



CHEMICAL EVOLUTION OF THE MOMOTOMBO RESERVOIR AND SILICA AND CALCITE SCALING POTENTIAL OF THE FLUID

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ABSTRACT

The Momotombo geothermal field has been in operation for almost 30 years and currently eight production wells sustain a gross capacity of 27 MWe. This report describes the chemical trends of the Momotombo reservoir fluid during the last years. The WATCH program was used to calculate the composition of the deep liquid. Quartz and Na/K geothermometers were used to compute an average temperature for each well.

One of the most evident changes in the chemical composition of the fluid is shown by the chloride content. In 1990 the chloride content was high, but now a strong decrease is notable; this is due to both the incursion of cold water due to exploitation. The quartz and Na-K geothermometers show indications of the presence of cold recharge water in most wells. However, an increase in temperature was observed in well MT-36, which suggests the influence of hot water from depth.

The scaling tendency of the Momotombo fluid during boiling was evaluated using the WATCH program. The calcite scaling potential has increased from 1990 to 2012.

1. INTRODUCTION

Nicaragua has the largest geothermal potential of the Central American countries due to the presence of the volcanic mountain chain Maribios that runs parallel to the Pacific coast. The Maribios volcanic chain consists of active volcanoes, some lagoons, volcanic structures, and extensive areas of hydrothermal activity, denoting the presence of a magmatic heat source at depth.

Geothermal exploration started in Nicaragua in 1960, showing the geothermal potential of the country and giving priority to the San Jacinto and Momotombo fields (Porras, 2008). The Momotombo field has been operated by ORMAT for more than 10 years. The installed capacity was 70 MWe but only 10 MWe were generated when the company took over the operation in 1999. Since then, Ormat has drilled several production and reinjection wells and carried out work-overs and cleaned several of the older wells. In April 2012, the current gross capacity of the Momotombo plant was 27 MWe; 6 MWe being provided by a binary cycle plant.

Significant changes have occurred in the Momotombo geothermal reservoir over time. The maximum production from Momotombo of 70 MWe was reached in 1989, but the output declined gradually down to 8 MWe by July 1999. The reservoir pressure dropped at the rate of 2 bar per year and this induced wide boiling in the shallow reservoir. Relatively rapid incursion of low temperature water into the reservoir occurred, resulting in cooling of the shallow reservoir (Porras, 2005). The colder inflow resulted in lower enthalpy and well scaling problems due to changes in the chemical conditions.

The chemical composition of geothermal fluids provides important information about production properties and reservoir temperature. It also provides good indicators for monitoring reservoir changes in response to production and allows evaluation and avoidance of scaling problems in wells and surface pipelines.

The main objectives of this study are to:

- 1) Compare and evaluate the chemical evolution of the thermal fluids of the Momotombo reservoir through the interpretation of chemical analyses of water and gas samples from geothermal wells, collected in 2012 and earlier samples from 1990, 1992, and 1996;
- 2) Calculate the chemical composition of deep liquid in the production wells in Momotombo geothermal field using the WATCH program; and
- 3) Assess the silica and calcite scaling potential of the Momotombo geothermal fluid.

The geochemical data used in this study are from Arnórsson et al. (1996), Arnórsson (1997; 1998), and a previously unpublished analysis of samples collected in February 2012 by the geochemistry team of the Nicaraguan Ministry of Energy and Mines (MEM).

2. BACKGROUND

2.1 Nicaragua geological setting

Nicaragua is located in the middle of the Chortis block, which is a unit of the continental crust that belongs to the Caribbean plate (Figure 1). The geothermal resources of Nicaragua are situated in the southwest sector of the country inside a wide subsidence zone known as the Nicaraguan depression.

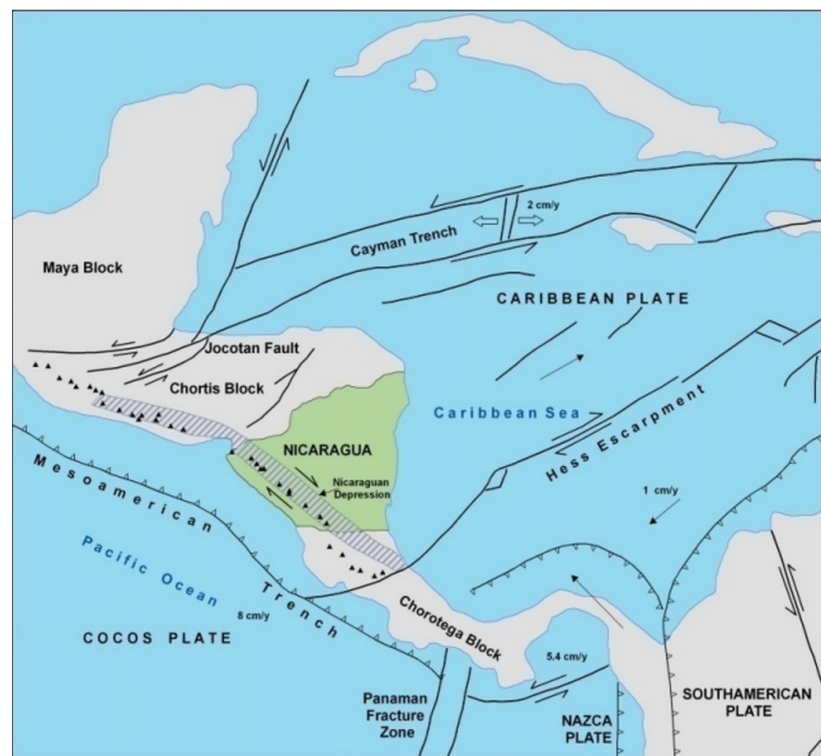


FIGURE 1: Tectonic map of the Central America and the Caribbean Region

2.2 Local geology in the Momotombo geothermal field

The Momotombo geothermal plant is located 40 km northwest of the capital, Managua, on the shores of Lake Managua and the foot of the active Momotombo volcano. The volcano is a part of the Cordillera

de los Maribios volcanic ridge on the Pacific coast of Nicaragua. It rises to an altitude of 1,297 m a.s.l. and is a relatively young volcano or only about 4,500 years old (MEM, 2008).

The Momotombo volcano is a strato-volcano, almost symmetrical, composed of basalts and andesitic-basalts, with intercalations of tephrite, breccia, tuffs and epiclastic materials of the same composition (MEM, 2008). The volcanic complex consists of several small volcanic cones and a large caldera located adjacent to and northwest of the Momotombo volcano (Porras, 2009).

Structurally, the geothermal field is characterized mainly by three fault systems running NW-SE, NE-SW and N-S (Figure 2). Regional faults are aligned in a N-S direction; the Momotombo fault and the SR fault are the principal NW-SE faults and Björnsson's fault is the main NE-SW fault. These faults allow the circulation of fluids in the hydrothermal system. The most productive wells are located mostly in a sector corresponding to structural crossing at the intersection of the faults of these three systems near Björnsson's fault (Porras, 2009).

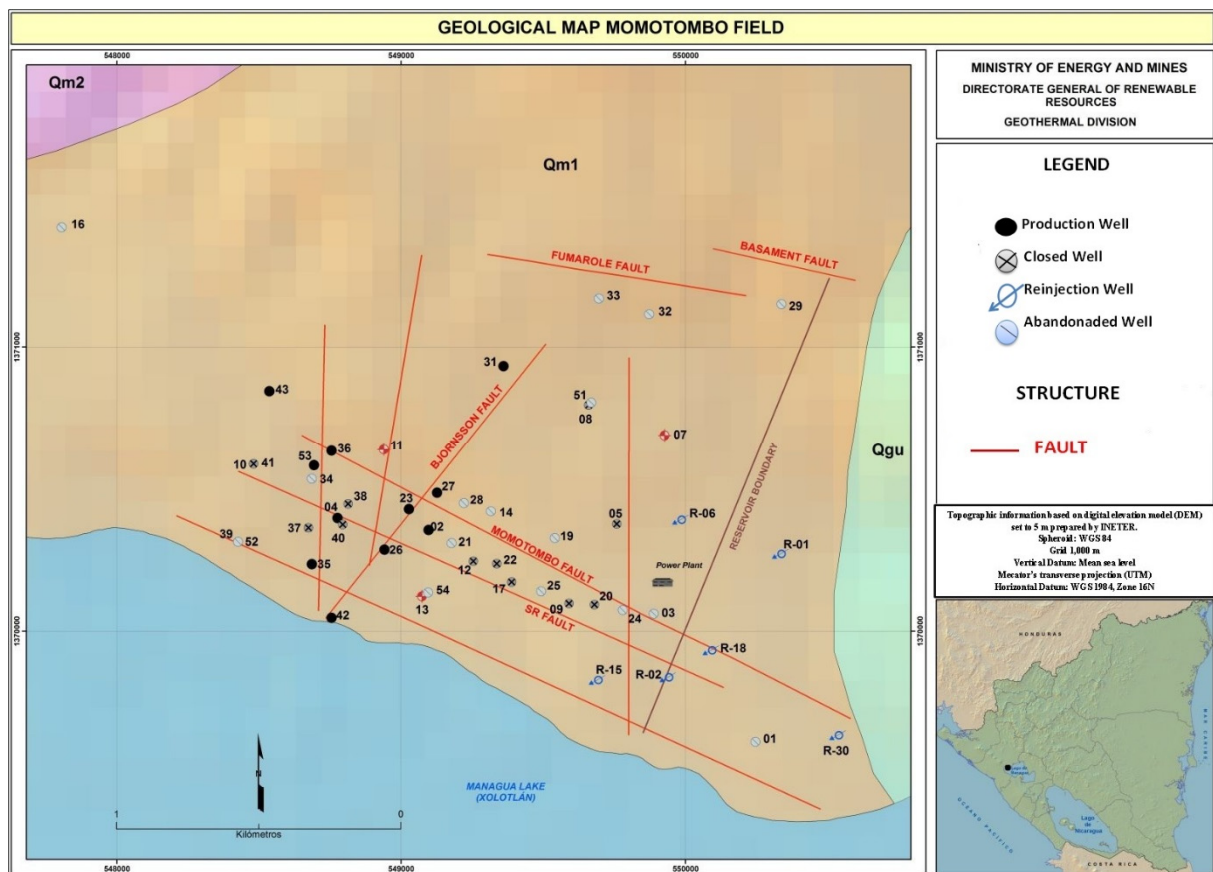


FIGURE 2: Geological map of Momotombo field, the main faults, and the location of wells (MEM, 2010)

The wells in the Momotombo field are distributed in about 3 km² area, but most of the wells are located in a 1.5 km² area. Based on the production zones intercepted in producing wells, the Momotombo reservoir is considered a single unit, but with different levels of permeability, referred to as shallow (300-800 m), intermediate (800-1,500 m) and deep (1,500-3,000 m).

Features of Momotombo geothermal reservoir: The shallow and intermediate layers have good permeability, but the deep layer has relatively low permeability. The high temperature fluid upflow is located in the western part of the field. There the hot fluids rise and cross Björnsson's fault to the southeast in the shallow aquifer along the Momotombo and SR faults.

Wells that have intersected the shallow aquifer east of Björnsson’s fault manifest obvious differences in their production, as some wells evolved rapidly to dry steam, such as wells MT-20 and MT-12 which ceased production in 1995-1996 while others continued to produce two phase fluid.

Conceptual model: The most recent conceptual model for the Momotombo geothermal system is described by Porras et al. (2007) and Porras and Björnsson (2010). The main features of the conceptual model are shown in Figure 3 (Porras and Björnsson, 2010). The figure shows a temperature cross-section from west to east. It clearly illustrates a hot (240-320°C) and vertical upflow zone, as well as a shallow reservoir layer (220-240°C). The shallow layer conducts deep fluids to the east. Also worth mentioning is a cold (100-150°C) fluid recharge from the east that appears to have been active in the natural state. The origin of the cold recharge is not clearly defined, but may originate from Lake Managua or incursion of meteoric groundwater.

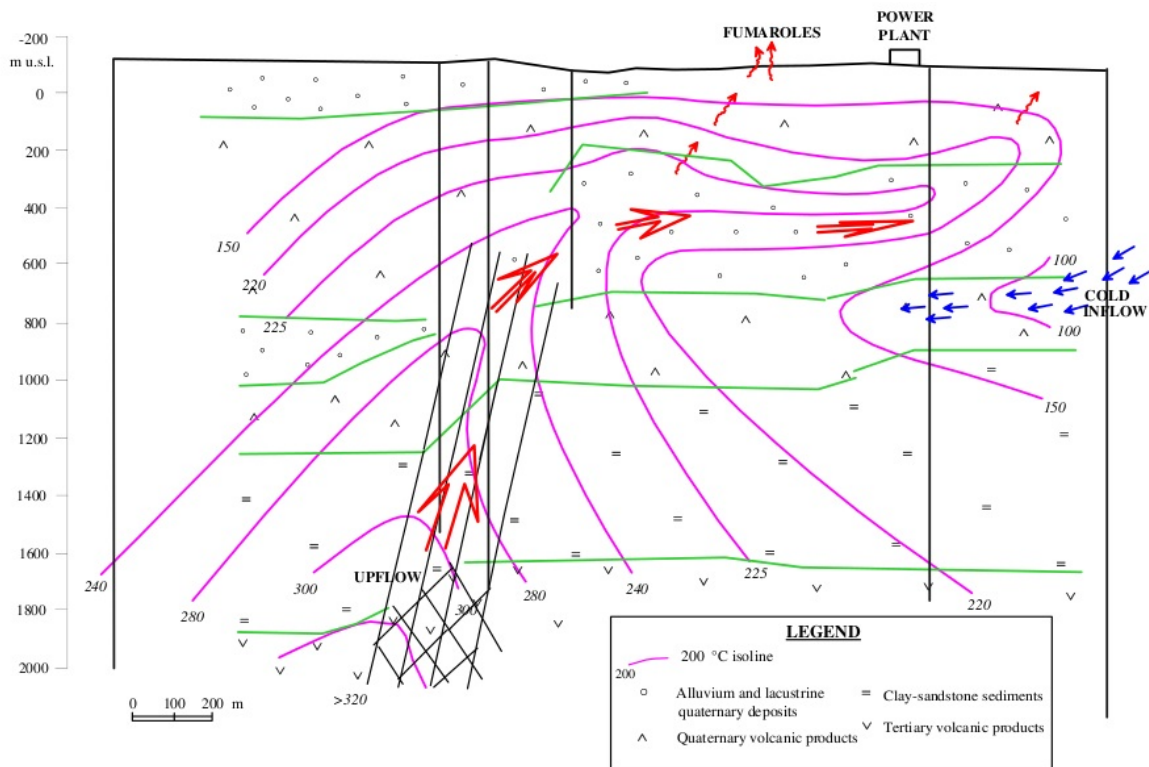


FIGURE 3: Conceptual model of Momotombo geothermal field and flow direction (Porras and Björnsson, 2010)

2.3 Production history

The Momotombo geothermal plant was built at the base of the volcano and has been in use for almost thirty years since the first unit of 35 MWe was commissioned in 1983. A second unit was installed in 1989 resulting in an increased steam production rate. With 70 MWe installed and running from 1989, the generation caused rapid cooling and decline in enthalpy and resulted in an overall decline in the performance of the geothermal field. In 1998 the electrical generation had dropped down to 11 MWe.

Until 1999, the geothermal system of Momotombo suffered from over-exploitation which induced excessive flashing of, and intrusion of cold water into the reservoir, resulting in a drastic decline of electricity generation (Porras, 2008). The average production decline was about 6.7 MWe/year in the period between 1991 and 1999.

In 1999 ORMAT took over the concession for 15 years. After ORMAT started managing the geothermal field, performance increased again; since then, the single flash units produce about 24 MWe, mainly unit 2, as unit 1 has since 1997 only been in operation when unit 2 is stopped for maintenance. Later, in 2002, two binary units with a total of 7 MWe were installed, bringing the total installed capacity to 77 MW (Egilsson et al., 2012). However, the current total production of the condensation turbine unit and the binary plant is only about 27 MWe.

Forty seven wells have been drilled in Momotombo field. Table 1 lists the current production wells in Momotombo and shows information about their location, drilling period, total depth and casing depth.

TABLE 1: Information about current production (P) wells in Momotombo

Well	Drilling period		Coordinates		Status	Elevation (m)	Depth (m)	Casing (m)
	Start	Finish	East	North				
MT-2	15.02.1975	06.05.1975	549094	1370162	P	62	490	356
MT-4	17.09.1975	26.05.1976	548769	1370195	P	74	1435	684
MT-23	22.09.1977	09.10.1977	549020	1370428	P	68	821	260
MT-26	24.11.1977	15.12.1977	548943	1370079	P	59	640	370
MT-27	18.12.1977	02.01.1978	549038	1370237	P	87	720	368
MT-31	27.06.1978	23.07.1978	549362	1370739	P	190	582	235
MT-35	23.10.1984	01.01.1985	548682	1370235	P	59	1444	602
MT-36	13.01.1985	02.05.1985	548752	1370435	P	97	1653	650
MT-43	29.09.1996	03.01.1997	548752	1370435	P	127	2495	
OM-53	05.07.2011	06.09.2001	548667	1370583	P	88	2053	1103

2.4 Chemical evolution of Momotombo geothermal field

Momotombo geothermal field has undergone changes over time with respect to the fluid composition. This is evidenced by the decrease in concentration of chloride in the discharge from many of the wells; the reservoir is liquid dominated, with sodium-chloride fluids and a moderate non-condensable gas concentration (about 1-2% at 1 bar-a); the initial water at Momotombo contained about 2700-3900 ppm Cl (Arnórsson, 1996).

Arnórsson et al. (1996) observed and demonstrated that the chloride content in the waters from most of the Momotombo production wells showed a marked decrease already in 1990 and 1992. The exceptions were wells MT-27 and MT-36. The interpretation for the deep liquid was calculated and evaluated with the aid of the WATCH program (Arnórsson et al., 1983). Actually the present report shows that these changes now occur in all Momotombo production wells, including MT-27 and MT-36, as well as MT-43 and OM-53, which were drilled in 1996-97 and 2001, respectively.

The change in chemical composition is related to an infiltration of meteoric water into the shallow aquifer where the productivity decline has been most prevalent.

3. METHODOLOGY

3.1 Sampling and analysis

The primary data used in this report are obtained from chemical analyses of water and steam discharges from wells in the Momotombo geothermal field. These wells are MT-2, MT-4, MT-23, MT-26, MT-27, MT-31, MT-35, and MT-36. The chemical analyses used in this study were reported by Arnórsson (1996, 1997, 1998) for samples collected in 1990, 1992, and 1996. Samples were collected from all

producing wells in February 2012 by the MEM geochemistry team. All the data used in this study are shown in Table 1 (Appendix I). In 1990, 1992, and 1996, liquid samples were collected from the weir box (i.e. at atmospheric pressure) whereas the samples from 2012 were collected using a Webre separator at different pressures, but the liquid phase concentrations were corrected so that they corresponded with the concentrations at atmospheric pressure from previous years.

Samples of geothermal liquid and steam collected for chemical analysis require specific techniques for sample preservation. Below, a short description will be given of the methods used for collecting water and steam samples and the analytical methods used to evaluate them.

The first step in chemically analysing samples is the collection. It is important that this step be properly carried out because all the following steps depend upon it. In February 2012, MEM collected two phase fluid samples using the Webre separator. When using a separator it must be ensured that the separation is good, i.e. dry steam is at the outlet and properly separated liquid does not have any gas bubbles when condensed. Figure 4 shows the representative samples that are collected from a two-phase well; this diagram was applied for samples from 2012. In previous years, liquid phase samples were collected from the weir-box and steam samples from the steam pipeline from the wellhead separator.

Steam samples were collected into gas sampling bulbs, which had been evacuated in the laboratory and contained 50 ml of 4 N of NaOH solution; this strong base is used to capture the major non-condensable gases (H_2S and CO_2) while residual gases (H_2 , N_2 , CH_4 , O_2) accumulate in the head space. The other samples for analysis of all components were filtered on site to prevent interaction with any suspended matter.

For the determination of cations, the samples were acidified with concentrated nitric acid, 20 drops to 1000 ml of the sample. Samples for pH measurement and analysis of HCO_3^- and CO_3^{2-} were collected in 250 ml amber glass bottles. These bottles have special caps that prevent entrapment of air under the cap. Samples for determination of Cl were not treated, except for filtration; samples for SiO_2 were collected in 100 ml plastic bottles, preserved with a dilution 1:10 with distilled and deionized water in order to avoid silica precipitation.

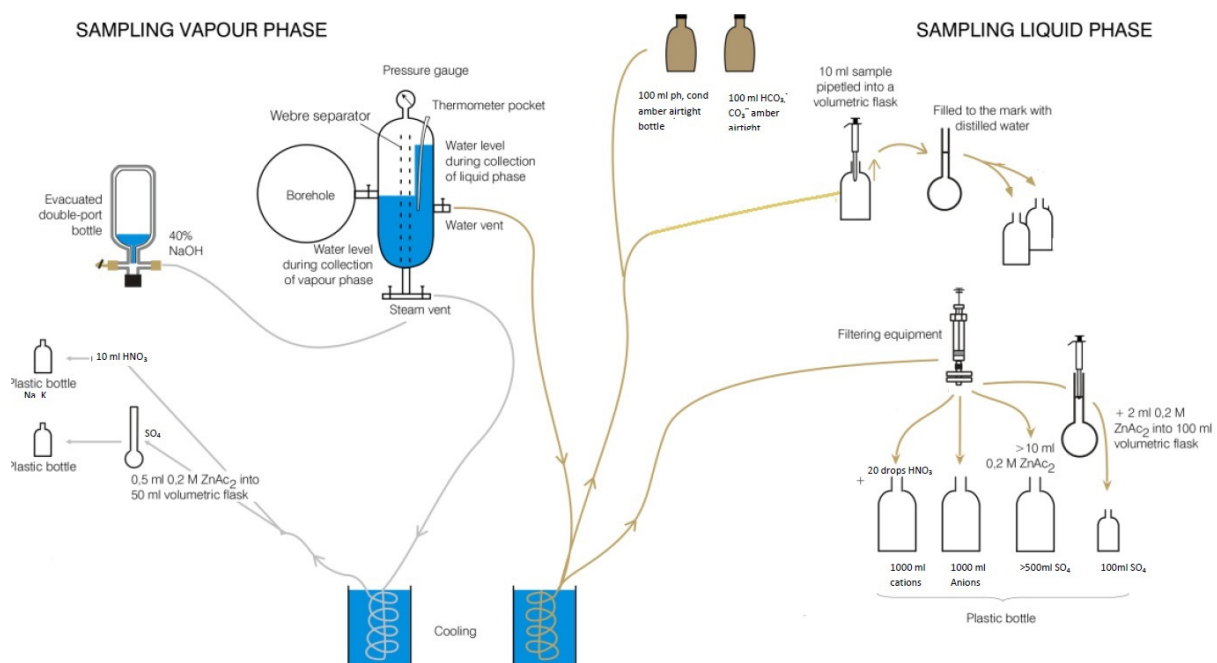


FIGURE 4: Diagram of sample collection from 2012 of two phase liquid in geothermal wells (Ólafsson and Ármannsson, 2006)

HCO_3^- and CO_3^{2-} were determined by volumetric titration; pH in the liquid phase was determined in the laboratory immediately upon return from the field (within 2-3 days) by calibrated pH electrodes; H_2S was determined titrimetrically using mercuric acetate and dithizone. The major aqueous components (Na, K, Mg, Ca), were analysed by atomic absorption spectrometry and UV-Visible spectrophotometer (SiO_2 and B); Cl was analysed by argentometric titration. It is necessary to mention that the measurements of pH and conductivity were made in situ and also in the laboratory.

3.2 Data handling

Analytical results for samples collected at different pressures are not directly comparable because the concentrations of the components both in water and in steam depend upon the pressure of separation. For this reason, it is necessary to compare the compositions at a common pressure. The results from the samples obtained in 2012 were, therefore, recalculated to a common pressure ($P=1\text{bar-a}$).

In this case we have:

$$h_{ps}^l = h_{WB}^v * X_{WB} + h_{WB}^l(1 - X_{WB}) \quad (1)$$

where h_{ps}^l = Enthalpy of liquid water at sampling pressure (kJ/kg);
 h_{WB}^v = Enthalpy of water vapour at weir-box (atmospheric) pressure (kJ/kg);
 h_{WB}^l = Enthalpy of liquid water at weir-box (atmospheric) pressure (kJ/kg); and
 X_{WB} = Steam fraction (-).

Equation 1 is rearranged to give:

$$X_{WB} = \frac{h_{ps}^l - h_{WB}^l}{h_{WB}^v - h_{WB}^l} \quad (2)$$

Based on the conservation of mass, the concentration of the component i in the liquid phase at the sampling pressure ($m_{i,ps}$) is given by:

$$m_{i,ps} = m_{i,WB}^v X_{WB} + m_{i,WB}^l(1 - X_{WB}) \quad (3)$$

where $m_{i,WB}^v$ = Concentration of component i in the vapour phase at weir-box pressure; and
 $m_{i,WB}^l$ = Concentration of component i in the liquid phase at weir-box pressure.

For non-volatile components it may be assumed that $m_{i,WB}^v = 0$ and thus the liquid phase concentration at weir-box pressure can be computed by:

$$m_{i,WB}^l = \frac{m_{i,ps}^l}{1 - X_{WB}} \quad (4)$$

4. GEOCHEMICAL DATA AND INTERPRETATION

4.1 Application of the chemical program WATCH

The computer program WATCH is a geochemical speciation program (version 2.4, Bjarnason, 2010). It is a useful tool for interpreting the chemical composition of geothermal fluids and for non-thermal waters. Chemical analyses of samples collected at the surface can be used to compute the composition of unboiled aquifer fluids. This program involves the calculations of several aqueous species using mass balance equations and chemical equilibrium.

The temperature, at which the program calculations are performed, refers either to equilibrium with quartz, chalcedony, the Na-K geothermometry temperature or a value which may be arbitrarily selected. This program is a useful tool because it can also be used for studying or evaluating the chemical changes with adiabatic boiling and conductive cooling.

In this present study, the WATCH program was used to estimate and evaluate the state of saturation of common scale forming minerals during adiabatic boiling of selected geothermal wells, when the calcite and amorphous silica in the fluid are cooled down from the aquifer temperature by adiabatic boiling; the tendency of the saturation states of calcite and silica are evaluated through the saturation index for each mineral.

4.2 Geothermometry

Chemical geothermometers can be used to estimate reservoir temperatures. The geothermometers are based on temperature dependent water-rock reactions which control the chemical and isotopic composition of the thermal water. The equilibrium between common minerals or a mineral group and a given water chemistry is temperature dependent. Therefore, the temperature indicated by the geothermometers is not necessarily the maximum temperature of the water, but the temperature at which the mineral and the water phase were last in equilibrium (Nicholson, 1993).

When the geothermometers are applied to estimate subsurface or aquifer temperatures, two basic assumptions are always made, specifically that temperature dependent chemical or isotopic equilibrium prevails in the source aquifer and that the fluid has not reequilibrated while the fluid travelled from the reservoir to the surface.

In the present report, solute geothermometers were applied to compute the reservoir temperatures for the samples from the Momotombo wells.

The solute geothermometers used in this study were the: quartz geothermometer by Fournier and Potter (1982) and the Na/K geothermometer by Arnórsson et al. (1998).

Quartz geothermometers

The quartz geothermometers are based on quartz solubility, which controls the silica concentration in geothermal fluids in high temperature geothermal systems. The quartz geothermometers of Fournier and Potter (1982) are most widely used for chemical geothermometry. In this report, Equation 5 was used for the quartz geothermometers:

$$T(^{\circ}\text{C}) = -53.5 + 0.11236 S - 0.05559 \times 10^{-4} S^2 + 0.1772 \times 10^{-7} S^3 + 88.390 \log S \quad (5)$$

where S refers to the concentration of SiO₂ in mg/kg and T is the temperature.

This equation applies to liquids that have undergone adiabatic boiling from the reservoir to atmospheric conditions.

Na-K geothermometers

The following equation for Na/K geothermometers (Arnórsson, 2000) was used:

$$\text{Na/K} = 733.6 - 770.551Y + 378.189Y^2 - 95.753Y^3 + 9.544Y^4 \quad (6)$$

where Y designates the logarithm of the molal ratio of Na/K.

The results in Table 2 show the geothermometry results found for the wells in the Momotombo geothermal field.

TABLE 2: Solute geothermometer temperatures for Momotombo wells

Well	1990			1992			1996			2012		
	Temperature			Temperature			Temperature			Temperature		
	Na/K	Quartz	TAve	Na/K	Quartz	TAve	Na/K	Quartz	TAve	Na/K	Quartz	TAve
MT-2	206	228	217	249	207	228	226	215	221	195	203	199
MT-4										200	203	203
MT-23	222	229	226	245	202	224	226	223	224	194	201	197
MT-26	232	231	231	253	228	240	232	212	222	203	200	201
MT-27	220	229	225	237	213	225	224	203	213	202	214	208
MT-31	209	223	216	229	216	223	209	235	222	216	236	226
MT-35	246	255	251	279	236	257	262	269	266	202	213	208
MT-36	277	269	273	314	265	289	303	282	293	322	306	314
MT-43												
OM-53										262	271.9	270.2

Well MT-43 no water sample available; Well OM-53 was drilled in 2001; TAve: Average temperature

The geothermometry temperatures have declined slightly over time. This is evident for most of the shallow wells (MT-2, MT-23, MT-26 and MT-27) which have declined by about 15 to 30 degrees since 1990 to about 200°C in 2012. Well MT-31, on the other hand, has remained almost stable. Well MT-35 had relatively high temperatures in the 1990s or around 250-265°C but the 2012 geothermometry results are much lower or only slightly above 200°C. Geothermometry temperatures of well MT-36 appear to be increasing with time. This may possibly suggest a recharge of hot fluids from depth. No samples are available from wells MT-4 and OM-53 before 2012 (Figures 1 and 2 in Appendix II).

4.3 Scaling potential

The scaling trend for geothermal wells in Momotombo field was evaluated with the program WATCH (Bjarnason, 2010). If the chemical composition of the fluid is known, the saturation index (SI) can be computed using the WATCH program. The equation of the saturation index is:

$$SI = \log \frac{Q}{K} \quad (7)$$

where Q is the activity product for the dissolution reaction of the mineral in question and K is the equilibrium constant for that reaction.

The trend for mineral precipitation or dissolution is indicated by comparison of K to Q. Log Q and log K are calculated by the WATCH program. The calculations of composition and speciation of the geothermal water in the reservoir can show whether the water is in general equilibrium and can estimate the temperature in the reservoir.

Using the results of the aqueous speciation calculations, the saturation index (SI) of minerals in an aqueous solution at different temperatures was computed. The value of SI for a given mineral is a measure of the saturation state of the water phase with respect to that mineral phase: The mineral is undersaturated when $Q < K$, the mineral is supersaturated when $Q > K$, and the fluid is in equilibrium with the fluid when $Q = K$.

The scaling potential is estimated by calculating $\log Q/K$; a positive value for the relative log solubility of a mineral means that the solution is supersaturated, but if it shows a negative value, it means that the solution is under-saturated (no precipitation).

The prediction of the scaling potential from geothermal waters is important for evaluation of the production characteristics of geothermal reservoirs. The evaluation of scaling potential includes an

assessment of the saturation state of the scale-forming minerals at reservoir conditions and under conditions that reflect production.

4.3.1 Silica scaling potential

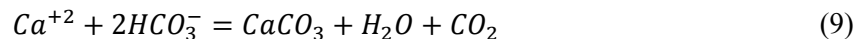
Silica scaling primarily occurs in surface equipment and reinjection wells and causes operational problems in geothermal power plants. The amount of silica dissolved in the geothermal water is controlled by quartz solubility in high temperature geothermal systems. The geothermal solutions are generally close to equilibrium with quartz. Solubilities of silica minerals decrease with decreasing temperature. Deposition of silica occurs when the concentration of silica exceeds the solubility of amorphous silica (Gudmundsson, 1983). Silica scales are deposited as amorphous silica upon concentration and cooling due to boiling. The precipitation of silica from geothermal fluids occurs in minutes or hours after over-saturation occurs.

4.3.2 Calcite scaling potential

The calcite scaling potential is determined by the concentration of calcium and carbonate species, which dictate the calcite solubility product:



In many geothermal systems the water is at or close to calcite saturation as this mineral is present in the reservoir rock. Water becomes oversaturated with respect to calcite as it flows up a well due to boiling, and CO₂ is lost to the steam phase resulting in the following precipitation reaction:



Calcite scaling is a very common problem in geothermal fields.

5. RESULTS AND DISCUSSION

The analytical results from the Momotombo wells are shown in Table 3. As mentioned above, the data from 1990 and 1992 represent annual averages as reported by Arnórsson et al. (1996). The 1996 data represent the analysis of individual samples collected and analyzed under the supervision of Stefán Arnórsson (Arnórsson, 1997; 1998). The 2012 samples were collected and analysed by the MEM geochemistry group in February 2012. With the aid of the program WATCH, interesting aspects such as calculated temperature geothermometers, saturation index and the chemical composition of the deep liquid can be assessed.

5.1. Reference temperatures

In order to estimate the reference temperatures and evaluate the aquifer temperature for the wells, the temperatures given in Table 2 were taken as the average temperatures of the quartz and Na/K geothermometers. These selected temperatures were then used for computations using WATCH for deep liquid concentrations and also the saturation index for the minerals calcite and silica during adiabatic boiling of selected geothermal wells.

5.2 Concentration of dissolved minerals in the deep liquid

The calculated average chemical compositions of the deep liquid in the production wells in Momotombo geothermal field are shown in Table 3. The data shown in this table were calculated using the WATCH program to derive the concentrations in the deep liquid.

TABLE 3: Chemical compositions in the deep liquid from Momotombo wells
(Concentrations are given in mg/kg)

Well	Years	pH	Na	K	Ca	Mg	SiO ₂	SO ₄	B	Cl	T NaK	TSiO ₂
MT-2	1990	5.1	2823.0	30.76	88.5	0.69	390.7	35.3	29.6	3997.4	206.2	232.9
	1992	5.3	1249	196.2	48.5	0.14	255.7	97.5	21.3	2143.3	248.3	198.3
	1996	5.5	923.8	119.8	17.8	0.08	310.7	160.5	16.0	1326.9	225.9	213.4
	2012	6.0	1304.1	125.3	50.6	0.18	277.7	152.6	22.1	2033.0	194.7	204
MT-4	1990*											
	1992*											
	1996	5.59	1699	292.32	23.74	1.35	533.5	17.5	23.74	2708.8	260.1	265.3
	2012	6.03	1287	123.66	49.96	0.17	274.2	150.7	21.85	2007.1	194.6	203.4
MT-23	1990	5.7	2370	291.71	62.92	1.153	381.1	32	21.61	3389	221.9	230.6
	1992	5.9	1690	256.63	60.47	1.41	237.3	48.11	26.73	2979.4	245.2	192.6
	1996	6.0	1884	240.36	49.47	4.10	435.5	72	26.26	2901.8	227	242.9
	2012		1340	124.35	44.24	0.09	271.4	151.34	22.62	2143.3	193.6	202.2
MT-26	1990	6.2	2273	305.66	51.76	1.22	383	40.16	26.48	3152	231.5	230.8
	1992	6.4	1690	274.99	58.91	1.60	341.3	42.92	26.87	2989.3	253.1	220.8
	1996	6	1715	230.87	41.82	4.11	300.8	54.06	24.08	2580.3	232	210
	2012	6.9	1148	118.65	38	0.08	265.5	150	20.48	1939	202.4	199.6
MT-27	1990	5.16	1679.0	236	57.2	1.43	287.3	50.3	26.5	2820.3	236.7	207.2
	1992	4.93	2258.0	273.7	60.4	1.44	384.1	30.7	20.2	3156.6	220.4	231.4
	1996		1740.0	216.9	42.5	2.53	299.6	70.3	23.7	2590.2	224	211
	2012		1468.2	150	42	0.00	326.4	110.6	25.6	2409.2	202	217
MT-31	1990	5.2	2324	254.19	65.36	1.113	366.3	36.79	21.31	3505.0	209.3	227.2
	1992	5.3	2200	290.39	81.01	1.52	310.7	75.24	34.44	3693	229.1	213.4
	1996	6.3	1792.2	195.4	57.9	5.2	417.3	61.2	22.2	2602	208.8	238.6
	2012	6.3	1611.5	187.8	42.0	0.1	417.4	54.4	30.9	2713	216.2	238.7
MT-35	1990	5.5	2028	309.13	17.92	0.39	505.5	35.77	23.77	3027.8	245.6	258.9
	1992	5.7	1418	291.21	17.32	0.37	364.2	26.01	20.68	2428.6	281.4	226.7
	1996	6.2	1324.7	232.6	8.4	1.1	557	36	16.39	1919.8	262.0	270.60
	2012	6.5	1297.0	131.7	29.6	0.0	340	63	22.07	2126.9	201.6	220.00
MT-36	1990*											
	1992	6.1	1083	304.83	11.02	0.58	384.8	6.58	21.02	1978.2	337.1	231.6
	1996	7.0	1592	399	20.17	1.70	590.2	7.2	24.5	2821.7	306	277.3
	2012	6.5	1606	443	14.59	0.00	690.9	13.0	34.6	2993.8	323	304.6

5.3 Chloride content

The concentrations of chloride in the deep liquid from 1990, 1992, 1996 and 2012 are presented in Figure 5. The evolution of the chloride concentration in the deep liquid changed with time for most wells. In almost all cases, the first data (1992) from each well showed a higher concentration followed by a decrease in chloride concentrations in 1994 and 1996. However, for some of the wells the chloride concentrations are generally very similar in 2012 as they were in 1996, while for other wells the chloride continued to decrease between 1996 and 2012.

As shown above, the Na/K and quartz geothermometers show declining temperatures with time that correspond to the chloride decline in most of the production wells in Momotombo:

Well MT-2: This well produces fluid from the shallow reservoir. In 1990 the concentration of Cl was about 4000 ppm. From 1991 until 1996 the concentration changed drastically to about 1500-1000

mg/kg. Actually this well has shown some recovery in the chloride concentration, with a concentration of about 2000 ppm in 2012.

Well MT-23 is located near the upflow zone. This well showed values of about 3150 ppm in 1990 followed by a significantly decline after 1992 and this trend continues in 2012.

Well MT-26: This well shows a decrease between 1990 and 1996, and from 1996 to 2012 the chloride content is still declining. Wells MT-27 and MT-31 also show a decrease in the chloride content.

Well MT-4: This is a deep well drilled to 1453 m in 1975 with good permeability, and is possibly located in the upflow zone at the western part of the field; it was observed that the chloride content decreased between 1996 and 2012, but there is limited information about the trend for this well for previous years.

Well MT-35 is 1444 m deep, located near the upflow zone. It showed a decrease in Cl in the first two years, but measurements from 1996 to 2012 indicated that the Cl concentrations remained relatively constant.

Well MT-36 was drilled in 1985 to a depth of 1653 m and is located near the upflow zone. Data are not available for 1990, but in 1992 the Cl concentration was rather low, or about 2,000 mg/kg; it had increased to close to 3,000 mg/kg by 1996. In 2012, the Cl concentration had increased even further to slightly above 3,000 mg/kg.

These changes in chloride content are seen in most of the productive wells and appear to be independent of the depth of the wells.

5.4 Sodium and potassium

The content of the minerals sodium and potassium in the deep liquid from 1990-2012 are shown in Figures 3 and 4 in Appendix II. The concentrations of these minerals showed the same tendency as chloride: in earlier times, wells MT-2, MT-36, MT-35, and possibly MT-31 presented high contents of Na and K. The concentrations of these components decreased with time but since 1996 these concentrations have been relatively constant. The interpretation for these changes is that these wells have been affected by recharge of fresh ground waters.

5.5 Calcium

The calcium content in the deep liquid for samples taken between 1990 and 2012 is presented in Figure 5 in Appendix II. Wells MT-2, MT-4, and MT-35 showed very high Ca concentrations in the first years with a fast decline for well MT-2 but with an increase between 1996 and 2012. Wells MT-4 and MT-35 also showed an increase after 1996. This is an obvious change in the calcium content unlike other wells which maintained a relatively constant concentration between 1996 and 2012 after a steady decrease in the first years.

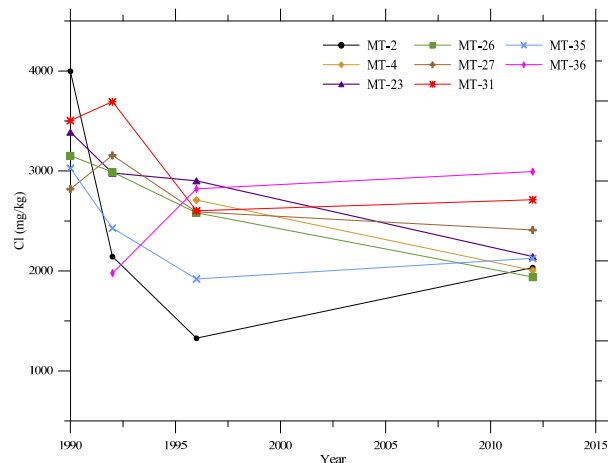


FIGURE 5: Chloride content over time in Momotombo wells

5.6 Calcite scaling tendency

In order to evaluate calcite tendencies in production wells, the chemical data from wells used in this report were considered. Figure 6 shows saturation state of calcite in deep liquid for all wells at reservoir conditions from 1990 to 2012. It can be seen from Figure 6 that the calcite saturation state in the deep liquid has been increasing with time.

The WATCH program was used to simulate adiabatic boiling for the fluids from different production wells in 1990, 1992, 1996, and 2012. Figures 7 and 8 show how the calcite saturation state of the liquid evolves upon boiling from reservoir conditions to 100 °C. Figure 7 shows represents the fluid data for 1990 and Figure 8 shows the 2012 data. Figures 7 and 8 depict the liquid saturation state in terms of SI as a function of temperature during adiabatic boiling. Complete equilibrium degassing is assumed during the boiling process.

The results from these wells in 1990, shown in Figure 7, demonstrate that the saturation state of calcite increased above supersaturation in all wells during the boiling process. Wells MT-2, 27 and 31, which were close to saturation at reservoir conditions increased their saturation state to ~0.5 log units above saturation. The other wells that were slightly supersaturated at reservoir conditions exhibited similar or slightly less increase in calcite saturation.

The corresponding results from 2012, shown in Figure 8, illustrate that boiling had more effect on the calcite supersaturation at that time. The increase in calcite supersaturation in 2012 was of the order of 0.75 for the cooler wells but less than 0.5 for the hotter ones. These results are consistent with the observation that the calcite scaling problem increased in the Momotombo field after 1996 (Porras and Björnsson, 2010)

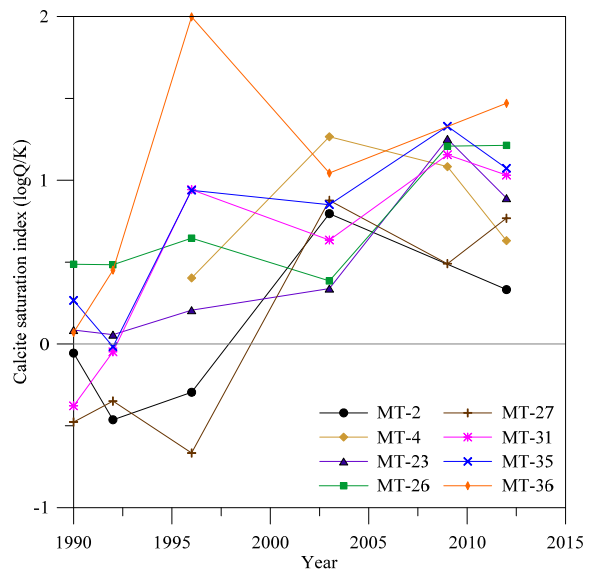


FIGURE 6: Calcite saturation index of fluids from Momotombo wells, 1990 to 2012

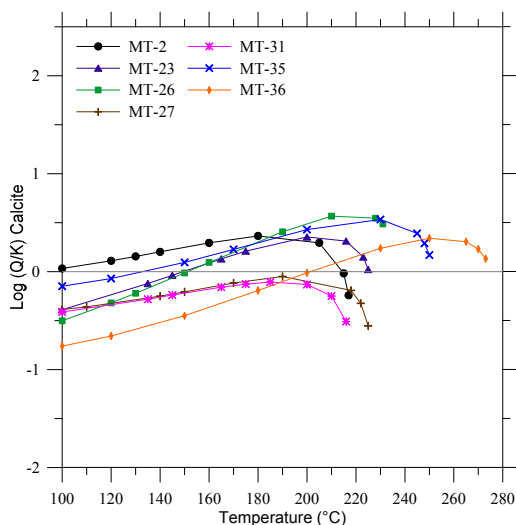


FIGURE 7: Evolution of calcite saturation upon adiabatic boiling of Momotombo deep liquid, 1990

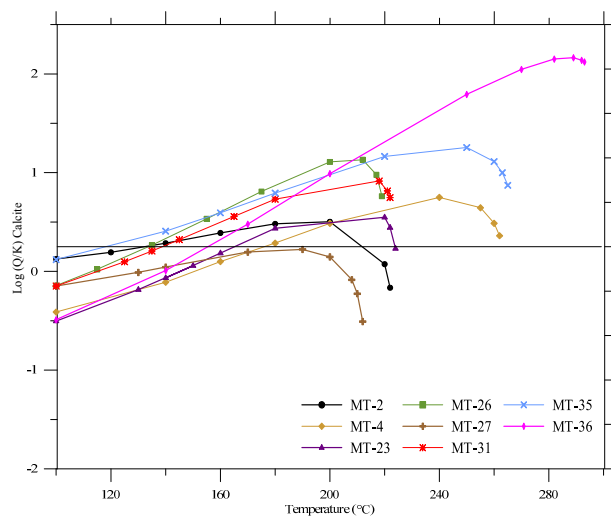


FIGURE 8: Evolution of calcite saturation upon adiabatic boiling of Momotombo deep liquid, 2012

5.7 Silica scaling tendency

Figure 9 shows how the silica concentration in geothermal solutions from the different Momotombo wells (in 2012) changes as they undergo adiabatic boiling. The figure shows how the solutions are close to equilibrium with quartz at reservoir conditions but that boiling increases the concentration of silica in solution and decreases the solubility of amorphous silica.

Amorphous silica saturation is reached for all the wells except MT-31, MT-36, and MT-53, when the geothermal solutions have boiled to some 100-110°C. Wells MT-31, MT-36, and OM-53 have higher reservoir temperatures and correspondingly higher silica concentrations at reservoir conditions. The fluid from these wells will, as a result, reach super-saturation with respect to amorphous silica at higher temperatures. In the case of well MT-36, amorphous silica saturation was reached at 198°C.

Figure 9 shows that silica scaling upon flashing should not be a problem in Momotombo, at least if the separated brines from wells MT-36 and MT-53 are mixed with brines from wells with lower temperatures. However, the use of heat exchangers in the binary units which extract heat from the separated brines will likely drive the solutions into super-saturation with respect to amorphous silica. As a result, Ormat has had to use inhibitors to prevent the precipitation of amorphous silica in the heat exchangers.

6. CONCLUSIONS

The chemical changes seen in the Momotombo system can be explained by changes in the geothermal system. The concentrations of Cl in the production wells indicate that the geothermal system is recharged by cold meteoric water coming from the east part of the field. The trend of declining Cl concentrations has slowed down or even been reversed in some cases since the early 1990s. This is most likely due to increased reinjection implemented after Ormat took over operation of the field. However, the chemical geothermometry indicates that the cooling trend continues.

The well temperatures are changing over time. The Na-K and quartz geothermometers make it clear that there is a strong decline, a result of meteoric water infiltration. The potential for silica scaling becomes smaller as the reservoir temperatures decrease. Calcite scaling problems, on the other hand, seem to be becoming more acute with time.

- The Momotombo geothermal field has generated electricity since 1983, but following increased production in 1989 the output has declined due to infiltration of meteoric water.
- There is an apparent decrease in the chloride content of the water since 1990, although this trend has reversed in some wells since 1996.
- The scaling potential of calcite and silica in brine boiled to different extents was calculated using the WATCH program.
- The liquid from most wells is under-saturated with respect to amorphous silica down to about 120°C.
- The deep liquid is super-saturated with respect to calcite, and calcite super-saturation is increased during boiling. Samples from earlier years indicated that the deep liquid in some wells was previously under-saturated with respect to calcite.

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APPENDIX I: Chemical analyses from wells and temperature and pressure profiles

TABLE 1: Chemical analysis of samples from Momotombo wells

Well	Year	Pressure (bar)	Water samples (concentration at 1 bar-a)													Steam samples (at sampling pressure)				
			pH	Na	K	Ca	Mg	SiO ₂	SO ₄	B	Cl	CO ₂	N ₂	CO ₂	H ₂ S	NH ₃	CH ₄			
MT-2	1990	7.58	8.02	3548	378	111.2	0.87	491	44.4	37.2	5024	29	12867	769	9.67					
	1992	6.57	8.14	1764	277	68.4	0.2	361	137.6	30	3028	27.7	15573	469	13.62					
	1996		8.6	1413.3	176.5	23.8	2.5	466	136.6	18.5	2004	27.3	365.1	7.5		0.227				
	2012	4	6.78	1443	138.6	556.6	0.2	307.3	168.9	24.5	2249.5	60.5	79.7	0.0						
MT-23	1990	7.79	8.09	3104	382	82.4	1.51	499	41.9	28.3	4438	18.5	2669	503	4.22					
	1992	7.05	8.23	2364	359	84.6	1.96	332	67.3	37.4	4168	30.4	2462	404	5.75					
	1996		7.9	1973	251.7	51.8	4.3	456	75.4	27.5	3038.7	23.8	47.6	1.3		0.065				
	2012		8.4	1469	139.6	48.5	0.1	297.5	165.9		2349.5	64.3	70.2							
MT-26	1990	7.68	8.09	3058	411	69.6	1.6	515	54	35.8	4238	38.1	742	461	4.53					
	1992	6	8.2	2422	394	84.4	2.3	489	61.5	38.5	4283	20.6	462	334	4.15					
	1996		8.4	2228.7	300.0	54.3	5.3	390.8	70.3	31.3	3352.9	19.5	27.5	1.3		0.024				
	2012	4.2	8.26	1272.5	131.5	42.1	0.089	294.3	166.3	22.7	2149.5	67.6	24.5	0.0		0.044				
MT-27	1990	7.9	7.89	2945	357	78.8	1.89	501	40	26.4	4117	21.9	16802	1051	5.98					
	1992	6.97	8.23	2291	322	78.1	1.96	392	68.6	36.1	3848	32.2	19841	662	8.04					
	1996		8.06	1971.7	245.73	48.20	2.87	339.5	79.7	26.9	2935	25.3	255.9	5.5						
	2012		8.41	1661	171	48	0.19	369.2	125.6	29.2	2724.4	55.9								
MT-31	1990	7.78	7.98	2944	322	82.8	1.41	464	46.6	27	4440	19.3	6147	1171	9.27					
	1992	5.51	8.17	2939	388	108.2	2.04	415	100.5	46	4933	33.3	11480	885	12.28					
	1996		8.5	2347.5	255.9	75.8	6.8	546.6	80.2	29.1	3409	18.2	22.4	8.6		0.24				
	2012		8.01	1870.7	218.0	48.1	0.1	484.5	63.2	35.9	3149	40.1	72.3	0.0		0.18				
MT-35	1990	7.96	8.38	2840	433	25.1	0.55	708	50.1	33.3	4214	40.3	18201.0	1241	5.98					
	1992	5.28	8.53	2235	459	27.3	0.59	547	41	32.6	3828	32	18200.0	1154.0	10.3					
	1996		8.9	1972.0	346.3	12.5	1.6	830	54	24.4	2858	7.25								
	2012		8.43	1463.2	148.6	33.4	0.0	383	128	24.9	2399.5	62.7	67.5	0.0		0.406				
MT-36	1991	6.47	7.63	2748	549	27.7	1.93	832	17.9	43.7	4499	34.6	16326.0	984.0	7.27					
	1992	8.19	8.35	2221	625	22.6	1.19	789	13.5	43.1	4058.0	26.4	17091.0	541.0	8.5					
	1996			2624	657	33.2	2.80	972.5	11.9	40.4	4649.6	32.37	471.8	7.9						
	2012			2467	681	22.4	0.00	1061.4	20.0	53.2	4599.0	51.8	133.4	0.0						

APPENDIX II: Chemical trends in the fluid of Momotombo's wells for some one component

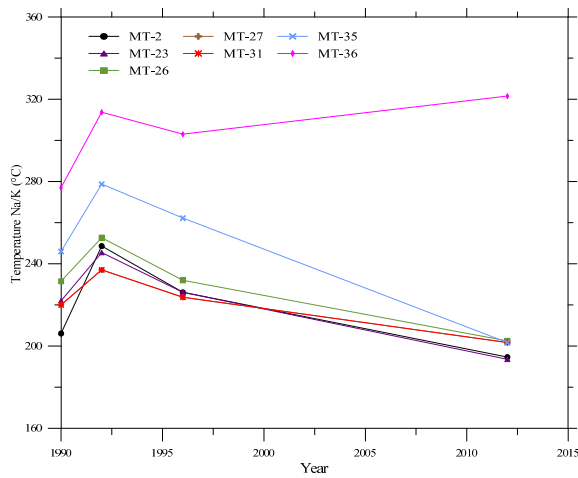


FIGURE 1: Changes in the temperature of Na-K over time

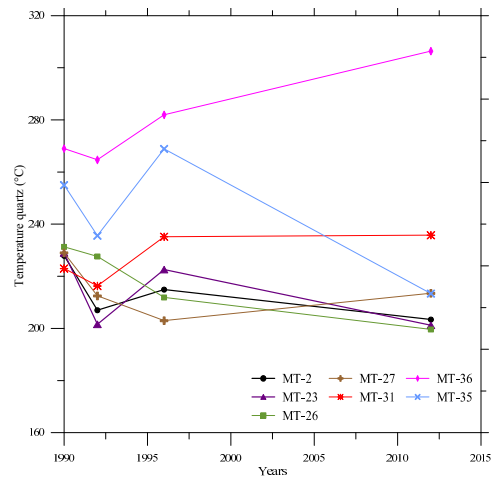


FIGURE 2: Changes in the temperature of Na-K over time

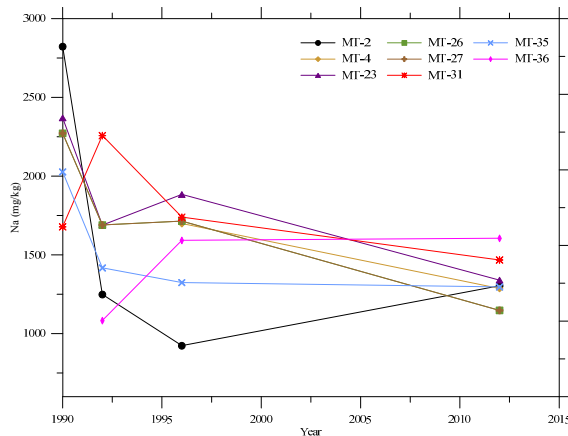


FIGURE 3: Content of sodium in the deep liquid

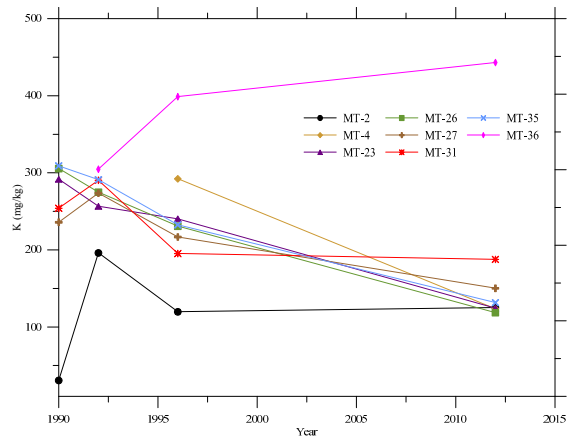


FIGURE 4: Content of potassium in the deep liquid

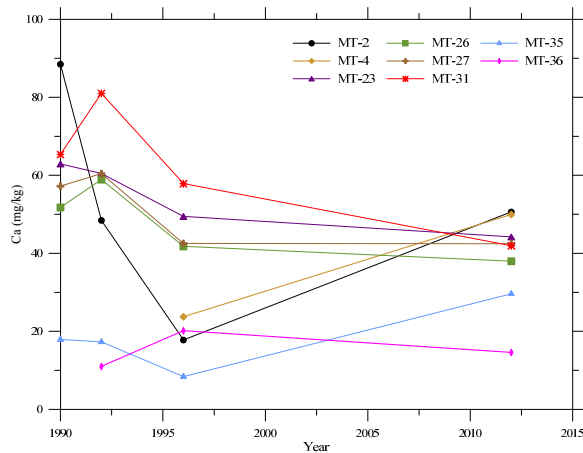


FIGURE 5: Content of calcium in the deep liquid

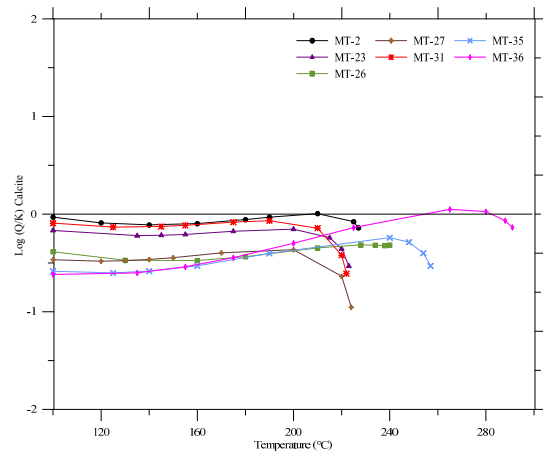


FIGURE 6: Saturation index for calcite, 1992