1953
OW-29	83	8.6	721	579	96	1.4	.3	.1	130	27.1	1.02	608	53.4	159	65	7	2480	3192
OW-714	90	9.67	522	570	106	1.6	Nil	Nil	169	68.4	2.69	635	58.7	174	159	3.2	2334	3267
OW-715	82	9.01	893	576	94	1.56	Nil	Nil	139.7	28.4	1.02	601	33	174	174	3.2	2156	2794
OW-716	81	8.01	635	624	124	2.34	Nil	Nil	60.3	82.5	.26	899	38	240	174	6.2	2908	3938

NB: All the pH were measured at either 20°C or ambient temperature
All the concentrations are in ppm

TABLE 3: Results of analysis from Olkaria laboratory

Loc.	Temp	pH	SiO_2	Na	K	Li	Ca	Mg	CO_2	SO_4	H_2S	Cl	F	I	Br	B	TDS	COND
MFB1	Amb	7.95	47	116	21	Nil	6.2	2.92	290	Nil	.13	28	4			.61	542	650
MFB2	Amb	6.9	139	65	26.2	Nil	29.3	5.03	308	22	.13	23	7			Nil	492	650
MFB3	Amb	8.06	53	99	20.8	Nil	6.1	2.66	264	Nil	.3	51	3			.04	432	660
MFB4	Amb	7.51	68	182	33.5	.08	5.4	1.78	408	39	.5	214	158			.5	636	910
LN	Amb	8.0	66	36	21.4	Nil	7.2	4.96	136.4	Nil	.2	22	3.8			.06	282	363
MRS	Amb	7.65	29	246	19.3	Nil	2.5	1.1	398	46	.26	89	.71			.01	874	1210
GPB	Amb	8.13	49	182	13.6	.06	1.8	.7	378	Nil	.2	95	1.9			.54	640	913
MYK	Amb	8.1	49	209	38	Nil	9.3	4.6	448	45	.3	31	.94			.04	828	1221
NWB	Amb	6.67	39	59	13	Nil	6.1	1.73	202	Nil	.13	30	1			Nil	382	890
MR	Amb	7.67	52	27	9.2	Nil	.8	.48	84	Nil	.3	25	16.5			.66	128	160
C-2704	31.5	8.34	59	433	46.9	.13	1.6	.89	871	28	.4	49	15			.55	1443	1800
C-1287	Amb	7.33	104	563	36.6	.16	2.9	3.26	915	47	.4	62	6			.6	1874	2500
C-3229	35	7.93	25	179	6.6	Nil	2.2	1.6	378	Nil	.4	57	6.6			.49	468	750
C-845	Amb	7.39	52	197	29.4	.21	3.3	1.95	519	Nil	.13	214	3.1			.51	898	1000
C-429	Amb	7.8	68	408	67.5	.34	24	4.54	950	Nil	.26	95	3.5			.64	1318	1900
ELM	45.5	9.15	98	1025	33.7	.18	Nil	Nil	1074	82	.7	555	99			1.3	2906	4000
KS	41.0	6.6	57	50	1.15	.05	2.5	1.14	123	Nil	.4	18	4.4			1.9	165	290
KJS	45	9.08	49	80	1.3	Nil	Nil	Nil	158	Nil	.3	28	11			.04	292	330
MS	Amb	6.34	60	32	7.4	Nil	2.3	Nil	114	Nil	.26	65	Nil			.03		
EW-01	85	9.70	919	2085	365	2.8	Nil	Nil	1804	123	4.08	1039	258			2.1	6718	10307
EW-04	82	10.00	325	810	77	.74	Nil	Nil	455	153	23.5	420	98			2.2	2637	4015
OW-23	88	9.44	749	350	43	2.3	.99	.02	226	20	1.63	259	161			4	1530	1953
OW-29	83	8.6	721	579	96	1.4	.3	.1	130	Nil	1.02	745	41			7	2480	3192
OW-714	90	9.67	522	570	106	1.6	Nil	Nil	169	28	2.69	665	63			3.2	2334	3267
OW-715	82	9.01	893	576	94	1.56	Nil	Nil	139.7	13	1.02	614	28			3.2	2156	2794
OW-716	81	8.01	635	624	124	2.34	Nil	Nil	60.3	71	.26	905	33			6.2	2908	3938

NB: All pH values were either measured at 20°C at ambient temperatures
All the concentrations are in ppm

TABLE 4: Ionic balances, log Q and log K values

Locat.	Ionic bal.	logQ $_{SiO2}$	log.K $_{SiO2}$	log.Q/K$_{SiO2}$	log.Q $_{CaCO3}$	log.K $_{CaCO3}$	logQ/K $_{CaCO3}$
MFB1	2.48	-2.938	-3.646	.708	-8.187	-8.457	.27
MFB2	5.38	-2.867	-3.646	.779	-8.835	-8.457	-.378
MFB3	-4.14	-2.908	-3.583	.675	-8.068	-8.490	.427
MFB4	-7.3	-2.841	-3.534	.693	-8.408	-8.520	.112
LN	-8.33	-3.299	-3.646	.347	-8.504	-8.457	-.047
MRS	8.07	-2.971	-3.583	.612	-8.569	-8.490	-.079
GPB	-9.75	-2.950	-3.583	.633	-8.371	-8.490	.119
MYK	2.22	-2.927	-3.583	.656	-7.618	-8.490	.872
NWB	2.92	-2.855	-3.646	.791	-9.739	-8.457	-1.283
MR	-5.99	-2.918	-3.646	.728	-9.464	-8.457	-1.007
C-2704	-4.89	-2.870	-3.510	.64	-8.001	-8.536	.535
C-1287	3.75	-2.824	-3.583	.759	-8.550	-8.490	-.06
C-3229	1.81	-3.063	-3.463	.4	-8.541	-8.569	.028
C-845	-3.73	-3.064	-3.583	.519	-8.234	-8.490	.256
C-429	-0.82	-2.725	-3.583	.858	-7.489	-8.490	1.001
ELM	-8.33	-3.299	-3.646	.347	-8.326	-8.666	.34
KS	-7.12	-2.910	-3.395	.485	-10.406	-8.625	-.781
KJS	-6.43	-3.292	-3.351	.059	-8.915	-8.666	-.249
MS	-1.96	-2.955	-3.498	.543	-10.719	-8.544	-2.175
EW-01	-7.21	-1.965	-1.906	-.059	-13.271	-13.374	.103
EW-04	-4.97	-2.736	-2.320	-.416	-10.879	-11.059	.18
OW-23	-9.82	-2.045	-1.880	-.165	-12.577	-13.561	-.984
W-29	8.36	-2.063	-1.880	-.183	-14.022	-13.561	-.461
OW-714	9.54	-2.171	-1.919	-.252	-12.629	-13.219	.59
OW-715	-9.11	-1.888	-1.970	.082	-13.615	-12.909	-.706
OW-716	- 0.85	-1.993	-1.905	-.088	-13.705	-13.365	-.34

4. THEORY OF GROUNDWATER CHEMISTRY

4.1 General

Reactions of minerals in rock units and aqueous solutions are controlled by the chemical potentials of the species in solution which depend on the temperature and pressure at the prevailing conditions. Shallow groundwater can be characterized by some major and minor ionic ratios. The ionic ratios have been used worldwide to trace the movement and relative ages of groundwater. A high Cl/SO_4 ratio has, for example, been taken to mean relatively old water. This is because hydrogen sulfide, which is the main source of sulfate, is oxidized at shallow depths, hence shallow waters have higher sulfate concentrations than deeper ones and the above ratio is lower for shallow water than deep waters.

In the Rift Valley such general rules may not apply because of various interfering physical and chemical processes. High evaporation rates have caused high concentrations of chemical constituents, resulting in saline lakes such as Lake Nakuru and Lake Elementeita. Volcanic and magmatic activity such as the emanation of carbon dioxide from depth in some parts of the Rift Valley have also influenced the chemistry of the groundwater (Du Bois and Wabu, 1970). Different rock types such as sedimentary and igneous rocks could also affect the chemistry of the Rift Valley groundwater.

Trace elements, that are conserved in solution, could be useful indicators of flow because the above processes may not affect them drastically. The concentrations of cations such as iron and manganese were too low for the present analytical capabilities. Their solubilities are affected by the pH and this complicates the interpretation of their chemistry. Halides, because of their ability to be conserved in solution, may be used in tracing the movement of groundwater.

4.2 Halogens

The halogens are the only family of elements which has persistent anionic characteristics and they are fairly coherent geochemically. However, the behaviour of individual halides in different compounds is variable. Their distribution in groundwater depends on the distribution of their host minerals.

4.2.1 Fluorine

Volatile fluorine compounds are hydrogen fluoride, and silicon fluoride, both of which have been reported in volcanic gases. Fluorine minerals, which are less abundant than chlorine ones, are mostly found in four groups i.e :

a) Fumarolic deposits which include sellaite (MgF_2) in dolomite rocks, ferruccite ($NaBF_4$) and hieralite (K_2SiF_6).

b) Pneumatolytic and hydrothermal deposits which include fluorite (CaF_2) in hydrothermal veins and as an accessory in granite rocks, fluoborite $\{Mg_3BO_3(F,OH)_3\}$ and villiaumite (NaF) in cavities of alkali rocks.

c) Accessory rock minerals which include topaz $\{Al_2SiO_4(OH,F_2)\}$ in greisenized granite and fluorapatite $\{Ca_5(PO_4)_3F\}$.

d) Pegmatitic minerals, which include cerfluorite $(CaCe)F_{2-3}$, cryolite (Na_3AlF_6).

Weathering of rocks containing fluorine compounds is sensitive to different climatic conditions and the nature of the original fluorine-bearing mineral. The fluorine concentration of the soil has been found to be related to the apatite content. Clays and argillaceous rocks are generally enriched in fluorine because of micaceous minerals (Day, 1964).

Apatite has been reported in dolerite rock in Olkaria geothermal field, (Muchemi, 1985). An abundance of fluorite as an alteration mineral has also been reported in the cavities of acid (rhyolite) rocks, in the same field. A granitic intrusion has been encountered in the bottom of Eburru well EW-01. Fluoride in the rift waters may, thus, be associated with rhyolite, dolerite and granite rocks.

4.2.2 Chlorine

It has been observed that acid fluids in geothermal reservoirs are rare and their occurences in geothermal systems are associated with recent volcanism (Truesdell, 1991). This, according to Truesdell (1991) probably indicates that the geothermal reservoir fluid was derived from volcanic fluid incompletely neutralized by reaction with feldspars and micas. The superheated steam containing HCl forms acid where it condenses or mixes with liquid at moderate temperatures (<300°C). The origin of steam with HCl, according to the same author, is the reaction of NaCl solids with rock minerals at high temperatures (>325°C). This is probably the main source of chlorine in dilute geothermal waters in addition to that present in meteoric water.

Chlorine can occur in nature in the following ways:

a) Chloride ions in solution and evaporites
b) Minerals containing chlorine such as chlorapatite $\{Ca_5(PO_4)_3Cl\}$ and sodalite ($Na_4Al_3Si_3O_{12}Cl$) (Day, 1964).

Apart from evaporation, there is no chemical process that has any appreciable effect on the concentration of chloride ions in aqueous solutions. The only compound which chloride ions can form is perchlorate ion (ClO_4^-) in the dissolution of evaporites.

4.2.3 Bromine

Bromine is a rather scarce element in the earth's crust and there are few natural concentrations of it. The bromine content of igneous rocks is higher than the normal crustal average, thus weathering of these rocks enriches bromine (Day, 1964). There is no indication that bromine occurs in any form but bromide ion, which is relatively unreactive, and thus, a convenient natural tracer in water flow studies, although it can be taken up by organisms and also incorporated into organic compounds such as in humus.

There are few independent bromine minerals in nature. They include bromargyrite (AgBr) and embolite (AgCl, Br) which are both secondary minerals of silver deposits. Bromine has also been found in volcanic emanations (Crowe et al., 1987). The bromide in the rift waters is most likely to be derived from igneous rocks and volcanic emanations since the area is volcanically active.

4.2.4 Iodine

Iodine is a rare element in the earth's crust. Iodine enters some minerals like sodalite and felspars by replacing Cl and OH, despite its large size. Volcanic emanations of iodine are minor and thus, most of it is derived from sea water and carried inland with sea spray. This is the main reason why there are such low iodine concentrations in water from the Rift Valley. Soils in the Rift Valley are relatively young and hence iodine deficient. Old soils have received sea spray for longer than young ones, hence are enriched in iodine. It is no surprise then that Rift Valley waters have very low iodine concentrations because of the distance from the sea. Some iodine minerals are iodoaegyrite (AgI), iodoembolite Ag(Cl,Br,I) and miersite (Ag,Cu)I.

Truesdale (1974) showed that molecular iodine is unstable in seawater and proposed that it may exist in the following forms:

$$I_2 \begin{array}{l} \nearrow IO_3^- + I^- \quad \textit{(Disproportionation)} \\ \left.\begin{array}{l} \rightarrow I^- \\ \searrow RI \end{array}\right\} \begin{array}{l} \textit{Strictly, chemical reduction} \\ \textit{(Organic matter ?)} \end{array} \end{array} \tag{2}$$

To be able to determine all the iodide in the solution, it is important to analyse for all the different forms. Therefore, it is unsuitable as a natural tracer in water flow studies.

4.3 Cations

Giggenbach (1988) showed that relative Na, K, Mg and Ca contents of thermal waters in full equilibrium derived through isochemical recrystallization of an average crustal rock are, at a given temperature and salinity, uniquely fixed. The solute pair Na-K equilibrates most slowly or only at elevated temperatures, while relative K-Mg-contents adjust much faster and at low temperatures. The system K-Ca is sensitive to variations in p_{CO2} and these subsystems have been combined in graphical techniques by Giggenbach (1988) to evaluate deep temperature and p_{CO2} conditions in geothermal systems on the basis of Na, K, Mg and Ca contents. Figure 8 illustrates the use of a Na/1000 - K/100 - $\sqrt{Mg}$ diagram with reference to fluids from some high temperature geothermal wells in Krafla, Iceland, where magmatic activity has disturbed the prevailing chemical equilibrium (Armannsson et al., 1987). In these wells there are basically two aquifers, an upper and relatively cool one that was little affected by magmatic activity and a lower much hotter one that was significantly affected. Well no. 2 is located close to the magmatic inflow and the sample illustrated is taken at the height of activity. Well no. 2 is located further away and the sample is drawn several years after the activity ceased. Wells no. 10 and 25 draw fluids from both aquifers but for the purpose of this diagram the lower aquifer properties have been isolated by calculation. The sample from well no. 10, was drawn at the height of the activity, but that from well no. 25 several years after the activity ceased. The diagram serves to illustrate the superficial effects on the upper aquifer fluids and the more lasting on the lower aquifer ones.

Weathering removes sodium from the rocks and typical minerals of sedimentary rocks are devoid of it. Sodium fluoride, sodium sulfate and sodium carbonate precipitate under certain conditions. There is no natural process which can render the sodium ion insoluble and immobilized except the ones mentioned above. An exchange reaction with potassium in aluminosilicates as shown becomes important with rising temperature,

$$K^+ + Na\text{-}feldspar = K\text{-}feldspar + Na^+ \tag{3}$$

and high temperature geothermal wells have been found to give a generally consistent trend in Na/K ratios with temperature. This property has been used to develop the Na/K ratio geothermometer (Ellis and Mahon, 1977).

4.4 Silica

The weathering of silicate minerals occurs in the following order:

Olivines > pyroxenes > amphiboles > felspars > micas

The feldspars, which are an important group of silicates, do not weather at the same rate. The lime-rich plagioclase is more readily attacked than pure albite or orthoclase. However, the alkali-rich felspathoid minerals like nepheline and leucite are weathered rather easily. Silicon in solution is in the form of SiO^-_4 ion or colloidal silica. The presence of both in solution is controlled by the pH.

In hydrothermal areas silica occurs at different temperature and depths in various forms: quartz, chalcedony, cristobalite, and amorphous silica. Quartz is the stable form of silica, but because the other forms are slow to be converted to quartz in near-neutral pH solutions, other forms exist. The solubility of amorphous silica controls the silica concentration of cold waters.

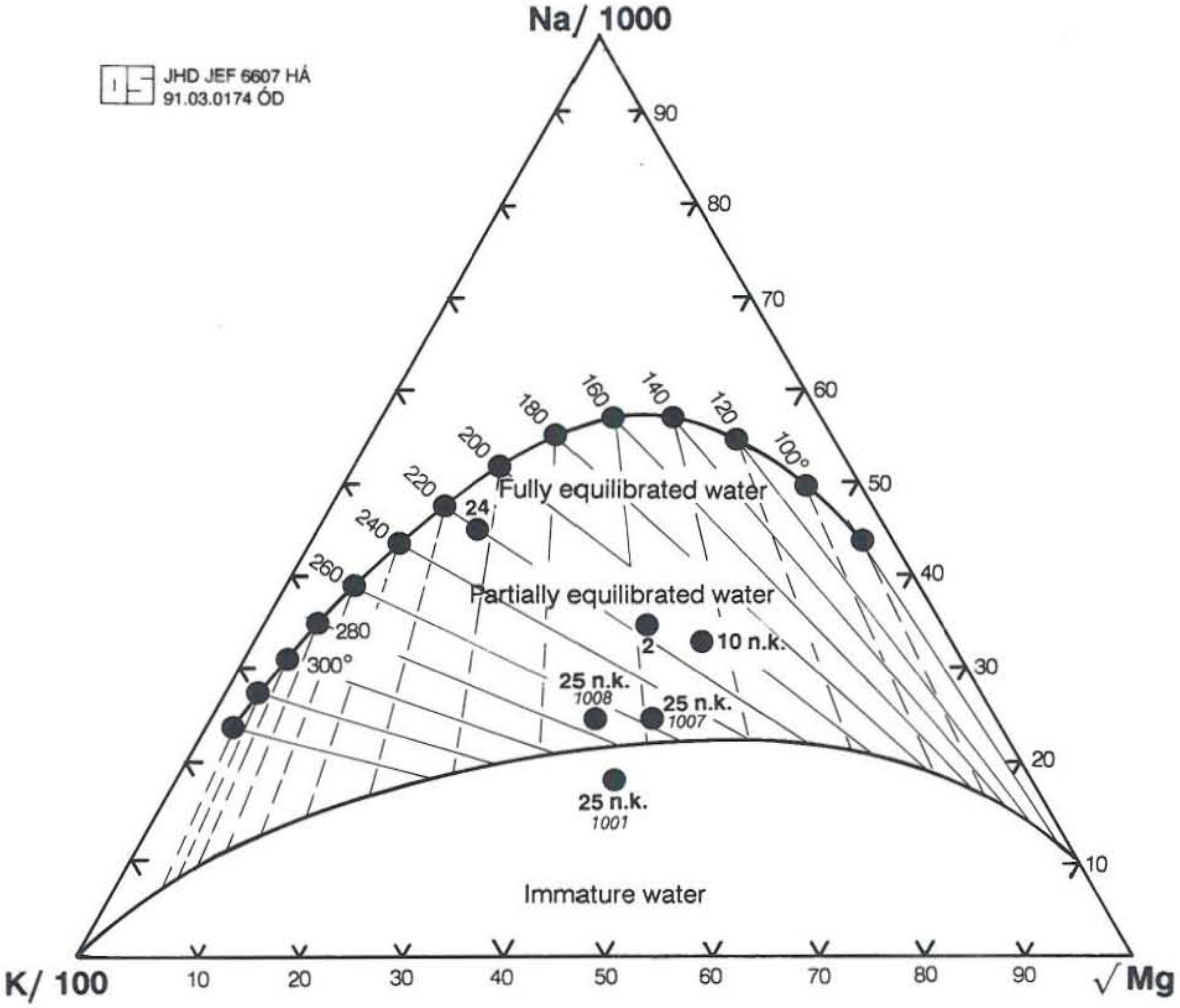


FIGURE 8: Diagram showing how Krafla fluids plot on Giggenbach's triangular diagram;
2 (well 2) - shallow aquifer close to magmatic acitivity, at the height of it;
24 (well 24) - shallow aquifer, off magmatic activity, several years after it ceased;
10 n.k. (well 10) - deep aquifer, close to magmatic activity, at the height of it;
25 n.k. (well 25) - deep aquifer, close to magmatic activity, several years after it ceased

5. EVALUATION OF DATA

5.1 General

Olkaria well OW-23 is situated at the edge of Hells Gate - Njorowa gorge. It is an average well producing about 2 MW_e of power. It is connected to the present 45 MW_e power plant. The water from this well is relatively dilute, compared to other Olkaria wells. Well OW-29 lies in the northern part of the Olkaria East field. It is a powerful well producing more than 5 MW_e of power. It is believed that it intersects the same fault which OW-16 has been speculated to intersect. The water from this well has a higher dissolved solid content than OW-23. Wells OW-714, OW-715, and OW-716 are located in Olkaria Northeast (Figure 5). OW-716 is at the edge of the field and is a powerful well producing about 5 MW_e of power. The liquid fraction of its mass flow is small and the water from this well is rich in dissolved solids. Well OW-714 is near the X-2 camp and it produces about 5 MW_e of power. Well OW-715 also produces about 5 MW_e of power and the liquid fractions of the mass flow of both wells are large. The chemical composition of water from the two wells is similar.

Lake Naivasha is recharged mainly by two rivers, Gilgil and Malewa, both of which flow into the northern part of the lake. The lake water sample was taken from the southern shore and is expected to be slightly concentrated with respect to chemical constituents due to evaporation. Musyoka's and Munyua railway station boreholes are between the lake and Mt. Longonot. The water from both boreholes is cold and does not seem to have been derived from geothermal waters. The chloride and sodium concentrations of the water from the two boreholes are higher than those of the water from the boreholes around Lake Naivasha. The Naivasha town borehole is the closest one to Lake Naivasha and the chemical composition of water from it is generally similar to that of the lake. All the Marula farm boreholes and the Green Park borehole are between lake Naivasha and Gilgil Town. Marula farm borehole 2 is close to the lake and its water chemistry is similar to that of the lake water. Marula farm borehole 4 is close to Kinangop Escarpment while the Green Park borehole is at the foot of the Eburru hills sloping towards Lake Naivasha. The sodium concentrations of the waters from these two boreholes are slightly higher than those of water from the other boreholes. The river Morendati is a tributary of River Gilgil, whose water is part of the recharge to Lake Naivasha. Its water is dilute, although the silica concentration is similar to that of the water from the neighbouring boreholes.

Eburru well EW-01 is situated in the Eburru crater and produces 2.5 MW_e of power. The water from this well is richer in dissolved solids than the ones at Olkaria. Well EW-04 which is about one kilometer from EW-01, could not discharge at all at first but after stimulation it could produce water at the local boiling point temperature. The water from this well has almost the same chemical composition as that in most Olkaria wells. The boreholes in the Elementeita area and Elementeita spring are believed to derive their waters from the outflow from the Eburru field. The water from Elementeita spring is at 45°C, and rich in dissolved solids. C-2704 and C-3229 are the only boreholes in this area with warm water, 31.5°C and 35°C respectively. The others, C-845, C-429 and C-1287, are at ambient temperatures, although the chemistry of water from them shows the influence of geothermal water.

The Kariandusi warm escarpment spring is situated to the north of Gilgil town. The water from this spring is free from any scaling and its chemical composition is similar to the River Morendati water. The Kijabe spring, which is also a warm escarpment spring, is situated at the foot of the Kikuyu escarpment. The water from this spring is more concentrated than that from the Kariandusi spring. The Mayer's Farm spring is also at the foot of the Kikuyu Escarpment and its water is at ambient temperature. The chemical composition of water from this spring is probably not related to that of the rift floor water under discussion.

Arnorsson and Barnes (1983) have studied the carbon dioxide waters of Iceland and suggested that waters containing >300 ppm CO_2, be defined as CO_2-rich. Using this, the waters from Marula farm boreholes 2 and 4, the Munyua railway station, Green Park, Musyoka's, C-2704, C-1287, C-3229, C-845, C-428 borehole waters, Elementeita spring as well as the Eburru well waters can be regarded as carbon-dioxide rich, but none of the other waters can be regarded as deficient in carbon dioxide. The concentration of carbon dioxide in groundwater controls the pH by reacting with water to form weak carbonic acid. The pH, in turn, controls the dissolution of most cations. Most ionic carbon in nature is in the form of carbonate and bicarbonate ions whose mobility is controlled by carbon dioxide either in the atmosphere or through magmatic emanations. A major factor in its water chemistry is the relatively poor solubility of calcium carbonate and thus, the potential deposition of calcite is an important control in the chemistry of natural waters.

5.2 Halide diagrams

Major and trace element concentrations plotted on correlation diagrams are a useful aid in understanding the movement of the groundwaters. Correlation diagrams were used to study the fractionation of elements and chemical changes in spring, River Morendati, Lake Naivasha and borehole (cold water and geothermal) waters. They are used to determine the degree to which the mixing of river water, escarpment spring water and groundwater determined the lake water composition. The influence of hydrothermal processes in geothermal waters were used to visualize the degree to which the river water, the escarpment spring water and the groundwater defined the lake and the geothermal water compositions.

Evaluation of the correlation between more than two species is most conveniently carried out by use of triangular diagrams. Their construction requires the conversion of absolute values to relative ones (percentages) through the application of linear scaling or normalizing factors. The advantage of a triangular diagram is its ability to represent data for solutions of different salinities in one diagram, so all points obtained for waters of the same chemical origin will plot on a line. It can also show up points representing the mixing of various waters.

5.2.1 Chloride / Bromide x 100 - correlation diagram

Chloride and bromide are conservative constituents in solution during the passage of groundwater, and the physical processes that take place during its passage may be reflected by the two. The chloride and bromide concentrations in most waters from the area are generally low. There is, however, a gradual increase of both anions away from the lake. The lowest concentrations are found in Kariandusi spring and River Morendati, but the highest in the geothermal fluids.

Figure 9 shows that a line can be drawn from the lake water values through the cold borehole ones to the geothermal ones. Values for Kariandusi spring, River Morendati and Marula Farm borehole 2 (just north of the lake) waters are slightly below the line. The Naivasha Town water is almost the same as the lake water. Another line can be drawn through the values for the Green Park borehole, Marula Farm borehole 4, Musyoka's borehole, Mayer Farm spring and Munyua Railway station borehole waters. None of these boreholes are directly north or south of Lake Naivasha, but slightly to the east or the west of the lake.

5.2.2 Fluoride / Bromide x 100 - correlation diagram

The borehole, lake, escarpment spring, and river waters have generally low fluoride concentrations while Elementeita spring and the geothermal wells have higher concentrations (Figure 10). The borehole waters north of Lake Naivasha generally have higher fluoride concentrations than those to the south. This is supported by analysis of the escarpment spring waters. It is also observed that Olkaria well waters have relatively lower fluoride concentrations than the Eburru well waters although that of EW-04 is low. Olkaria well OW-23 water has a relatively higher fluoride concentration than water from other Olkaria wells.

Since the fluoride concentration of the water depends on the rock units the water must have interacted with, then the rocks north of Lake Naivasha, the pantellerites and the basalts which are dominant in this part of the area, must control it. In Olkaria peralkaline trachytes and comendites probably control the fluoride concentration.

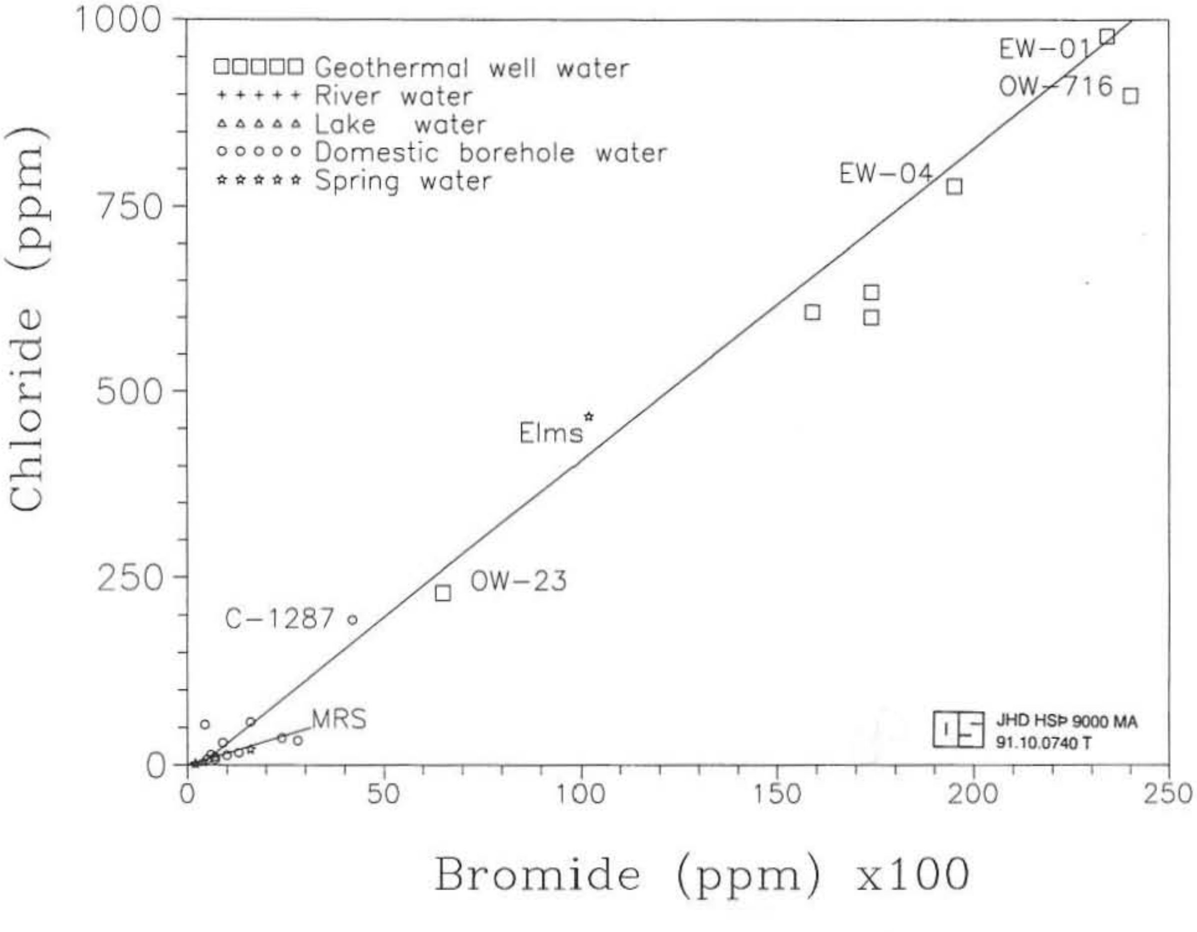


FIGURE 9: Chloride / Bromide x 100 - correlation diagram

5.2.3 Iodide x 1000 / Bromide x 100 - correlation diagram

The iodine concentration in Rift Valley water is very low, as expected, because of the great distance from the sea. The iodine concentration in almost all the waters in the rift is the same, except for that from the Munyua Railway station borehole whose concentration is higher than that of warm and cold borehole waters (Figure 11). The geothermal well water has a higher iodine concentration, with Eburru well water containing more than Olkaria well water. Olkaria OW-23 water contains relatively less iodine than the rest of the well waters and Elementaita spring water contains much less than expected. This may be because iodide ion was the only form determined. Other forms may exist.

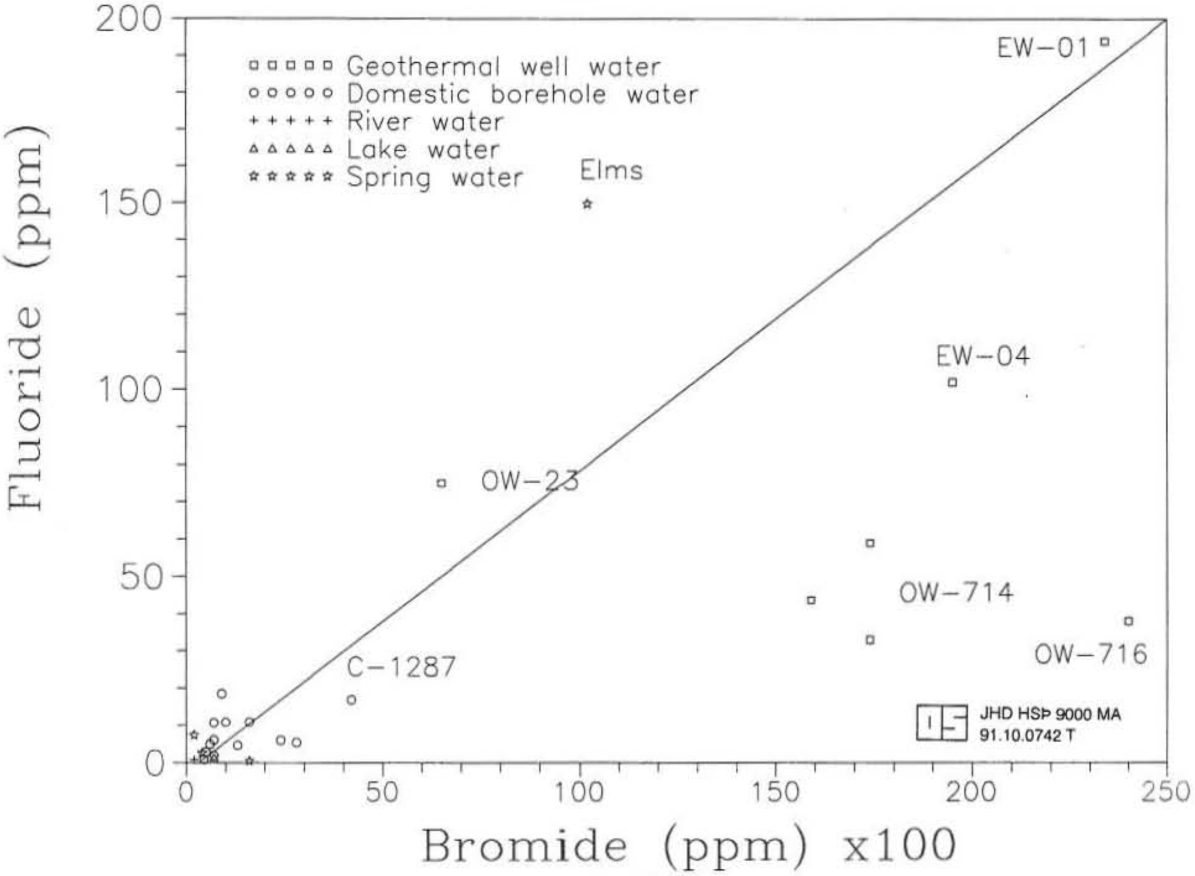


FIGURE 10: Fluoride / Bromide x 100 - correlation diagram

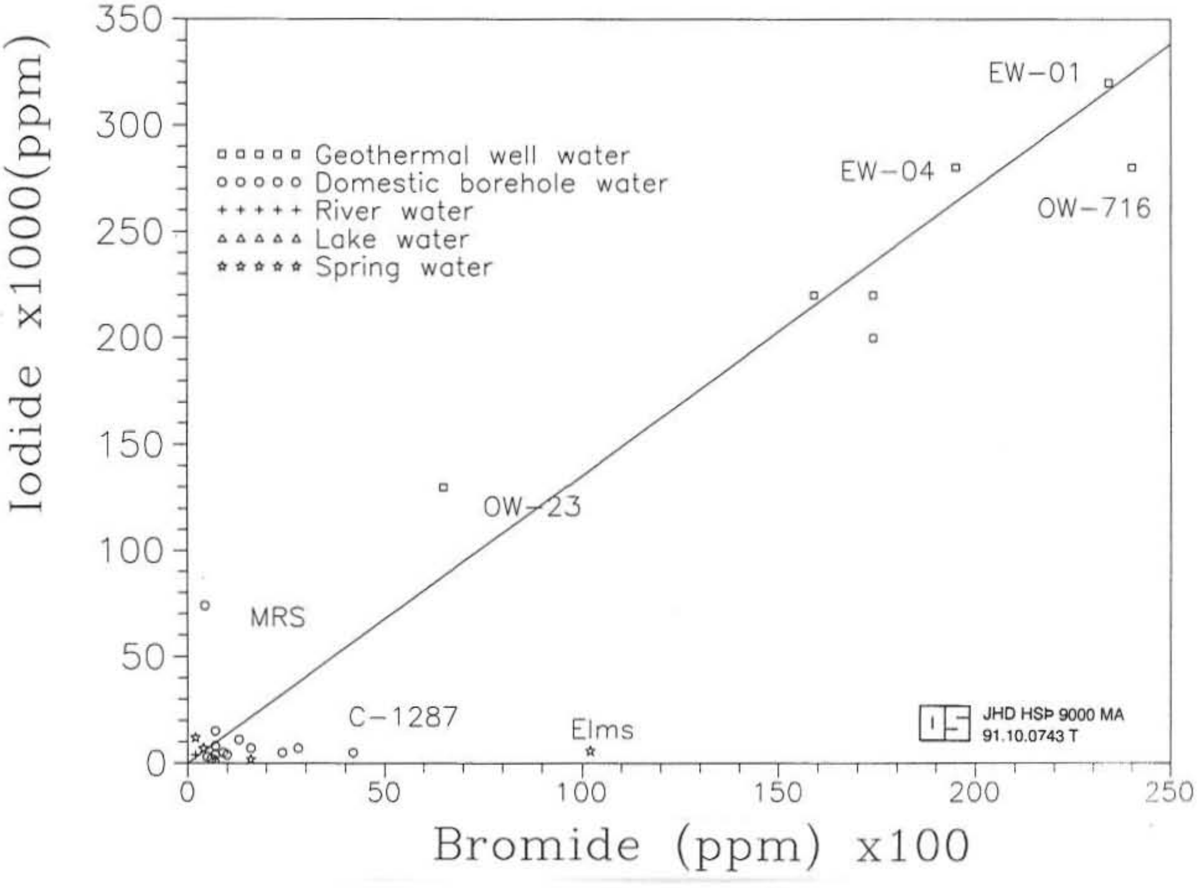


FIGURE 11: Iodide x 1000 / Bromide x 100 - correlation diagram

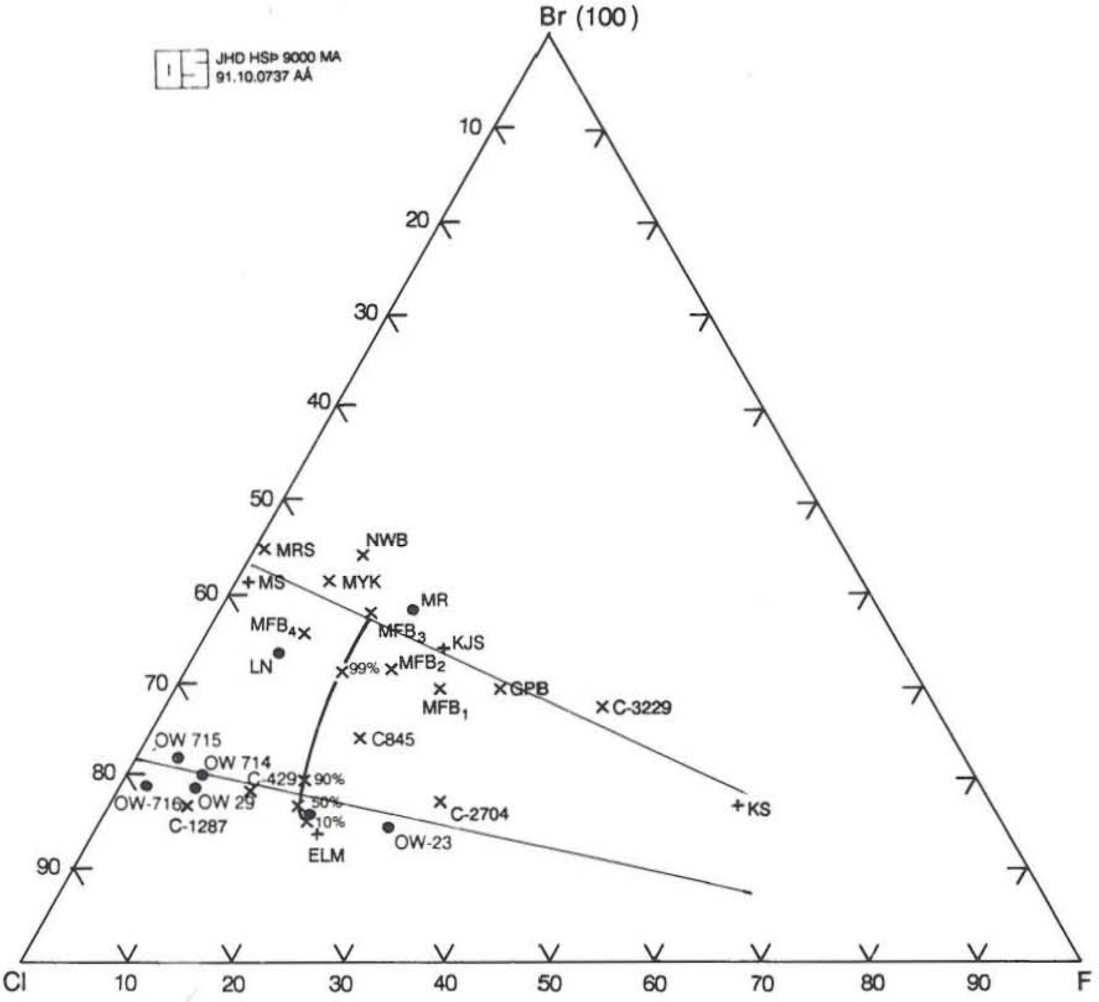


FIGURE 12: Cl - F - Br x 100 - diagram

5.2.4 Cl - F - Br x 100 - diagram

Figure 12 shows two groups of waters. The first group represents the groundwater in the rift floor, including the escarpment springs, lake and river waters. The points spread towards the fluoride corner. Kariandusi spring water is at the end of the spread with the highest fluoride ratio, while Munyua railway borehole and Mayer Farm spring waters are at the other end with the lowest fluoride ratio. Lake Naivasha water plots slightly away from the spread towards the chloride corner, while Naivasha Town borehole (NWB) water plots away towards the bromide corner. The diagram has also been used to study the mixing of the Rift Valley groundwater and geothermal water (see 6.1).

The second group is composed of waters from geothermal wells and boreholes and springs associated with geothermal activity. They plot almost parallel to Cl-F line with Olkaria wells OW-715 and 716 waters near the chloride corner and C-2704 towards the fluoride corner.

5.3 Cation diagrams

Cations considered in the study are sodium, potassium, calcium and magnesium because of their coexistence in full equilibrium assemblage at a given temperature. Correlation as well as triangular diagrams are also used to study chemical processes of the water in the area.

5.3.1 Sodium / Bromide x 100 - correlation diagram

Sodium concentrations in the borehole waters range from 50 ppm (NWB) to 580 ppm (C-1287). The Mayer's Farm Spring water has the lowest, and Kijabe spring the highest sodium concentration among the escarpment springs. Geothermal well waters generally have relatively high sodium concentrations, and water from Eburru well EW-01 has a higher one than Olkaria well waters.

Figure 13 shows that the values for lake, river, escarpment spring and most borehole waters are clustered near the origin. Values for Elementeita borehole waters, Elementeita spring and Olkaria OW-23 waters are in the middle and Eburru well EW-01 water at the end of a line that connects cold borehole water and geothermal water values. Olkaria well water values plot well off this line, but if a line connecting values for Olkaria well waters and lake water is drawn, no borehole water values plot on it. Values for C-2704 and C-1287 waters plot above the first named line and Mayer Farm spring and Munyua Railway station borehole water values plot below it.

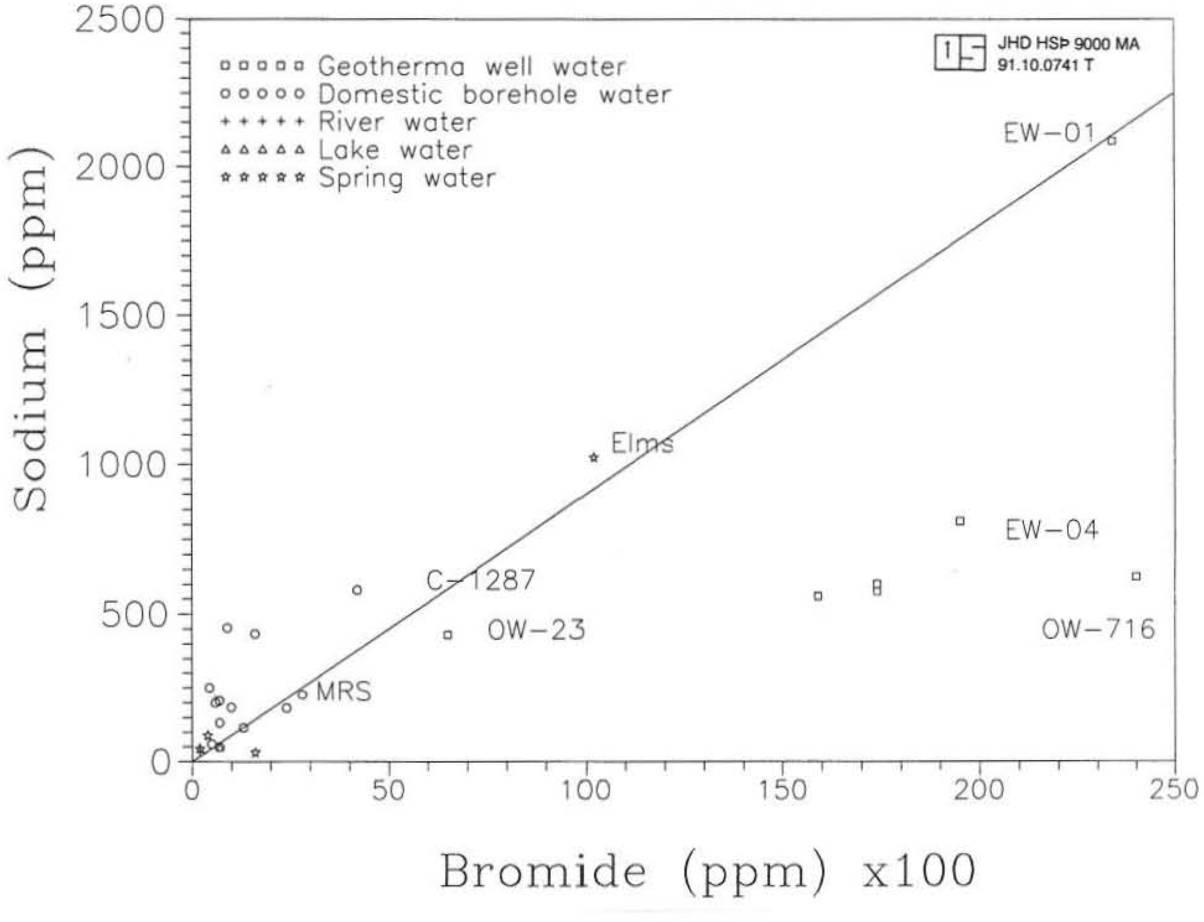


FIGURE 13: Sodium / Bromide x 100 - correlation diagram

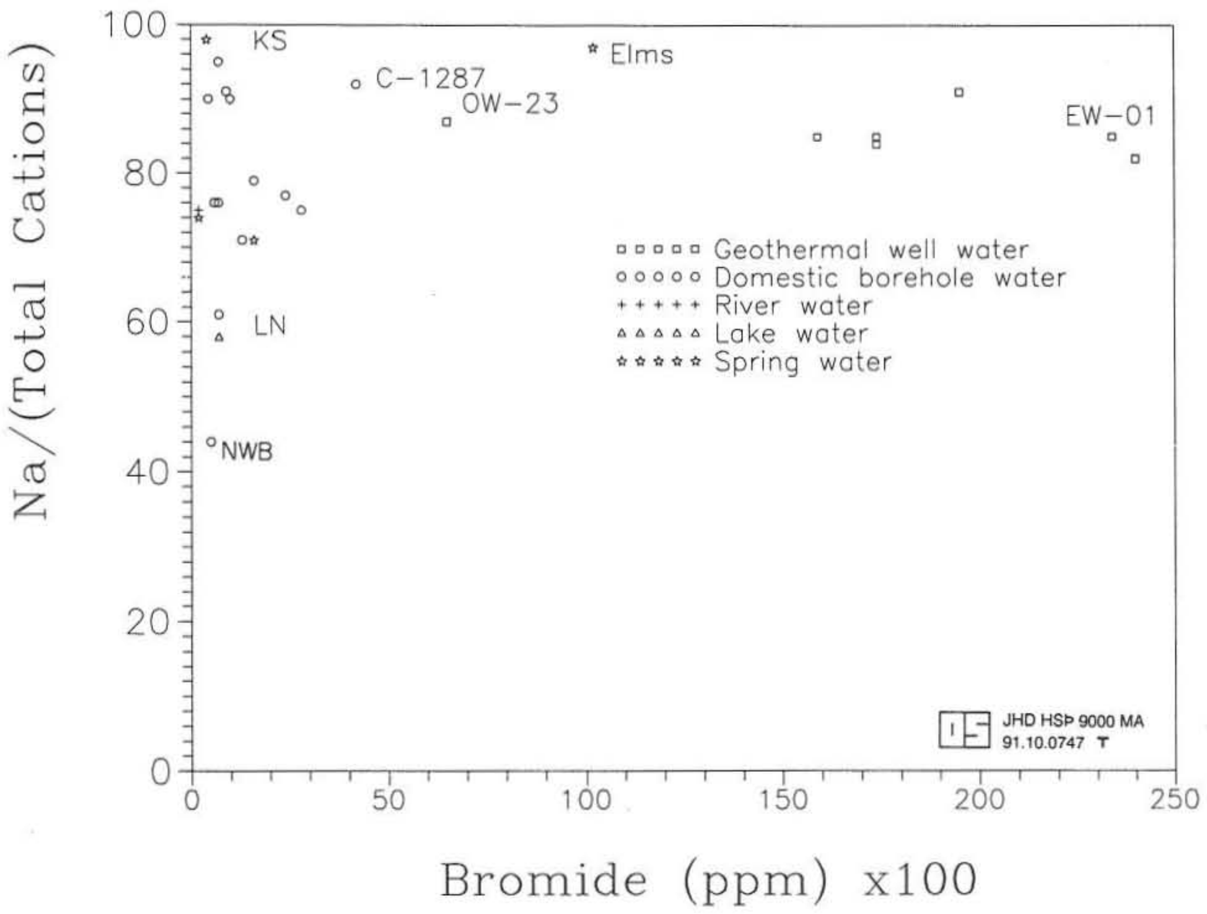


FIGURE 14: Na/(Total cations)% / Bromide x 100 - correlation diagram

5.3.2 Na/(Total cations)% / Bromide x 100 - correlation diagram

The sodium concentration was expressed in terms of its percentage of total cations to facilitate the observation of changes occurring as water moves from the escarpment to the rift floor. This was done to see the effect of weathering of feldspars and other minerals.

Figure 14 shows three types of water as follows:
a) High Na/(Total cation) ratio and low bromide concentration
b) High Na/(Total cation) ratio and high bromide concentration
c) Low Na/(Total cation) ratio and low bromide concentration

The first group consists of escarpment spring, river and all borehole waters except those from the Musyoka's, Munyua Railway station and C-1287 boreholes which fall within the second group. The second group of geothermal well and Elementaita spring waters, as well as waters from boreholes that did not fit into the first group as mentioned above. The third group consists of Lake Naivasha and Naivasha Town borehole waters.

The diagram shows that the waters from the escarpment, or near it, have high Na/(Total cation) ratios due to extensive weathering of feldspars, and as the water moves towards the rift floor, other cations are dissolved and lower this ratio. In the lake water the ratio is low, perhaps due to other processes that favour dissolution of the other cations as may be expected from the water's relatively long residence time in the lake. In geothermal well waters the ratio is high, due to conservation and high solubility of sodium ion, while the others are precipitated or have low solubilities. At elevated temperatures, sodium is involved in ionic-exchange with potassium which lowers this ratio.

5.3.3 Sodium / Chloride - correlation diagram

The rift floor borehole waters tend to plot parallel to the sodium axis, suggesting that sodium is extracted fairly fast from the rocks while chloride is conserved. It is difficult to draw a line connecting the borehole waters and the geothermal waters. The values of the rift floor and rift escarpment waters plot close to the origin representing first sodium uptake then evaporation. The sodium values for geothermal waters are controlled by ion exchange after evaporation (Figure 15). The sodium concentration for waters from C-429, C-2704 and C-1287 are slightly higher than the rest of the values of the rift floor waters. This may suggest the influence of geothermal water in these waters. The chloride concentration for water from Olkaria wells, except OW-23, is relatively high but that of the Eburru well EW-01 water is the highest. The reasons for this may either be that the Eburru well EW-01 water has undergone more evaporation than the Olkaria one, or that the origins of the two waters are different.

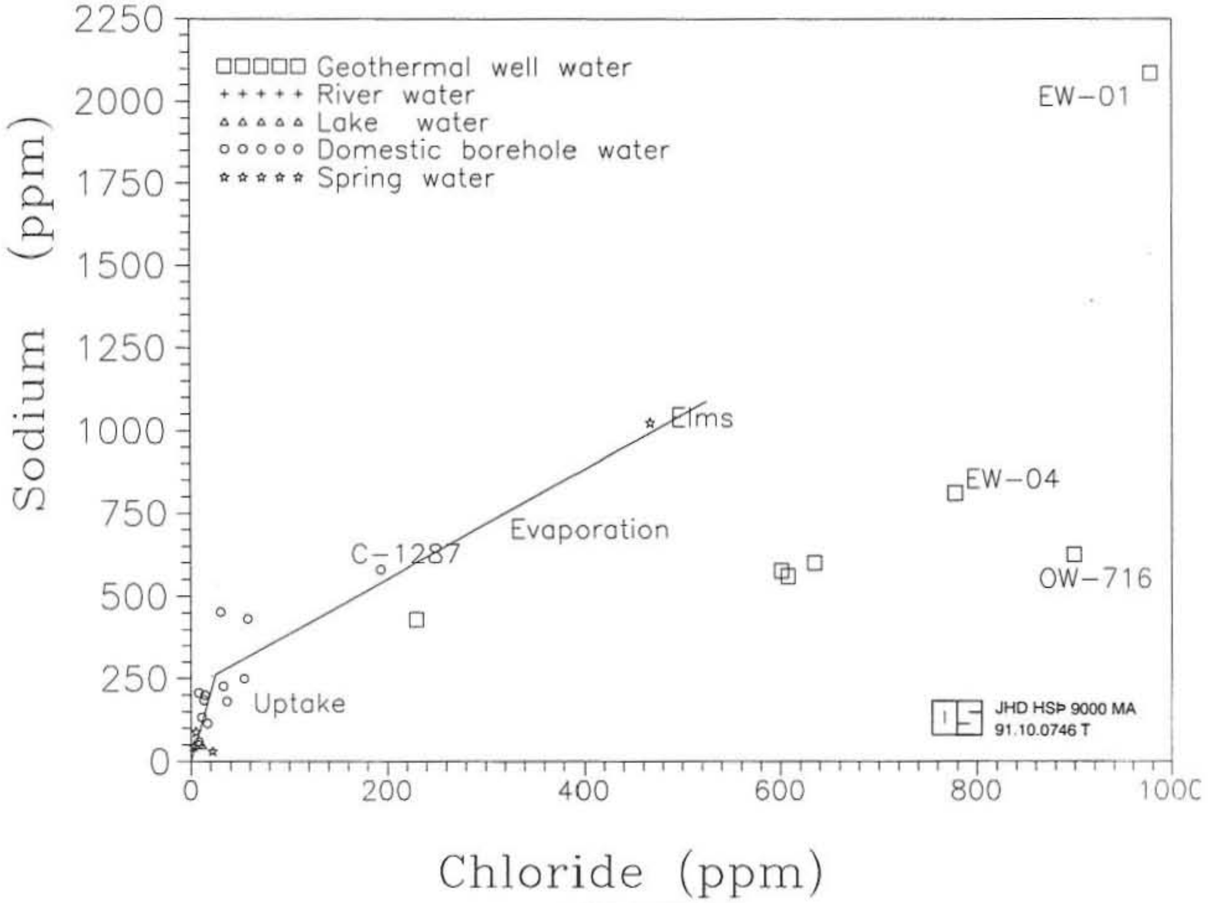


FIGURE 15: Sodium / Chloride - correlation diagram

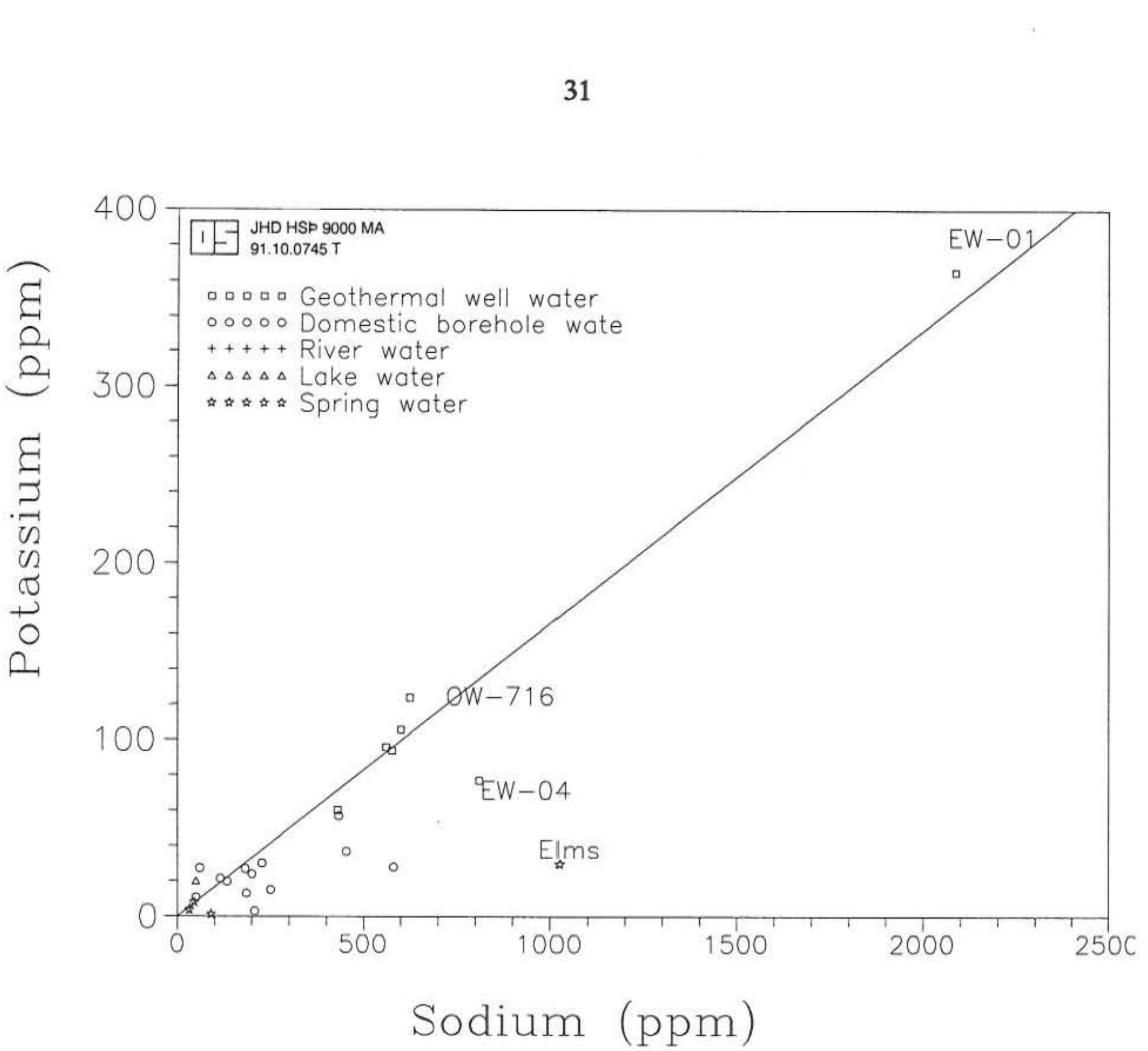


FIGURE 16: Potassium / Sodium - correlation diagram

5.3.4 Potassium / Sodium - correlation diagram

A line connecting potassium and sodium values for the groundwater and those of the geothermal wells can be drawn (Figure 16). The values for EW-04, C-3229, C-1287, C-2704, Munyua railway borehole (MRS) , Green Park borhole (GPB) and Elementeita spring waters plot slightly away from the line. The values for Kijabe spring (KJS) and Mayer's Farm spring (MS) also plot away from the line. The sodium concentration for Green Park borehole, Munyua railway station borehole and escarpment spring waters may be controlled by dissolution rather than ion-exchange. The potassium concentration for waters from EW-04, Elementeita boreholes which plot away from the line and Elementeita spring is low because potassium is taken up in the formation of clay minerals.

5.3.5 Log (meq Na) / log (meq Cl) - correlation diagram

A log-log plot was done to see the effect of evaporation of water in the rift floor. As mentioned earlier, the cation and anion concentrations increase away from the lake. The log-log plot shows whether the increase is due to evaporation in the rift floor. If the points lie on a 45° line, regardless of initial ratio between the initial concentrations of the species being plotted, then the increase would be due to evaporation and not interaction with rocks.

Figure 17 shows that all the borehole, lake, river and escarpment spring waters plot in the general direction of a 45° line. The geothermal well waters and Elementeita spring water plot slightly away because sodium is exchanged with potassium in thermal waters. The diagram suggests that the increase of chloride away from Lake Naivasha is controlled by evaporation.

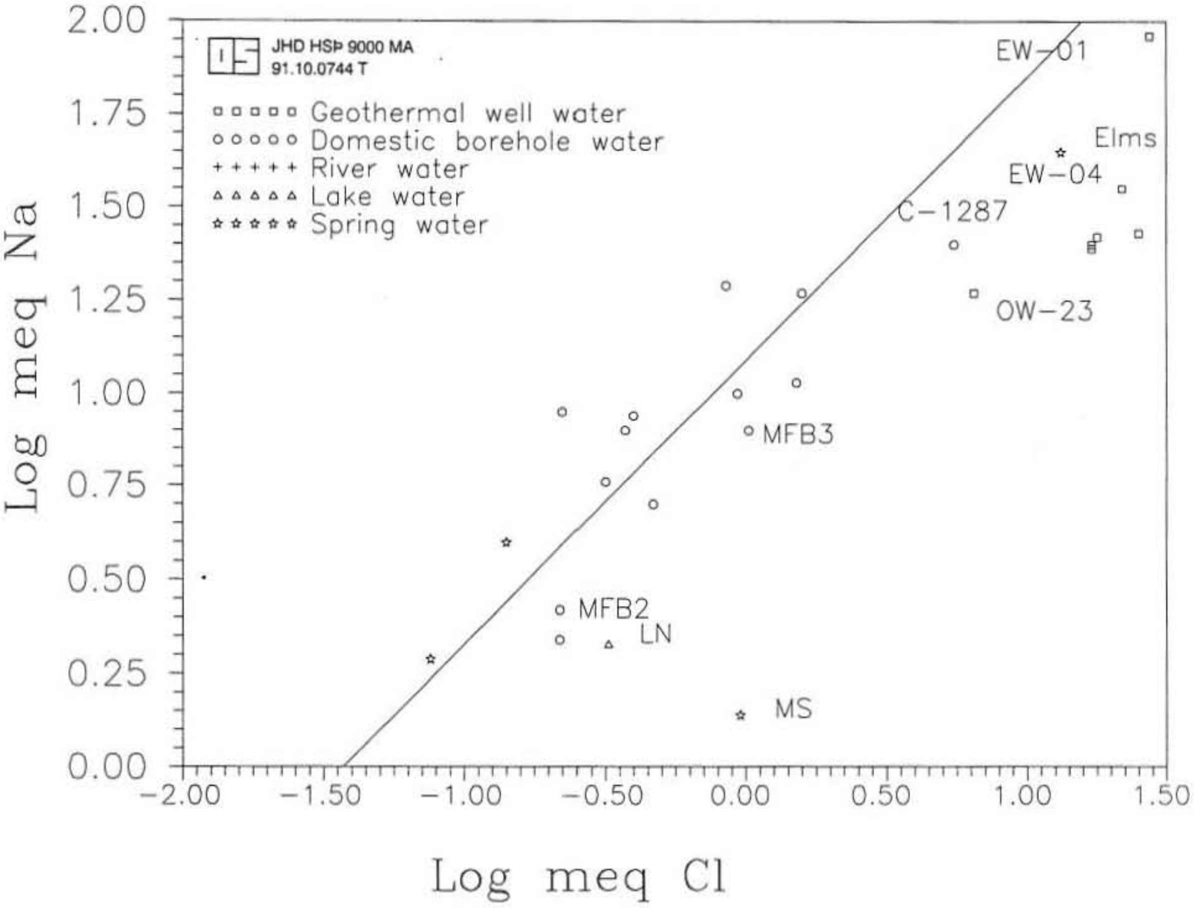


FIGURE 17: Log (meq Na) / log (meq Cl) - correlation diagram

5.3.6 Na - K - Ca - diagram

Figure 18 shows four types of waters. The first group is composed of lake water, Marula borehole 2 and Naivasha Town water supply borehole waters. These waters plot near the Ca corner. The second group is composed of waters from Mayer's Farm spring, C-845, River Morenadati, Marula Farm boreholes 1 and 4, Musyoka's borehole, Kariandusi spring, and C-429. The group cluster around 75% Na and 10% K and calcium is lower than the first group. The third group is composed of Munyua railway station borehole, C-1287, C-2704, Green Park and C-3229 borehole waters. This group has lower calcium than the second group. The fourth group is composed of geothermal wells, which plot along the Na-K line, and Elementaita spring, Kijabe Spring which plot at the apex Na.

The data for two boreholes to the west of the lake were extracted from British Geological Survey report and plotted on the diagram. Maella (MLB) borehole, which is close to the lake, plotted among the first group, while the Ndabibi (NDB) borehole,which is further west, plotted among the second group.

The diagram shows the influence of carbon dioxide on calcium. The calcium concentration of waters with high carbon dioxide concentrations tends to be low.

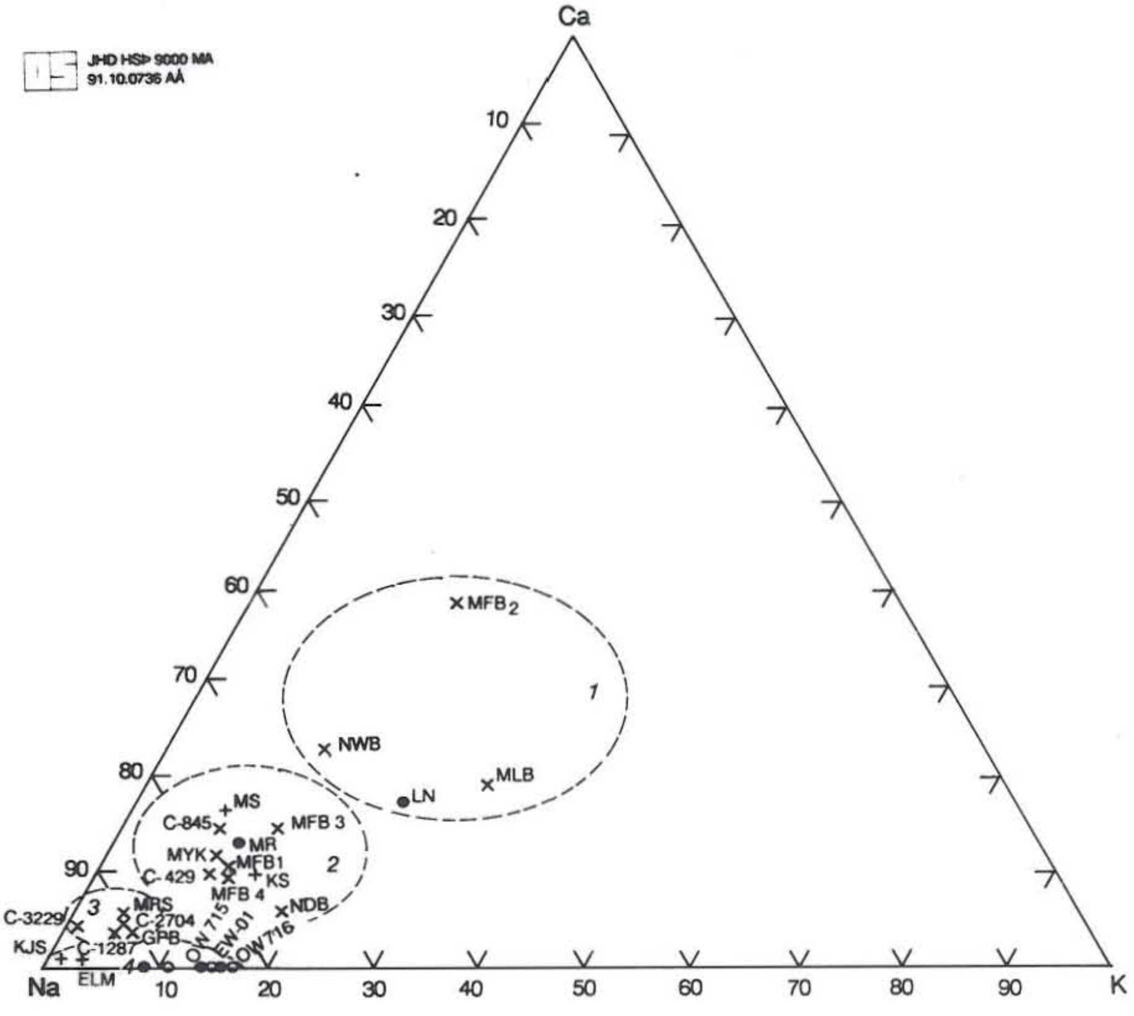


FIGURE 18: Na - K - Ca - diagram

5.3.7 Na / 1000 - K / 100 - √Mg - diagram

Figure 19 shows that all the waters from the cold boreholes except C-2704 and C-1287 are immature. Water from Lake Naivasha plots away from the other immature waters. This may be due to evaporation and some other processes taking place in the lake. Waters from Kijabe spring, C-2704, and C-1287 are the only ones which are partially equilibrated. Waters from Olkaria wells are all partially equilibrated while Eburru well waters are fully equilibrated at 280°C and 250°C respectively. Water from Elementeita spring plots above the equilibration curve so it is taken to represent fully equilibrated water but possibly mixed with a cooler water at around 150°C.

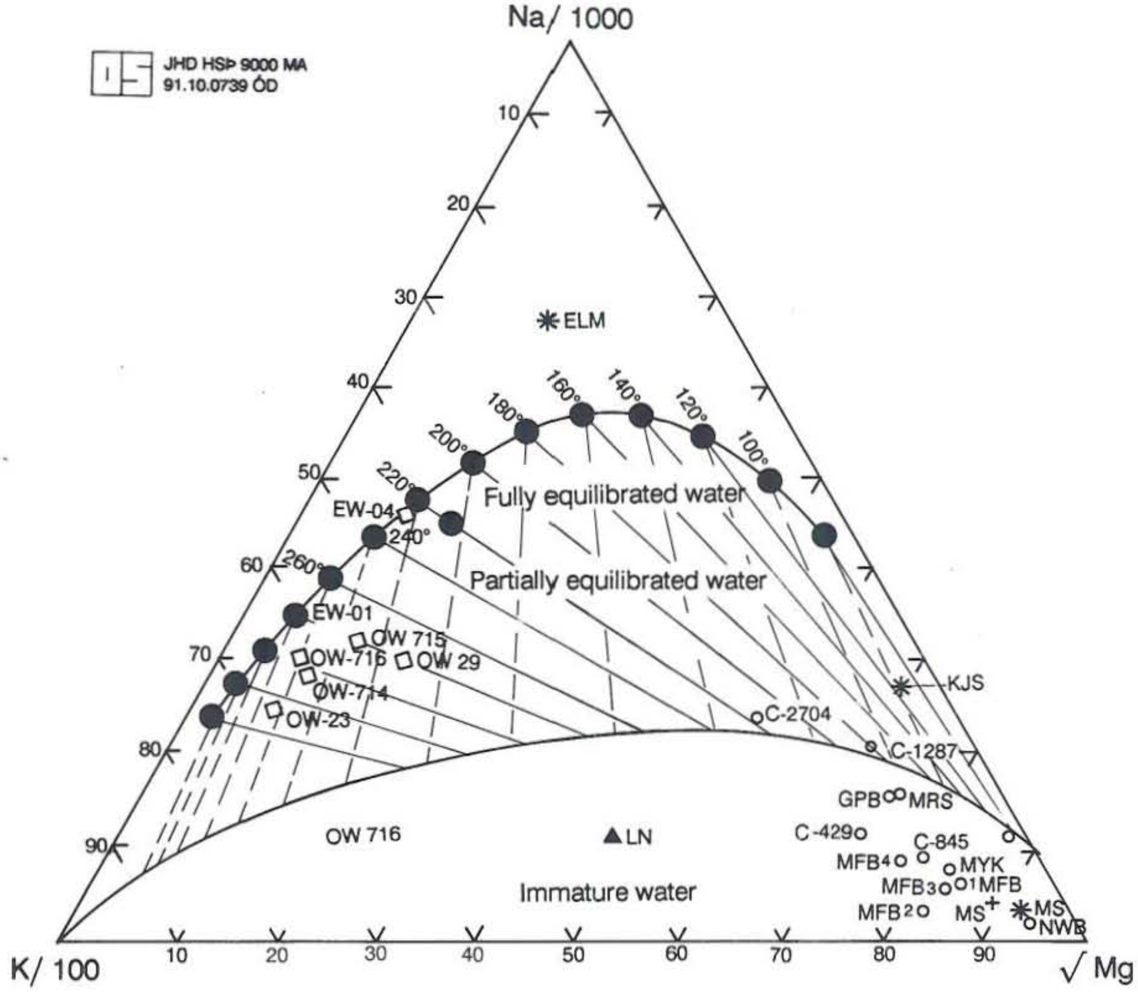


FIGURE 19: Na / 1000 - K / 100 - √Mg - diagram

5.4 Silica

All the waters in the rift floor are over-saturated with respect to chalcedony while geothermal waters, except for water from OW-715, are under-saturated (Table 4). The waters from EW-01, OW-715 and OW-716 are supersaturated with respect to quartz, while the other geothermal waters are undersaturated. No relationship of silica with other constituents were found for the escarpment, rift floor and geothermal waters.

6. DISCUSSION

6.1 Summary of results

The various diagrams used in the study have shown that the escarpment waters, the rivers and the groundwater in the rift floor are related to the lake water. Since the lake is at the culmination of the rift floor, its water recharges some of the boreholes to the north and south of it. The diagrams have provided chemical evidence for this suggestion. Since the concentrations of many constituents increase away from Lake Naivasha (Figure 17), the lake is not likely to be an exposed groundwater table where the concentrations would increase towards the lake due to a relatively high evaporation on the lake. This is because in an exposed groundwater table, the flow should be in one direction, e.g. from the rift floor level to the lake, and away from the lake in the opposite direction. This is not observed in the study, where the flow is from the lake in both northern and southern directions.

The Cl/Br diagram (Figure 9) shows a strong correlation between the escarpment, rift floor and the geothermal waters. Both Olkaria and Eburru well waters have almost the same Cl/Br ratio and that may mean that both reservoirs get their waters from the same origin. It is not clear from this study whether the geothermal reservoirs get their recharge from the escarpment waters only or from the rift groundwater, since there is a good correlation between waters from all the locations in the study area. The study agreed well with the isotope studies and, therefore, it may be suggested that the geothermal reservoirs of both Olkaria and Eburru fields are recharged by rift groundwater. Lake Naivasha recharges most of the boreholes around it. Well OW-23 water is the one with the lowest chloride and bromide concentrations, although the ratio between the two anions in the water is almost the same as the one for the other wells. This may mean that water enters Olkaria geothermal reservoir near this well.

The Cl/Br values for the waters from the Green Park borehole, Marula Farm borehole 4, Musyoka's borehole and Munyua railway station borehole seem to plot on a different line than those for the rest of the boreholes. These boreholes are not directly north or south of Lake Naivasha and may be the permeability towards them is poorer than that to the north and south of the lake. Bromide becomes more concentrated with respect to chloride upon intense evaporation. The waters in these boreholes may have undergone more intense evaporation than those from the rest of the boreholes and water from the lake may take a relatively long time to reach these boreholes.

Dilution factors between waters from Eburru well EW-01 and the waters from the boreholes with relatively high chloride and bromide concentrations and Elementaita spring were calculated (Table 5). The bromide and chloride dilution factors between EW-01 and EW-04, Elementeita spring,

TABLE 5: Dilution of constituents from EW-01 water to some other waters

Dilution to	Cl	Br	Na	K	F
EW-04	1.26	1.2	2.57	4.74	2.75
Elm Spring	2.11	2.29	2.03	12.17	1.86
C-1287	5.05	5.57	3.59	13.04	16.52
C-429	16.94	14.6	4.82	6.4	25.6
C-2704	32.54	26.0	2.29	9.86	13.92
C-845	69.3	39.0	10.42	15.21	5.58

C-1287, C-429, and C-2704 show the conservative nature of the two ions. Water from C-845 has different dilution factors for bromide and chloride, suggesting that water from this borehole may not be derived from geothermal water from Eburru. The dilution factors for Na, K, and F for waters from the same wells are not consistent, because of other processes that affect them.

In Figure 10 all the Olkaria well waters, except OW-23, plot away from that of Eburru well EW-01, but EW-04 water plots with Olkaria well waters. OW-23 water has a relatively high fluoride concentration compared to the rest of Olkaria waters. The reason why the Olkaria well waters have lower fluoride concentrations may be due to different rock types, but the results for the OW-23 water may suggest that processes other than leaching from different rock types could cause this. The sodium concentration of Eburru well EW-01 water is higher than that of Olkaria well waters. This may be explained by the fact that Eburru waters are fully equilibrated with reservoir rocks. The waters from all the locations are over-saturated with respect to silica, except for the geothermal well waters. Silica is dissolved in water to a greater extent than it is precipitated since the amorphous silica which controls the precipitation is much more soluble than quartz which controls the dissolution. The rate comes into it because the precipitation of quartz is slower than that of amorphous silica. The geothermal well waters have high silica concentrations corresponding to the reservoir temperature of the field. Table 4 reveals that most of the geothermal well waters are slightly under-saturated with respect to chalcedony whereas cold borehole waters are saturated with respect to it.

The iodide concentration is almost uniform for all the rift floor waters, including Elementeita spring. The reason may lie in the form of iodine determined in the laboratory. As mentioned earlier, iodine can exist in various forms as iodide, a molecular compound, iodate and as an organic compound. What was analysed was the iodide ion.

The Na/(Total cations)% was calculated to check the weathering of feldspars with the water flow from the rift escarpment to the rift floor. Figure 13 shows that Marula Farm borehole 2, Naivasha Town borehole and Lake Naivasha waters have the lowest percentage of sodium. The diagram may suggest that as the water flows from the rift escarpment towards the rift floor, sodium is dissolved more quickly from feldspars and other sodium minerals than the other cations. As the water moves on, the other cations are also dissolved and the percentage drops. In the lake the percentage further drops because of other processes, such as ion-exchange and the dissolution of other cations. The lake water then flows to recharge the boreholes, and evaporation controls the sodium concentration at lower temperatures. As the residence time becomes shorter again when the water leaves the lake, sodium uptake can be expected to become faster than that of the other cations again, and the percentage rises. The geothermal activity both in Olkaria and Eburru further raises the percentage because although ion-exchange with potassium controls its concentration, the concentrations of the other cations are very low.

The two boreholes close to Lake Naivasha could derive water from a part of the lake which is buried. The differences between the Na percentage of total cations in the lake water and the water from these two boreholes may be due to evaporation in the open lake. This may be supported by the fact that the concentrations of many species in the waters from these places are similar. The diagram may suggest that waters with high Na percentage of total cations and low bromide concentration could be flowing towards the rift floor, and the ones with high Na percentage of total cations and high bromide concentration could be flowing along the rift floor. If this is true, then Kijabe spring, C-3329, C-2704, Green Park borehole,River Morendati, C-845 and Marula Farm borehole waters flow towards the rift floor, while Marula Farm borehole 3 and 4, C-429, C-1287, Musyoka's borehole, Munyua railway station borehole, Elementeita spring and all the geothermal well waters flow along the rift floor.

The Cl - F - Br - diagram (Figure 12) was used to separate the local groundwater and the geothermal or mixed water. A mixing curve between water from Marula Farm borehole 3 and EW-01 was drawn. It showed that mixing up to 90% of Marula Farm 3 borehole water and 10% of Eburru well EW-01 water plotted in the geothermal water zone. According to this diagram then, C-429, C-1287, C-2704 waters may have resulted from the mixing of geothermal water from Eburru field and groundwater. Water from C-845 may not be derived from Eburru outflow except to a small extent. Although the water from C-3229 has a relatively high temperature, it may not be derived from outflow from Eburru geothermal field. The temperature of the waters from Kariandusi spring and the Kijabe spring is relatively high, but they do not appear to have any relationship with geothermal water from Eburru.

The Na/1000 - K/100 - $\sqrt{Mg}$ - diagram (Figure 18) shows that only C-2704, C-1287 and Kijabe spring waters are partially equilibrated geothermal waters. Borehole C-3229 water however, plots on the immature sector, although its temperature is elevated. Water from the Kijabe spring is partially equilibrated suggesting that it may be an outflow from another system. Water from Kariandusi spring may derive from a shallow water which has been in contact with the hot rock for a short time.

Comparison of the study with the findings of Allen et al., (1989) shows very good agreement. The piezometric map (Figure 2) agrees well with the present study except that the water from rift groundwater appears to enter Olkaria geothermal field from the east according to the present study and not from the north. There is no evidence to suggest that the water from Lake Naivasha flows beyond Lake Elementeita as the water in C-3229 which is west of Lake Elementeita, appears to be derived from the Mau Escarpment. A contour map showing the distribution of Naivasha lake water (Figure 3), again agreed well with the present study except in the Eburru area. According to the map, there is no flow from the lake to this area. However, the present study has shown a very good correlation between the lake water and geothermal water at Eburru. Darling et al., (1990), on the other hand, suggested that about 20% of the Eburru water may be derived from Lake Naivasha.

6.2 Conclusions and recommendations

In this study it has been possible to show that geothermal reservoirs at both Olkaria and Eburru may be getting some of their recharge from the rift floor waters which may be recharged by Lake Naivasha. It has also been shown that waters from boreholes C-1287, C-2704, C-429 and Elementeita spring are outflows from Eburru geothermal field. The waters in C-845 and C-3229 may result from a mixture of Eburru geothermal water and groundwater from the Mau Escarpment. From the study it is unlikely that Lake Naivasha is an exposed groundwater. It has not been possible to calculate the amount of outflow from the lake in this study and therefore it is difficult to determine how the exploitation of the geothermal resources affects the lake.

The data that was used in the report may be limited and more sampling of water from the area of study has to be done for a definite conclusion. More Olkaria well waters have to analysed for bromine to confirm the direction of groundwater entering the field. Monitoring of water levels around Lake Naivasha is recommended to determine the possible effect of geothermal exploitation at Olkaria on it. Further work to estimate the outflow of water from the lake and inflow into it is also recommended.

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