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AN APPROACH FOR GEOCHEMICAL ASSESSMENT OF CHIPILAPA GEOTHERMAL FIELD

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ABSTRACT

It presents a systematic methodology to evaluate the reservoir characteristics of Chipilapa-Ahuachapan geothermal field through the highly diluted natural manifestations (springs and domestic wells) in its surroundings. The manifestations are classified in three main groups according to their mechanism of formation: *high salinity water (HSW), medium salinity water (MSW)*, and *Sulfated Water (SW)*. The reservoir temperature at Chipilapa geothermal field is around 220°C which is estimated with application of various chemical geothermometers. The isotopic studies indicate that the heating of local meteoric water with the separated steam of deep reservoir fluids is a dominating process in the formation of springs and domestic wells fluids. The process of formation of primary and secondary vapor explains the isotopic composition of fumaroles.

INTRODUCTION

To evaluate prospects of a geothermal field, the geochemical studies of natural manifestations, springs and fumaroles are of great help as they provide preliminary estimates of reservoir characteristics and hydrothermal model of the system. As geochemistry of fumaroles is yet not very clear, the geochemical exploration is basically based on spring water samples. If the springs are highly diluted (i.e. containing a very small component of deep reservoir fluid), it is quite difficult to obtain concrete results. Thus it requires a special attention in interpretation of the data of such highly diluted natural manifestations.

The Chipilapa geothermal field is located in the western part of El Salvador, in north-west of the coastal cordillera, the east of Ahuachapan City, and south-west of Turin and Atiquizaya localities (Nieva et al, 1990). Ahuachapan geothermal system is located west of Chipilapa geothermal field and its has an installed capacity of 90 MWe. Chemical analyses of production fluids from Ahuachapan geothermal system indicate a gradient in temperature and calculated reservoir chloride concentration from 265°C and 9000 ppm Cl in the western part to 235°C and 6000 ppm Cl in the eastern part (Truesdell, 1989). This is considered as a mixing of cooler and less saline water.

Stewart (1990) reassessed the isotopic work of Nuti et al (1986) with the aim to obtain reservoir conditions. The isotopic composition of the fumaroles indicates their formation from high temperature (200°C) steam within the geothermal aquifer.

In the present article we report the results of geochemical studies obtained under the project "Geoscientific and Reservoir Engineering Studies of the Chipilapa Geothermal Field". This project contemplates Geochemical, Geophysical, Geological and Reservoir Engineering studies to estimate geothermal potential of the Chipilapa system to produce electricity.

GEOCHEMICAL EVALUATION OF NATURAL MANIFESTATIONS

The hydrothermal activities at Chipilapa geothermal field are evident in the form of a number of fumaroles, cold and hot springs, and hot water domestic wells. A program of continuous monitoring the chemical behavior of natural manifestations has been carried out by 'Comisión Ejecutiva Hidroeléctrica del Río Lempa' (CEL) during 1980 and 1983. These data have been compiled by Nieva et al (1990) to define the program of sampling of the manifestations for chemical and isotopic studies in order to assess geothermal potential of the field.

The chemical and isotopic ($\delta^{18}O$ and δD) analyses of the samples collected during 1990 are given in the Table 1. The chemical analyses were performed at 'Centro de Investigaciones

Geotérmicos de CEL, El Salvador', whereas the isotopic analyses are carried out at 'Instituto de Investigaciones Eléctricas, México'. There is a good agreement in the chemical analyses of these samples and that of the sampling points analyzed during 1980 and 1983.

Classification of the Manifestations

In an internal report of CEL, it has been observed the existence of various types of waters from Ca-Mg-HCO_3 type to Na-Cl type, and sulfated waters (CEL, 1986). This classification is based on the utilization of comparative diagrams such as Pipper diagram. Nieva et al (1990) have shown that the springs waters have a very small percentage of deep geothermal fluid, one has to take care in case of classification of such manifestations.

Giggenbach (1988) proposed a triangular diagram of Na, K, and Mg, using the thermodynamic properties of stable minerals to distinguish waters in equilibrium with high temperature minerals, waters formed of partial equilibrium, dilution or mixing, and shallow waters. The fluids from Chipilapa-Ahuachapan geothermal system are plotted in this triangular diagram (Figure 1). The fluids obtained from the drilled wells of Ahuachapan geothermal system are situated at the rock-water equilibrium curve. It also indicates the equilibrium temperature of 260°C. Whereas the fluids from the springs fall in the region of shallow waters. This may be due to high dilution with superficial water or re-equilibrium with rocks at low temperature. However, there exists a good correlation in concentration of Na and K, which supports the highly dilution of geothermal fluid with local meteoric water.

With bi-variable diagrams of concentration of dissolved species in the fluids of the manifestations, Nieva et al (1990, 1990a) have shown the existence of various types of geothermal waters, although the fluids are highly diluted with local meteoric water. The manifestations may be grouped in the following dominant types: *High Salinity Water* (**HSW**) *which are derived with mixing of high saline water (separated fluid of deep reservoir fluid) and meteoric water , Medium Salinity Water* (**MSW**), *formed with dilution of medium saline geothermal component with meteoric water* and *Sulfated Water* (**SW**), and mixture of these waters. Under this classification the meteoric waters belongs to both groups, HSW and MSW as they are end member of tendencies of the groups in bi-variable diagrams. The SW manifestations have very low salinity, but high concentration of bicarbonates and sulfates. These are in general located in the high mountain range in the south of the Chipilapa-Ahuachapan geothermal field, whereas the manifestations related to HSW and MSW are located in the low elevation part in the north the geothermal system.

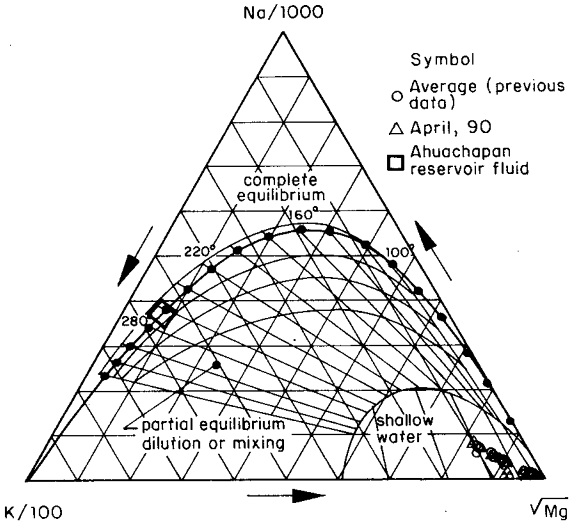

Fig. 1: Triangular diagram in relative contents of Na, K, and Mg to evaluate rock-water interaction equilibrium temperature of a geothermal system (Giggenbach and Stewart, 1982).

Chemical Geothermometers

The reservoir temperature of Chipilapa geothermal system is estimated by applying Na-K-Ca (Fournier and Truesdell, 1973), Na-K-Ca with Mg correction (Fournier and Potter, 1979), Cation Concentration (Na-K-Ca-Mg, Nieva and Nieva, 1987) and Na-K (Fournier, 1979) geothermometers. These geothermometers show a wide variation in underground temperature. The Na-K-Ca geothermometer indicates temperatures up to 215°C, whereas the temperatures measured by the Na-K geothermometer are mostly around 260°C. However, the geothermometers which consider the correction of Mg, such as Na-K-Ca with Mg correction and Cation Concentration (CCG) geothermometers, show quite low temperature. The high concentration of Mg in these samples, relatively, indicates that the thermal component of water might have suffered a re-equilibrium at low temperature during ascending to surface or its composition has been altered sufficiently with mixing of high proportion of superficial cold waters.

It has been observed that the temperature measured for the high concentration samples of MSW

Table 1: Chemical and isotopic analysis of natual manifestations in surroundings of Chipilapa-Ahuachapan geothermal system.

Sample	Date	Na	K	Ca	Mg	Cl	SO4	CO3	HCO3	SiO2	B	Fe	Li	Sr	pH	Elec. Cond.	T (°C)	Charge bal.( )	$\delta^{18}O$	δD
Meteoric water with very low proportion of geothermal component																				
F724	11/04/90	22.6	5.6	25.0	11.7	6.5	12.5	2.5	156	90	0.07	ND	ND	0.12	8.54	318	30.3	3.9	-7.89	-57.3
F737	11/04/90	25.3	5.7	37.5	18.2	22.9	18.7	3.6	182	89	0.07	ND	ND		8.58	460	28.2	5.4	-7.32	-53.4
P438	11/04/90	37.0	6.9	22.0	11.0	23.2	14.0	5.4	150	94	0.38	ND	0.06	0.13	8.54	380	31.5	2.9	-7.43	-56.5
P448	10/04/90	37.2	9.6	28.8	13.1	26.9	12.0	7.2	183	85	0.36	0.9	0.08	0.17	8.57	420	30.4	1.6	-7.48	-52.7
P457	27/06/90	38.2	7.4	29.0	13.6	27.7	12.0		200	89	0.5	0.76	0.08		8.16	400	30.0	1.7	-7.62	-57.3
P481	27/06/90	37.2	7.5	30.0	11.2	43.5	11.3		209	89	0.3	0.21	0.07		7.26	390	29.4	-3.1	-7.54	-54.0
M2	11/04/90	35.4	6.2	24.6	10.0	23.9	13.3	3.6	156	96	0.31	ND	0.06	0.13	8.50	370	30	1.8	-7.50	-55.7
Thermal water belongs to MSW group																				
F717	11/04/90	201.0	23.0	13.9	3.6	75.0	29.9		461	143	2.70	0.3	0.67	0.12	8.26	968	62.3	0.7	-7.21	-50.6
F730	11/04/90	187.0	23.6	15.1	3.5	81.8	27.9	22.8	394	156	2.70	ND	0.66	0.13	8.74	940	57.6	-1.1	-7.39	-51.7
F733	11/04/90	128.0	20.8	34.0	7.0	80.7	30.4	10.8	337	137	1.50	ND	0.46	0.27	8.64	810	50.6	-2.0	-7.24	-50.6
F733E	11/04/90	132.0	21.0	34.0	7.2	78.2	29.7	4.8	358	152	1.52	ND	0.48	0.23	8.54	824	50.6	-1.2	-7.26	-52.4
F734	11/04/90	164.0	23.0	23.4	4.7	80.2	29.3	10.8	387	150	2.20	0.2	0.59	0.18	8.69	919	57.6	-1.1	-7.29	-50.1
F735	11/04/90	175.0	22.8	20.4	4.2	86.9	28.7	15.6	376	143	2.40	ND	0.60	0.13	8.69	940	59.3	-0.4	-7.28	-52.2
F757	11/04/90	109.0	17.5	22.4	4.6	46.7	26.0	13.8	265	128	0.92	0.3	0.32	0.18	8.64	640	40.3	0.5	-7.22	-52.5
F760	11/04/90	100.0	15.2	18.7	4.6	37.2	22.2	6.0	256	128	0.68	1.3	0.32	0.18	8.37	588	38.4	1.6	-6.91	-51.7
P468	27/06/90	174	20	23.8	6.0	61.8	25.4		447	132	2.1	ND	0.53		7.88	880	44.2	2.2	-7.07	-51.3
Thermal water belongs HSW group																				
F719	27/06/90	154	25.2	29.8	12.1	185	17.8	2.4	254	128	4.3	0.06	0.4		8.34	940	42.4	0.3	-7.41	-52.8
F740	20/06/90	229.0	39.0	28.0	10.3	342.0	19.9		244	133	6.5		0.12		8.00	1400	37		-7.04	-51.4
F741	27/06/90	70	15.7	26.8	12.8	104	10.7		162	96	1.6	0.1	0.11		7.83	597	29.3	1.0	-7.47	-53.3
P412	11/04/90	139.0	25.2	36.8	12.6	183.0	16.4	12.0	220	133	4.20	1.6	0.40	0.25	8.64	960	34.3	0.6	-7.26	-53.0
P413	11/04/90	154.0	24.4	30.4	10.0	170.0	9.5	12.0	232	118	3.90	0.5	0.41	0.20	8.62	962	36.3	2.8	-6.39	-51.3
M1	11/04/90	148	23.6	28.4	10.6	187	17.1	4.8	265	136	3.9	ND	0.47		8.43	1000	44.4	-3.7	-7.21	-54.5
Sulphate water (SUL)																				
F716	11/04/90	16.2	7.5	43.0	12.8	4.0	49.8	1.2	136	102	0.07	ND	ND		8.46	387	40.0	9.0	-7.42	-51.4
F720	11/04/90	24.0	5.6	20.9	9.2	9.6	20.6		122	92	0.22	ND	0.05	0.12	7.95	295	28.3	5.9	-7.07	-51.3
F726	10/04/90	29.9	9.5	53.0	11.2	0.4	95.4	6.1	158	81	0.03	ND	0.06	0.07	8.56	460		3.3	-7.91	-55.6
F727	10/04/90	29.3	9.6	49.0	10.8	0.3	98.3	3.6	153	76	0.02	ND	0.04	0.12	8.49	454	33.3	1.8	-7.94	-55.3
F728	10/04/90	12.0	2.7	36.4	8.3	3.5	33.4		133	64	0.02	ND	ND	0.20	6.98	300	24.4	9.4	-7.14	-50.6
F729	10/04/90	11.5	2.2	39.5	8.4	4.0	40.6	1.8	132	64	0.01	ND	ND	0.17	8.42	310	28	0.6	-7.27	-52.5
F747	5/04/90	23.4	6.2	64.0	14.2	2.3	138	1.2	168	121	0.06	3.5	0.04		8.49	522	38.6	-1.7	-7.71	-49.4
P469	11/04/90	15.1	4.5	28.2	8.2	2.0	48.4		101	87	0.04	ND	ND	0.25	8.09	309	27.5	2.8	-5.97	-47.3
P526	10/04/90	12.5	4.1	22.6	10.8	2.7	2.6	3.0	135	102	0.04	ND	ND	0.12	8.48	250	24.9	4.3	-7.06	-48.9
M28	05/04/90	49.8	17.8	24.6	5.9	2.6	126.0		85	219	0.48	ND	0.04	0.20	7.48	455	81	4.1	-6.43	-49.0
Water formed with mixing of HSW–MSW																				
F722	11/04/90	165.0	23.4	21.4	6.5	136.0	21.4		301	146	3.60	ND	0.56	0.13	8.14	940	45.6	1.6	-7.10	-50.1
F725	10/04/90	8.7	4.1	21.0	6.5	3.1	22.1		52	64	0.03	ND	ND		8.03	250		19.7	-7.69	-52.7
F752	11/04/90	167.0	20.8	20.0	6.3	105.0	21.7		371	133	2.80	0.3	0.59		8.28	940	51.3	-0.4	-7.30	-51.5
F754	11/04/90	167.0	22.2	15.0	7.0	118.0	22.0	15.0	331	146	3.60	0.2	0.59	0.13	8.70	959	59.6	-2.5	-6.99	-53.2
P410	11/04/90	71.5	16.6	36.4	16.0	140.0	12.7	4.2	139	101	2.30	0.3	0.08	0.32	8.48	700	28.8	0.4	-7.08	-54.2
P414	11/04/90	166.0	23.6	22.4	7.0	149.0	20.9	24.0	248	144	3.70	0.4	0.56	0.15	8.66	462	41.3	0.5	-6.99	-55.8
P414	27/06/90	164	24.2	22.8	7.8	152	20.5		297	139	3.7	0.14	0.49		7.62	860	41.7	1.4	-6.99	-52.5
F744	10/04/90	10.2	3.3	21.2	3.9	1.9	27.5		76	54	ND	ND	ND		8.22	235	21.7	1.1	-7.74	-54.6

group with various geothermometers are quite consistence. The geothermometers CCG and Na-K-Ca with Mg correction show very low temperature except samples 717 and 730. It may be concluded that the samples 717 and 730 have little effect in alteration of chemical composition due to mixing of cold waters. Thus the samples (717 and 730) provide information about deep temperature as in the range 220-230°C.

ISOTOPE HYDROLOGY OF CHIPILAPA-AHUACHAPAN GEOTHERMAL SYSTEM

The isotope compositions ($\delta^{18}O$ and δD) of the springs and the domestic wells, together with the condensed waters from fumaroles (Stewart, 1989) and the total discharge composition of five productive wells (AH-6, AH-19, AH-22, AH-24, and AH-31) of Ahuachapan geothermal system (Nieva et al, 1990) are shown in Figure 2.

Stewart (1990) has reported the isotopic compositions of rainfall at different altitude in the region, which were collected and analyzed by Nuti et al (1986). These samples fall close to the global meteoric water line ($\delta = 8\ \delta^{18}O + 10$) with a mean deuterium excess of 10.3‰. He argued that these samples should not be used to determine the mean isotopic composition of local meteoric water as the average isotopic composition of these rainfalls because they only cover three months of one year. The weighted mean isotopic composition ($\delta D = -47.0$, $\delta^{18}O = -7.0$) of six years rainfall at San Salvador, which is about 120 km from the studied area and has a very similar geographic setting, is a good alternative to consider the average meteoric water composition and the local meteoric line as passing through this point with a gradient of 8. The meteoric line and this point are also shown in the Figure 2.

MIXING MODELS

The geothermal fluids are, in general, formed by an interaction of hot rocks and local meteoric water which infiltrates through faults and fractures in the field. During their ascent to superficies, these fluids cool to a temperature equal or less than the local boiling point by the three important processes: *(i) Adiabatic cooling:* steam separation due to adiabatic expansion of the fluid with decreasing pressure, *(ii) Mixing:* dilution and mixing with waters derived from shallow sources, and *(iii) Conductive cooling:* heat loss in heating country rocks. Normally, the three processes take place in formation of manifestations. However, it is possible to understand mechanism occurred during ascent of the

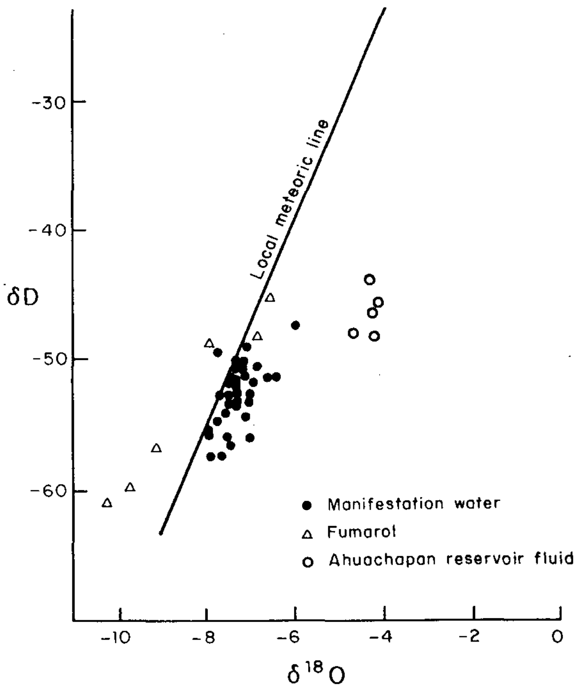

Fig. 2: The isotopic relation ($\delta^{18}O$ vrs. δD) of Chipilapa geothermal field.

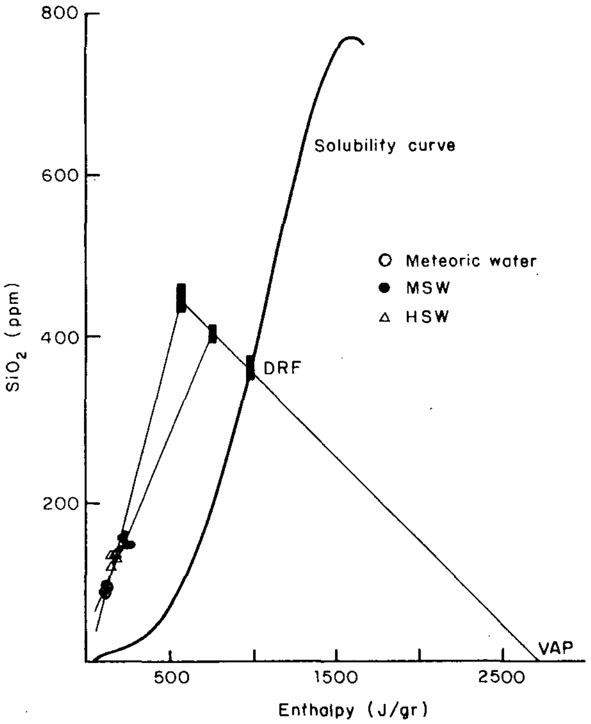

Fig. 3: A mixing model diagram of Enthalpy vrs. SiO_2. It demonstrates the formation of the HSW and MSW groups with mixing of meteoric water and separated deep reservoir fluid at 130-140°C, and 170-180°, respectively.

deep fluids through mass and energy balance equations, if the first two processes have major contribution.

The formation of the two groups manifestations, HSW, and MGW is demonstrated through an quartz solubility vrs. enthalpy diagram (Figure 3). The solubility curve of quartz is a locus of all the points of quartz concentration which are in equilibrium at corresponding enthalpy or temperature (Fournier and Potter, 1982). The reservoir temperature between 220–230°C suggests the equilibrium concentration of SiO_2 in reservoir fluid in between 340–360 ppm. The extrapolated least square fitted lines in the points corresponding the two groups are also shown in the Figure 3. According to this mixing model the reservoir fluid flushes in two phases (vapor and liquid) and then the flushed liquid mixes with the local water in formation of natural manifestations. The model indicates that the group HSW formed by flushing at 130–140°C, whereas MSW formed by flushing at 170–180°C.

The evidences obtained during drilling of wells CH-7 and CH-8 at Chipilapa geothermal field also support the reservoir temperature around 220°C. The chloride concentration of reservoir fluid, calculated according to this model from HSW, should be in between 2200–2450 ppm, whereas MSW indicates only 380–400 ppm (Nieva et al, 1990a). This anomaly arises on account of differences in formation mechanism of these two groups of water and it is used in nomenclature of these groups.

The isotopic mixing model provides an important clue to understand the mechanism of natural manifestation formation. The isotopic composition of condensed waters from fumaroles in the Ahuachapan-Chipilapa field has been explained with a hypothesis of mechanism of formation of primary and secondary vapor in the hydrothermal system (Stewart, 1990). The primary steam originates from the separation of geothermal fluids. This steam may be absorbed in superficial aquifer and may cause its boiling. The steam produced through the boiling this superficial aquifer is named as secondary steam (Giggenbach and Stewart, 1982). Stewart (1990) postulated existence of underground water of 80°C with isotopic composition ($\delta D = -48$, $\delta^{18}O = -7.25$) to explain the phenomenon in formation of manifestations in Ahuachapan-Chipilapa geothermal field.

Nieva et al (1992) explain the evolution of isotopic composition of fumaroles and the waters of groups, HSW and MSW through the mixing mechanism of local meteoric water and components of geothermal fluid according to model proposed by Giggenbach and Stewart (1982). The isotopic composition of deep geothermal water ($\delta^{18}O = -4$ and $\delta D = -45$) is chosen same as reported by Stewart (1990) and the local meteoric water is considered as a cold, low saline spring with isotopic composition ($\delta^{18}O = -7.5$ and $\delta D = -54$). The data points corresponding to the fumaroles, lie in between the curves related to isotopic composition of primary steams from undiluted deep water and secondary steam from primary undiluted steam.

HYDROGEOTHERMAL MODEL OF CHIPILAPA FIELD

Figure 4 shows a schematic diagram of the Chipilapa's hydrogeothermal model which is an outcome of the above evidences. The local meteoric water infiltrates deeply in formation of deep reservoir fluid (DRF) which is reservoir at Ahuachapan geothermal system at 260°C. This DRF separates at 220–230°C in formation fumaroles in the high mountain range and reservoir fluid at Chipilapa geothermal system. A mixture of DRF and primary and secondary condensed vapor (PCV and SCV) are diluted with meteoric water (MW) in formation of the two HSW and MSW. The manifestations of the group are located at low elevation part in the north of the field . The springs associated with sulfated water are found generally near to these mountains. The sulfated water formed by heating of meteoric water with the separated steam. This explains existence a heat source under the mountainous part of the field which is located in the south of the Chipilapa-Ahuachapan geothermal reservoir. The fluid is flowing laterally from the high elevation to low elevation in the north of the system.

CONCLUSIONS

The geothermal model of Chipilapa is a lateral flow model. The local meteoric water infiltrates deeply through faults and fracture in the upper part of mountain range and gets heated up to 260°C. The reservoir fluid at Ahuachapan geothermal system are in rock-water interaction equilibrium at 260°C. As chemical geothermometers indicates 250–270°C reservoir temperature and all the data points corresponding to geothermal wells fall near to the equilibrium curve at the point of 270°C. The chemical geothermometers indicate the reservoir temperature of 220–230°C at Chipilapa geothermal field. The most of the manifestations (springs and domestic wells) in the lower portion of the

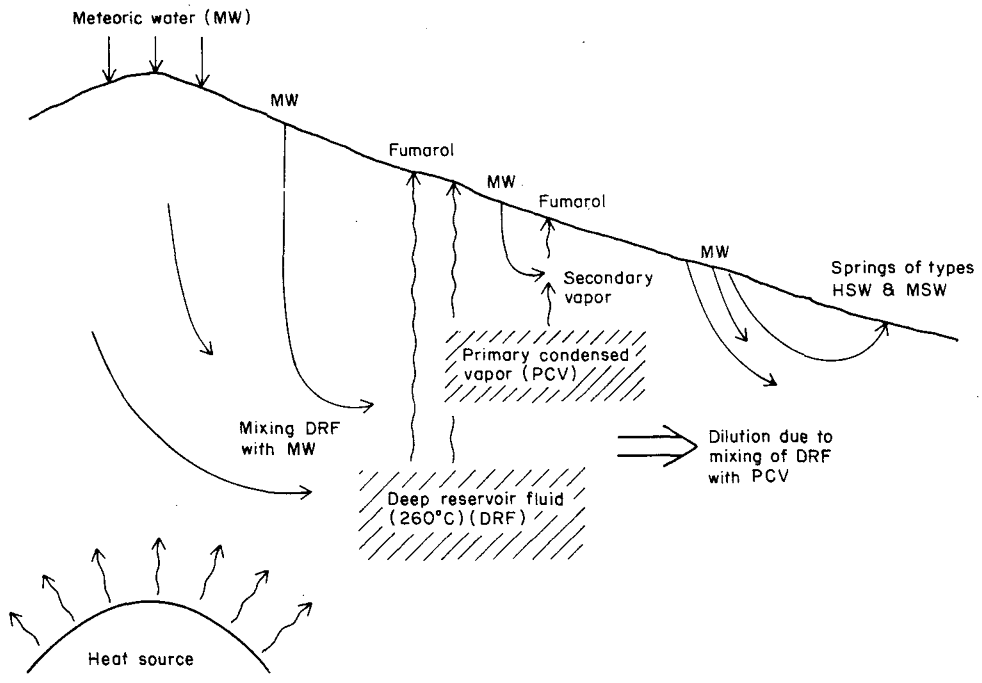

Fig. 4: Sketch diagram of hydrothermal model of Ahuachapan-Chipilapa geothermal system.

field are grouped in two classes, high salinity water (HSW) and medium salinity water (MSW), according to their formation mechanism. The chemical and isotopic studies of the fluid obtained through the drilled wells at Chipilapa geothermal field will contribute significantly in improvement of the presently preliminary model of the system.

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