

UNDERSTANDING THE HYDROLOGICAL PROCESSES OF THE BERLIN GEOTHERMAL FIELD, EL SALVADOR, BASED ON STABLE ISOTOPE DATA

José Tenorio Mejía¹, Franco D'Amore² and Jane Y. Gerardo³

¹ Comisión Ejecutiva Hidroeléctrica del Rio Lempa, C. E. L., El Salvador
² International Institute for Geothermal Researches, CNR, Pisa, Italia
³ Isotope Hydrology, International Atomic Energy Agency, Vienna, Austria

ABSTRACT

The isotopic investigation carried out in the Berlin geothermal field, indicates that the upflowing geothermal fluid represented by $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of -3.4 ‰ and -43 ‰ was intersected by well TR-5. The relationship between $\delta^{18}\text{O}$ and Cl indicates that steam separates at various proportions and temperature as the fluid ascends to the surface. The residual liquid characterized by heavier isotope contents are tapped by wells TR-9, 2 and 3. The steam is postulated to find its way into the numerous fumaroles common in the Berlin geothermal field. TR-5 as well as the rest of the other wells, are recharged by meteoric waters likely with $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of -7 ‰ and -49 ‰, respectively, which remains to be validated by additional isotopic measurements from meteoric and geothermal waters. A mixing line connects the meteoric end member and the geothermal waters at a slope which indicates that the parent source water is heavier in stable isotopes, likely andesitic in composition.

INTRODUCTION

The Berlin geothermal field is located at an elevation between 600 and 900 masl (figure 1) in the northern slope of the Berlin-Tecapa volcanic complex, approximately 112 km ESE of San Salvador, El Salvador. The geothermal system is associated with the activity of the Berlin volcano, which rises to an elevation of 1300 masl. It is located within a 20 km wide graben enclosing the active volcanic axis of Central America. In the late Pleistocene, the caldera collapsed due to an explosive eruption from a stratovolcano which overlay a Tertiary volcanic basement. The

geothermal reservoir is located within a layer of andesitic to andesitic basaltic lavas and tuffs belonging to the Tertiary basement. The permeability is controlled mainly by a fault system trending NW-SE.

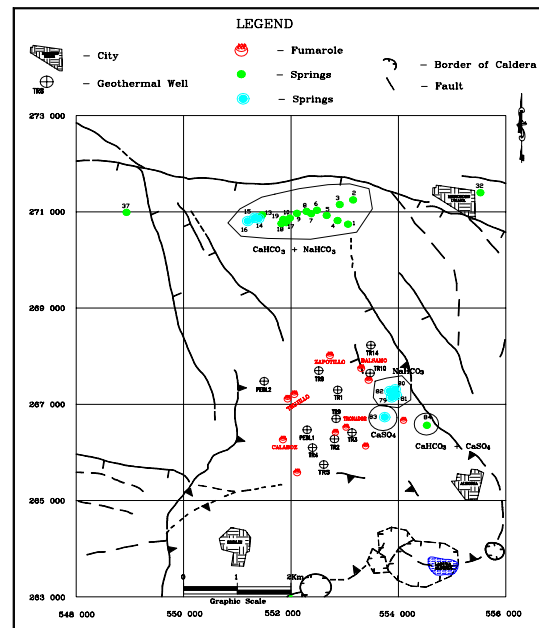


Fig.1. Location of Berlin geothermal field

Six deep wells drilled between 1978-1981, out of which four turned out to be good producers, proved the existence of a geothermal system of commercial interest. The geoscientific surveys carried out in the area, showed the presence of a water dominated geothermal reservoir at 2000 m deep, having a temperature in the range of 280-305 °C, reservoir chloride concentration from 3000-6200 mg/kg, and enthalpy from 880-1289 J/g (table 1). The temperature contours indicate a

flow from well TR-5 from South to North (figure 2).

WELL	TR-1	TR-2	TR-3	TR-5	TR-9
T meas.(°C)	234	298	296	302	295
Clres (mg/kg)	3143	5159	6209	2994	4274
Ysep	0.21	0.32	0.35	0.39	0.30
Enthalpy(J/g)	880	1149	1210	1289	1090
Psep (bara)	1.9	7.4	8.0	7.8	8.2

Table 1. Baseline characteristics of the drilled wells in Berlin geothermal field

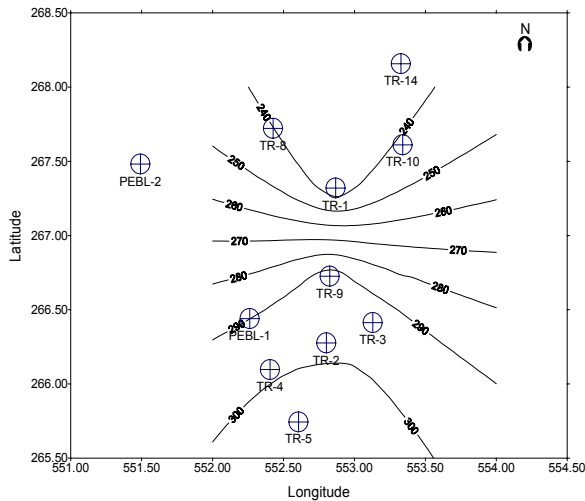


Fig. 2. Map contours of the measured temperature for the wellfield

GEOCHEMISTRY

Figure 3 shows the triangular diagram of Cl-SO₄-HCO₃ of the different waters characterizing the Berlin geothermal system. Local springs cluster in the bicarbonate corner, indicating their superficial origin. The deep geothermal fluid is manifested on the surface by spring F-20 whose composition suggests a mixing between water of deep geothermal origin with water of volcanic origin.

The geothermal wells on one hand occupy the chloride corner indicating their equilibrium with the surrounding rocks. The Na-K-Mg diagram (Giggenbach, 1988), showed in figure 4, further indicates this equilibrium conditions, showing that all the geothermal waters of the wells are mature and equilibrated with rock at about 320 °C.

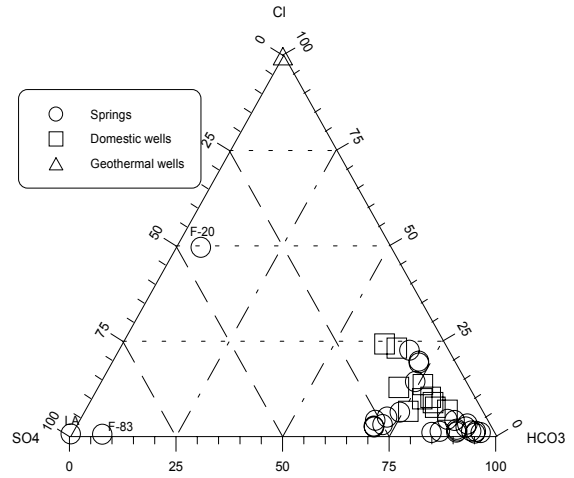


Fig. 3. Relative Cl-SO₄-HCO₃ content in Berlin geothermal area

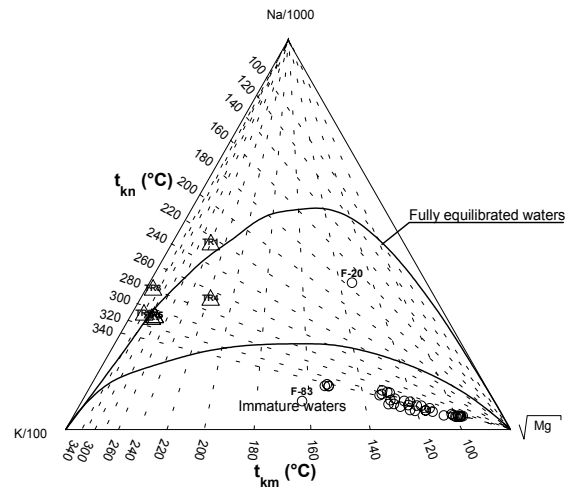


Fig. 4. Evaluation of the Na-K-Mg geothermometer, Berlin geothermal area

The chloride-enthalpy diagram (figure 5) indicates the main processes occurring in the geothermal system. It is postulated that the fluid feeding the well TR-5 is the most representative of the deep system. The fluids of wells TR-2 and TR-9 are produced by boiling consequently increasing the chloride contents and decreasing the temperature. Well TR-3, however, could be explained by boiling of a deep geothermal fluid with a chloride content and an enthalpy of approximately 4400 mg/kg and 1700 J/g, respectively, which when boiled-off increased chloride levels and decreased the enthalpy.

Several geothermometers were used to calculate temperature values, using chemical data from Table 2.

WELL	DATE	Na	K	Ca	Mg	Li	Cl	SO ₄	HCO ₃	SiO ₂	B
		mg/kg									
TR-1	1986	1711	154.4	144	0.093	0	3143	54.2	28.137	220.8	64.3
TR-2	Jun-20-95	3036	680	74.1	0.0666	11.36	5159	3.808	9.0	600.4	99.6
TR-3	1991	3663	624	148	0.0195		6209	8.58	20.7	578.5	116
TR-4*	Apr-27-93	1650	246	27.5	0.58		2867	89.7	37.2	428	82
TR-5	May-12-95	1623	359.9	18.3	0.0854		2994	6.588	3.7	730.8	72.6
TR-9	Jun-22-95	2422	553	49	0.168	10.36	4274	3.85	26.7	726.6	86.8

TR4* deep sampling to 1900 m.

Table 2. Chemical composition for geothermal wells in Berlin geothermal field at reservoir conditions during exploitation

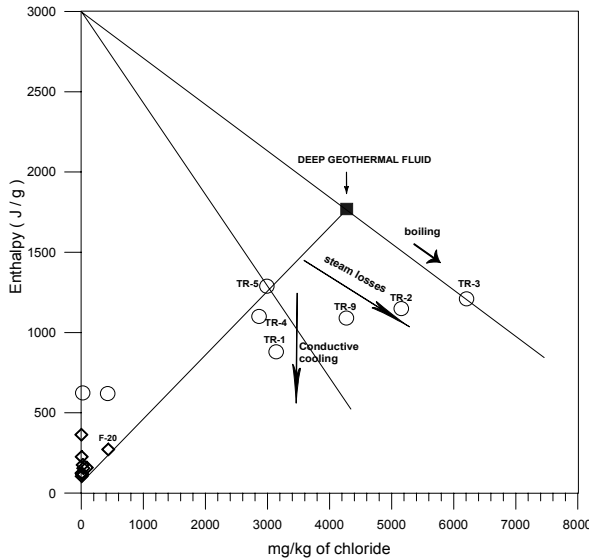


Fig. 5. Chloride-enthalpy diagram, showing the parent water and the mixing, boiling and cooling lines

The NaKCa with Mg correction geothermometer (Giggenbach, 1988), reflects the temperatures closest to the measured values (Table 3).

WELL	T _{meas.}	T _{NaK}	T _{NaKCa}	T _{qzt}	T _{K/Mg}
TR-1	234	208	204	203	248
TR-2	298	297	289	275	353
TR-3	296	267	264	276	326
TR-4	300	254	250	326	176
TR-5	302	296	292	304	304
TR-9	295	300	290	290	351

Table 3. Temperatures evaluated with cation geothermometer

Note: T_{Na-K}, Fournier (1979a), T_{Na-K-Ca}, Fournier and Truesdell (1973), T_{qzt}, Arnórsson (1985), T_{K-Mg}, Giggenbach (1988)

ISOTOPIC COMPOSITION OF THE FLUIDS

Selected hot and cold springs, fumaroles and geothermal wells were, analyzed for chemical and isotopic (¹⁸O, ²H, ³H) composition to obtain a better understanding of the hydrological processes in the Berlin geothermal system, as part of the International Atomic Energy Agency (IAEA) Technical Assistance Project, ELS/8/005, to El Salvador. The chemical analyses of waters (see table 2) were done by the CEL Chemical Laboratory and the water isotopic analyses were carried out in the isotope Hydrology Laboratory of the IAEA, Vienna, Austria (table 4). The geothermal waters from the geothermal wells were collected by a mini Webre separator. All chemical data are reported at reservoir conditions, calculated by a computer code. The isotopic data was calculated to reservoir conditions based on the following: (Henley, et. al., 1984)

$$H_r = yH_v + (1-y)H_l \quad : \text{enthalpy balance.}$$

$$\delta_r = y\delta_v + (1-y)\delta_l \quad : \text{isotope balance.}$$

$$10^3 \ln \alpha \quad : \text{isotopic fractionation factor}$$

$$\delta_r = \delta_l - 10^3 \ln \alpha \quad : \text{isotope composition at reservoir condition}$$

where H_r is the enthalpy at reservoir condition (r), H_l is the enthalpy in the liquid (l) and vapor phase (v); y is the steam fraction; δ_r, δ_l and δ_v are the isotopic compositions in the reservoir, liquid and vapor after separation, respectively.

SAMPLE	DATE	Measured values		Reservoir condition		Clres mg/kg	ENTHALPY kJ/kg
		$\delta^{18}\text{O} \text{ ‰}$	$\delta^2\text{H} \text{ ‰}$	$\delta^{18}\text{O} \text{ ‰}$	$\delta^2\text{H} \text{ ‰}$		
F-79	Jun-13-95	-6.68	-45.30			4.33	222
L.A.	Jun-13-95	-1.42	-12.20			5.53	101
F-84	Jun-13-95	-7.26	-61.10			7.94	101
F-1	Jun-14-95	-7.00	-49.90			7.64	117
F-5	Jun-14-95	-7.03	-48.50			5.78	115
F-16	Jun-09-95	-7.16	-49.00			22.03	155
F-83	Jun-14-95	-0.98	-25.80			1.5	375
F-20	Jun-15-95	-6.17	-42.60			408	272
P-4	Jun-15-95	-7.06	-47.40			89.16	159
BERLIN*	Jul-19-95	-5.68	-33.60				
C.GEOT.*	Jul-26-95	-8.00	-56.70				
M.UMAÑA*	Jul-26-95	-8.98	-65.20				
TR-2	Jun-20-95	-2.35	-42.80	-2.64	-43.09	5159	1310.7
TR-3	1991	-5.8 (v)	-41.1 (v)	-2.60	-41.10	6209	1280.0
TR-5	May-12-95	-3.05	-43.10	-3.36	-43.41	2994	1438.1
TR-9	Jun-22-95	-2.62	-40.80	-2.99	-41.17	4274	1189.7

(*) = Rainfall samples

(v) = steam sample

Table 4. Isotopic composition for waters samples (shallow and deep water).

The local meteoric water line was calculated based on the weighted monthly isotopic averages of rainfall data from the Ilopango Station, San Salvador (IAEA, 1992). This data defines a linear regression equation of $\delta^2\text{H} = 7.92 * \delta^{18}\text{O} + 9.336$, with a correlation coefficient $r^2 = 0.957$ and $n = 70$ samples (Figure 6) very similar to the world meteoric line (Craig, 1963). This meteoric water line is assumed valid for Berlin geothermal area, considering the positions of shallow waters and the recent rain water samples.

The isotopic data for wells (figure 7), indicates that waters such as those from Laguna de Alegria (L.A.) and spring F-83, have undergone isotopic fractionation due to evaporation.

This enriched their isotopic composition to a maximum of -12 ‰ in $\delta^2\text{H}$. Spring F-20 having a temperature of 65 °C , shows slight enrichment in both ^{18}O and ^2H . As this spring discharges neutral equilibrated chloride-sulphate water, it is considered to represent a mixture of volcanic water with the NaCl water of the deep geothermal fluid.

Assuming that the upflow is represented by well TR-5 as indicated in the chloride-enthalpy diagram (figure 5), figure 7 would indicate a mixing trend between the meteoric end member and TR-5.

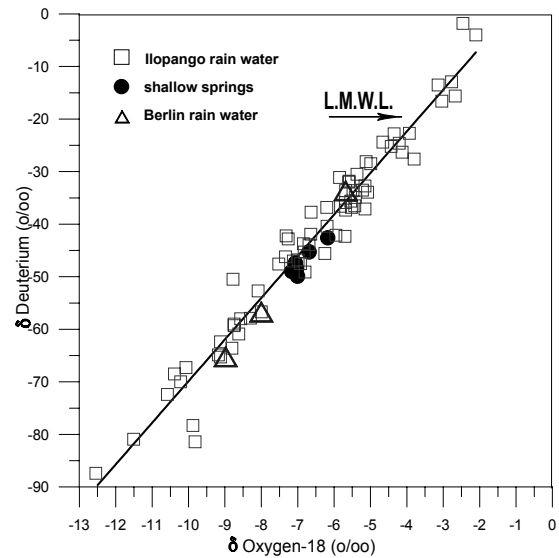


Fig. 6. Local meteoric water line defined by the equation $\delta^2\text{H} = 7.92 \delta^{18}\text{O} + 9.336$ and $r^2 = 0.957$, with $n = 70$ samples (data from IAEA, 1992)

If this mixing line is extrapolated, it would indicate a parent source that is isotopically heavy, likely andesitic in composition (Giggenbach, 1991).

YEAR	TOTAL PRECIP.	TRITIUM W.Means	$\delta^{18}\text{O}$ ‰ W.Means	$\delta^2\text{H}$ ‰ W. Means	DEUT. EXCESS W.Means	Temp. Aver.
1968	1818	22	-8.02	-60.9	3.3	22.7
1969	1596	20	-10.04	-67.3	13.1	23.3
1970	1759	26.5	-7.45	-44.8	14.9	23.2
1971	1721	19.6	-7.97			22.8
1972	1543	14.7	-5	-30.2	10.8	23.5
1973	1347	10.3	-6.68	-44.1	9.3	24
1974	1802	9.4	-6.08	-39.2	9.1	23.1
1975	1552	9.1	-7.27	-48.2	10	22.9
1976	1745	8.1	-6.15	-39.9	9.3	22.8
1977	1625	9.6	-5.76			23.2
1978	1808	10.1	-5.72	-39.6	6.2	23.2
1979	1664	5.5	-7.49	-50.5	9.5	23.4
1980	2142	5.9	-5.91	-37.1	10.2	23.5
1981	472	4.9	-3.95			
1983	1496		-6.39	-40.9	10.3	
1984	956		-6.42	-55.9	9.3	
Means	1509		-6.77	-45.8	9.5	23.2
S.D.			1.3	9.7	3	0.3

Table 5. Rainfall Isotope Data, Ilopango Station, San Salvador (I.A.E.A., 1992)

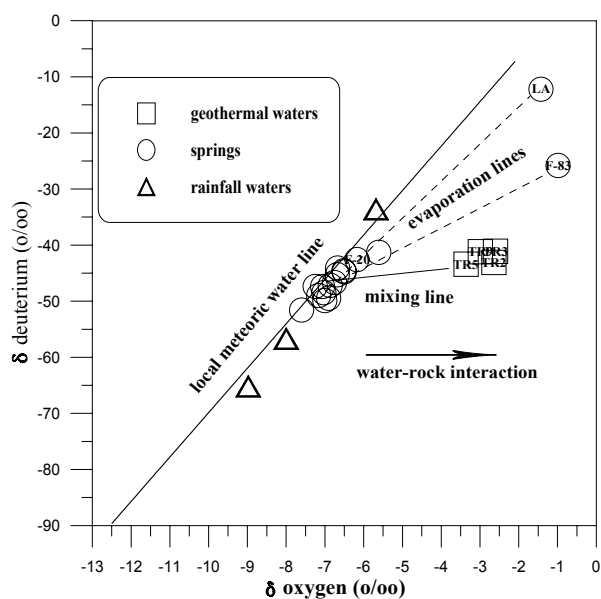


Fig. 7. Relationship $\delta^{18}\text{O}$ and $\delta^2\text{H}$ showing the main processes occurring in the geothermal area. The dashed lines show different evaporatio proportions and the solid line indicates the mixing trend. The LMWL is defined as in fig. 6

The mixing line could, however, not be connected to the other wells since their isotopic composition apparently are results of steam separation as the fluid, represented by TR-5, upflows and losses steam at its ascent or migration to the other wells. The steam is postulated to find its way into the

fumaroles characteristic of Berlin geothermal field. Then, for wells TR-2, TR-9 and TR-3 relative to TR-5, the enthalpy and temperature decline as $\delta^{18}\text{O}$ and $\delta^2\text{H}$ become more positive.

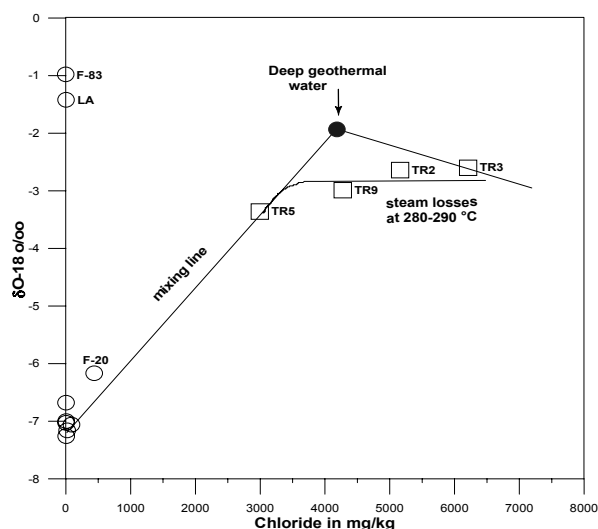


Fig. 8. Chloride and $\delta^{18}\text{O}$ relationship, showing the mixing trend between shallow waters and the deep andesitic water to produce the geothermal fluid

A plot of the chloride content vs. $\delta^{18}\text{O}$ is shown in figure 8 to further illustrate that mixing occurs between upflowing geothermal fluid (TR-5) and shallow waters (considering also the spring F-20).

It also illustrates that separation of various proportions of steam from TR-5 and the deeper geothermal water occurs at temperatures between 280 - 290 °C. The spring Laguna de Alegria and F-83, show an enrichment in $\delta^{18}\text{O}$ due to surface evaporation. The fluid of spring F-83 is the product of vapor condensation, probably from the steam that separates from the geothermal fluids. Postulating that the deeper geothermal fluid has a chloride content of 4400 mg/kg (figure 5), figure 8 indicates that this water will have an $\delta^{18}\text{O}$ content of about -2‰.

CONCLUSIONS

The Berlin geothermal reservoir is characterized by sodium-chloride waters with reservoir chloride up to 3000 mg/kg at upflow tapped by well TR-5. The dilute waters are mainly HCO_3 found in the shallow aquifers. Sulfate waters related to the condensation into the groundwater of H_2S rich steam mainly manifested in fumaroles, are also found to a limited extent.

The chemical composition at reservoir conditions in the geothermal fluid is as follows:

TDS	: 5,800 ppm.
Chloride	: 3,000 ppm
Silica	: 730 ppm
pH	: 5.7
Temperature	: 305 °C
Enthalpy	: 1,300 J/g
$\delta^{18}\text{O}$: -3.4 ‰
$\delta^2\text{H}$: -43.4 ‰

Isotope and chemical data indicates that well TR-5 is the most representative of the deep geothermal water. This geothermal water is a result of the mixture between meteoric and isotopically heavy parent water, likely andesitic in composition. The upflow at TR-5 originates from a postulated deep geothermal water which has a value of Cl close to 4400 mg/kg, $\delta^{18}\text{O}$ of -2 ‰ and $\delta^2\text{H}$ of -40 ‰. As the fluid ascend, it boils at about 280 - 290 °C. The separated waters enriched in chloride and isotopes is tapped by the wells TR-2, TR-3 and TR-9. The diagram Cl - enthalpy suggests that the main processes occurring in the system are steam losses (prevalent for well TR-3) from the deeper geothermal water and conductive cooling. Steam separation from well TR-5 produces the fluids at TR-2, TR-3 and TR-9. The fluid of well TR-4 is produced from the TR-5 by mixing with meteoric water. The fluid of the wells TR-1 and TR-8 are

produced from the fluid of TR-5 by conductive cooling.

The local meteoric water line (LMWL) is defined by the equation $\delta^2\text{H} = 7.92 * \delta^{18}\text{O} + 9.336$ from the monthly isotope rainfall data from the Ilopango Station. This line is very similar to the global meteoric water line defined by Craig (1963). The general fluid flow direction from the upflow is from South to North.

REFERENCES

Arnórsson S. and Svavarsson H., 1985. Application of chemical geothermometry to geothermal exploration and development. Geothermal Resources Council Trans., 9, 293-298.

Fournier R.O., 1991. Water geothermometers applied to geothermal energy, ed. D'Amore F., UNITAR-UNDP, New York, 253-273.

Fournier R.O. and Truesdell A.H. 1973, An empirical Na-K-Ca geothermometer for natural waters. Geochim. Cosmochim. Acta, 37, 515-525.

Giggenbach W. F., 1988. Geothermal solute equilibria. Derivation of Na-K-Mg-Ca-geoindicators, Geoquim. cosmochim. Acta, 52, 2749-2765.

Giggenbach W.F., 1991. Isotopic composition of geothermal water and steam discharges, in Application of Geochemistry in Geothermal Reservoir Development, ed. D'Amore F., UNITAR-UNDP, New York, 253-273.

Henley, R.W., Truesdell A.H., Barton jr P.B., 1965. Fluid mineral equilibria in hydrothermal systems. Society of Economic Geologists, vol. 1.

I.A.E.A., 1992. Statistical treatment of data on environmental isotopes in precipitation. Technical Reports N° 331, Vienna, Austria.