

## ISOTOPE GEOCHEMISTRY AS INDICATOR OF RESERVOIR PROCESSES IN BACON-MANITO GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

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### ABSTRACT

The local meteoric water line for the Bacon-Manito Geothermal Production Field may be represented by the equation:  $\delta^2H = 8 \cdot \delta^{18}O + 13.4$ . Based on the analysis of the available data, most of the thermal waters within the resource were derived from rainwater. The isotopic signatures of the acid-sulfate springs indicate steam-heating and are affected mainly by evaporation. The lake waters were also affected by evaporation, except for Lake Naghaso which apparently has deep brine component and is affected by steam-heating. Similarly, the neutral-chloride springs have deep-fluid signature.

The Bacman Geothermal Production Field is comprised of a single geothermal system, which is centered within the Botong area. The Osiao-Pangas (OP) wells tap the center of the resource and encounter fluids which are already products of boiling of the parent water. The parent water, which closely resembles OP-4D, has an isotopic composition of:  $\delta^{18}O \approx +2.0 \text{ ‰}$  and  $\delta^2H \approx -26.0 \text{ ‰}$ . The fluids at the upflow are isotopically enriched (+4.0 ‰) and become depleted (-3.9 ‰) as it outflows towards north-northwest in the central Palayang Bayan and southwest in the Cawayan sector. The fluids along the outflow path are products of dilution between meteoric waters and the parent water. Wells situated at the margins, like CN-2RD and CN-3RD are tapping steam-condensate type of fluids. Although there are limited data, the outflow possibly extends towards the Manito area farther north.

After seven years of production, the most prominent processes occurring in the reservoir are boiling and dilution. Isotopic trends indicate that the central Palayang Bayan sector has been diluted with fluids coming from the western

part. This fluid, termed as the Masakrot fluid, is isotopically depleted, slightly cooler, less mineralized and has lower gas and boron contents. The effect of dilution is manifested by the depletion of  $^{18}O$  and  $^2H$  in the central wells. Although not clearly indicated by the isotope data, boiling could also be occurring in this part of the reservoir. Chemical trends, e.g. increasing discharge enthalpy and gas and chloride concentrations, show that boiling does occur in some wells. These mean that the dilution process masks the effect of boiling in the isotopic signatures of the fluids. The OP wells, on the other hand, are showing enrichment in the isotopic composition. As pressures draw down, these wells experience boiling in the reservoir.

### 1.0 INTRODUCTION

Bacman Geothermal Production field is one of the producing fields of PNOC-EDC. It is situated at the boundaries of the provinces of Sorsogon, and Albay in the Bicol Region. To date, there are three power plants installed at the production field and these are connected to the Luzon grid. These are Bacman-1 (110 MWe), Bacman-2 Cawayan sector (20 MWe) and Bacman-2 Botong sector (20 MWe). There are 20 production wells supplying these power plants (Fig. 1).

As in any other geothermal field, once production commences, changes start to occur in the reservoir. The changes are monitored as these have implications in the capacity of the field to produce. These changes are detected through geochemistry monitoring, as well as monitoring the variations in the physical parameters of the well (e.g. massflow, wellhead pressure (WHP), enthalpy). One geochemistry technique that has been proven to be helpful is through the use of stable isotopes. The

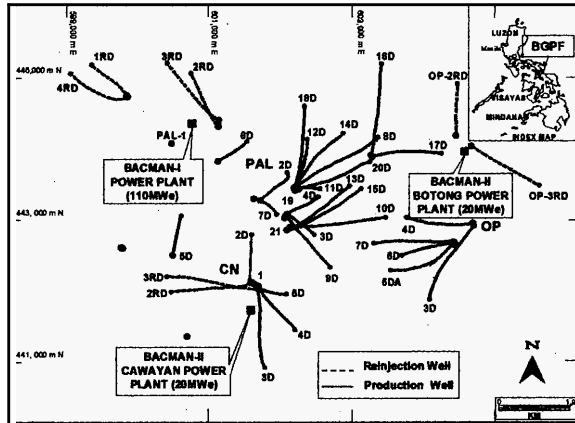


Figure 1. Location map of the BGF production and reinjection wells. Inset map shows location of BGF in Philippine Archipelago. (Modified after Maturgo et al., 2000).

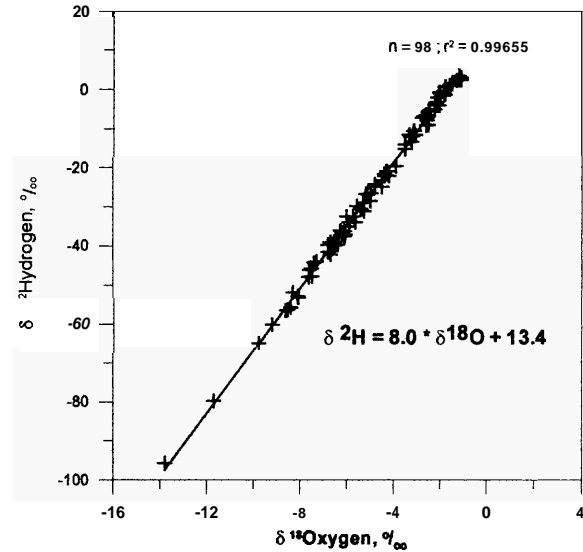


Figure 2. Local meteoric water line of BGF.

objectives of this report, therefore, are : (a) to establish the baseline geothermal isotope hydrology in Bacon-Manito, and (b) to determine the different processes occurring in the geothermal reservoir through variations in isotopic compositions of geothermal fluids.

Collection of water and steam samples for isotope analysis had been done for all surface waters (e.g. springs and lakes) and well discharges. Rainwaters from the different rainstations were also analysed for the calculation of the local meteoric water line (LMWL) of the Bacman Geothermal Production Field. All 1983-1984 samples were sent to the Institute of Geological and Nuclear Sciences at Lower Hutt, New Zealand for analysis of  $^{18}\text{O}$  and  $^2\text{H}$ . The 1990 samples, analysed for  $^{18}\text{O}$  and  $^2\text{H}$ , were sent at the Center for Application of Isotopes and Radiation (CAIR) in Indonesia and at the IAEA laboratory in Vienna, Austria (Buenviaje and Solis, 1993). The isotope samples from 1996 to 2000 were, however, analysed at the joint DOE - PNOC-EDC stable isotope laboratory in Manila.

## 20 STABLE ISOTOPE COMPOSITION OF FLUIDS

### 21 Local Meteoric Water Line

Rainwater samples were collected from the four stations installed at different elevations and

locations within the resource of BGF. These are at Bonga (600 masl), Botong (475 masl), Inang Maharang (285 masl), and Balasbas (150 masl). The rainfall data from the period 1990 to 1998 delimit a local meteoric water line (LMWL) for BGF (Fig. 2). The equation of the LMWL is given by:

$$\delta^2\text{H} = 8 * \delta^{18}\text{O} + 13.4 \quad (1)$$

This is consistent with those calculated from the different geothermal fields in the Philippines, where an a priori slope of 8 is generated and the excess deuterium ranges from 13-14 ‰. Preliminary calculations for BGF, however, indicated an **excess** deuterium of 13.7 ‰ (Buenviaje et al., 1993 and Caranto, 1999). This is slightly higher than the latest value of 13.4 ‰, as earlier calculations included rainfall data only until 1994. Mt. Apo's LMWL has an excess deuterium of 14.0 ‰ (Salonga, 1996) while Leyte has 13.7 ‰ (Alvis-Isidro et al., 1993).

From the meteoric water line generated, a Meteoric Water Index can then be calculated for BGF. This is found to be:  $\delta^{18}\text{O} = -5.08$  ‰ and  $\delta^2\text{H} = -27.2$  ‰. This represents the average isotopic composition of precipitation from the different stations.

## 2.2 Springs and Lake Waters

Tables 1a and 1b show the isotopic and chemical composition of springs and lake waters found within the resource sampled in 1983 and 1990, respectively. In 1983, some springs were sampled during the dry season while others were sampled during the rainy Season. The 1990 sampling, on the other hand, was conducted mostly during the dry Season (April-May). No springs were sampled at different Seasons in one year, thus no conclusion can be made to determine the effect of the changing Seasons in the isotopic composition of the springs. Most of the springs do not show significant changes between 1983 and 1990, and compositions may just be within error ranges.

Figure 3 shows the  $\delta^{18}\text{O}$  vs  $\delta^2\text{H}$  plots of the springs and lake waters along with the generated LMWL. The bicarbonate and mixed bicarbonate-sulfate springs plotted along and very near the LMWL, which indicate that these waters are meteoric in origin or were just derived from rainwater.

The three lake waters, namely, Lake Naghaso (LN), Lake Osiao (LO) and Lake Rangas (LR) exhibit a positive-shift from the LMWL. This shift is due to the enrichment of both  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  which could be an effect of the high evaporation rate at the surface of lake waters. The evaporation process tends to enrich the residual liquid. The stagnant nature and probably the sizeable area of lake waters are more susceptible to evaporation processes, compared to a flowing spring where the waters continuously move, therefore leaving little time for evaporation to occur or none at all.

Most of the acid-sulfate waters also plotted along the LMWL, again suggesting their meteoric origin. The groundwaters were just heated up by the ascending steam giving rise to steam-heated waters. There are few acid-sulfate waters, though, which are isotopically enriched like Naghaso (NG), Malangto (MO) and Inang Maharang (IM) springs. This positive-shift again indicates an isotopic enrichment. There are two reasons which could contribute to this positive shift among acid-sulfate waters. One is evaporation process similar to lake waters. A ponded acid-sulfate spring where there is no flow is subjected to evaporation resulting to an enriched water. The other is

boiling (steam loss) and condensation effects (Blattner and Hulston, 1990; Buenviaje and Solis, 1993). This means that the enrichment in the springs is a product of boiling of the deeper fluids in the reservoir.

Among the acid springs, there is one which showed a depletion in  $\delta^{18}\text{O}$  and a negative-shift from the LMWL. This is exhibited by the Damoy spring. Damoy spring is a cold-bubbling pool and has predominantly  $\text{CO}_2$  with minor  $\text{H}_2\text{S}$  gas (Solis et al., 1994). According to the interpretation of Solis et al. (1994), the cold water spring could have exchanged its heavier oxygen isotope with another  $^{18}\text{O}$ -containing fluid, in this case, with the abundant  $\text{CO}_2$  gas, rather than with the surrounding rock; hence the depletion of  $^{18}\text{O}$ .

There are only four neutral-pH chloride springs in the area. Pawa (PW) and Osiao (OW) springs are plotted along the LMWL indicating that these springs are predominantly rainwater. Buang (BU) and Parong (PR) springs are shifted to the right of the LMWL indicating isotopic enrichment. Their enrichment is due to geothermal brine contribution, as evidenced by their high chloride concentration, and not due to evaporation like the acid-sulfate waters. Parong springs, which are situated along the seashore, could owe its high chloride concentration to seawater mixing aside from geothermal contribution.

## 2.3 Well Discharges

Table 2 lists the isotopic content of the discharged wells starting from baseline (1983-1990) to 2000. The following discussion will establish the isotopic characteristic of the fluids prior to production. The changes in the isotopic content brought about by production will be discussed in the succeeding sections.

Figure 4 shows the plot of  $\delta^{18}\text{O}$  vs  $\delta^2\text{H}$  for the production wells. As expected, all wells are shifted to the right of the LMWL, indicating enrichment. The most shifted wells are those of OP-6D, followed by OP-3D and OP-4D. The cluster of the wells define a regression line of :

$$\delta^2\text{H} = -0.61 \cdot \delta^{18}\text{O} - 25.2 \quad (2)$$

The wells (PAL, CN, MO) are generally clustered in one area, except for OP wells which are the most isotopically shifted. This suggest

Table 1a. Isotopic composition of springs, 1983-1984.

Name	Elevation (m)	Date	Temp °C	pH @ 25 °C	Cl	SO <sub>4</sub>	SiO <sub>2</sub>	<sup>18</sup> O	<sup>2</sup> H
					mg/kg			permille	
Parong 1	0	5/27/83	104	5.2	6229	616	230	-2.95	-14.4
Parong 2	0	5/27/83	100	5.3	6634	652	223	-2.87	-12.9
Buang 1	5	6/30/83	37	7.9	4698	288	80	-4.07	-26.5
Pawa 1	15	5/26/83		6	17.7			-5.41	-32.6
Pawa	10	7/1/83	23		10.6			-4.97	-28.8
Pawa 2	10	7/1/83	62	7.9	1519	103	171	-4.59	-28
Naghaso 1	5	5/26/83	66	2	5438	89	341	-0.63	-18.8
Naghaso 2	5	5/26/83	98	2.4	4362	75	281	-0.84	-19.4
Naghaso 3	5	5/26/83	85	2	5396	89	341	-0.66	-19.1
Naghaso 4	5	5/26/83	75	2	5674	95	346	-0.6	-15.8
Naghaso 5	5	5/27/83	80	2.3	1793	92	244	3.53	-10.2
Naghaso 6	5	5/27/83	71	2.6	1725	95	212	1.91	-13.3
Naghaso	5	5/26/83	27	6	20.4			-5.49	-31.7
Inang Maharang1	285	5/26/83	100	6.1	14.2	120	122	-0.65	0.8
Inang Maharang 2	285	5/26/83	97	5.8	16.8	229	131	1.31	8
Inang Maharang	315	10/12/83	34	7.6	43.8	212	133	-5.53	-30.1
Inang Maharang 3	280	10/12/83	53	7.7	39.9	101	160	-5.45	-29.2
Damoy	660	5/28/83	25	3	18.6			-5.69	-30.9
Damoy	660	5/28/83	26	3	22.8			-5.7	-27.1
Puting Bato	450	5/28/83	26	4	6.3			-5.7	-32.3
Tinapian 2	0	6/30/83	22	3.2	8.6	88	48	-5.56	-28.4
Tinapian 1	75	6/30/83	20	5.4	9.1	88	82	-5.39	-27.3
Balasbas	55	6/30/83	82	4	10.4			-2.55	-25.5
Balasbas	55	6/30/83	50	4	10.6			-4.43	-28.3
Balasbas	55	6/30/83	38	5	12.9			-4.85	-27
Balasbas 2	54	7/11/84	50	5.7	11			-4.66	-29.5
Calpi	85	7/1/83	33	4	11.7			-5.2	-27.4
Pangas	790	10/21/83						-7.51	-44.5
Pangas	790	8/18/83	26	0.5	14.8	1016	143	-5.89	-31.4
Pangas 2	790	10/21/83	26	2.6	23.7	743	94	-6.78	-40.1
Cawayan 4	600	10/21/83	24	4.1	12.4	100	57	-5.52	-32.9
Cawayan	600	10/21/83						-7.51	-44.5
Balabagon 1	5	5/27/83	62	7.3	70.7	12	162	-5.24	-26.5
Balabagon 2	5	5/27/83	36	7	14.7	10	105	-5.39	-28.6
Malangto 1	35	5/27/83	98	7.9	24.6	40	134	-5.33	-28.2
Balading 1	35	6/30/83	24	8	78.4	9	85	-5.24	-28.1
Banao	125	7/1/83	36	6	9.1			-5.24	-28.3
Banao 2	125	7/1/83	20	7.2	10	0.75		-5.06	-30.2
Sta. Cruz	55	7/18/83	16	7.5	10.4	5	70	-5.74	-31
Sta. Cruz	55	7/18/83	21	7.8	11.3	9.9	72	-5.84	-31.4
Alinao 1	275	8/13/83	32	8.1	25.2	105	141	-5.67	-30.3
Alinao 2	275	8/13/83	19	8.7	13.1	37.2	60	-5.84	-31.7
Palhi 1	5	9/8/84	27	6.7	14.1	8.1	74	-6.08	-38.5
Sta. Cruz 1	220	7/18/83	30	8.7	29.7	125	110	-5.95	-30.4
San Lorenzo 1	430	7/19/83	32	7.7	22.6	272	136	-5.62	-27.1
San Lorenzo	340	7/19/83	32	7.7	29.7	125	110	-5.59	-29.4
San Lorenzo		7/19/83	16	8.1	21.7	319	133	-5.81	-30.6
Balasbas 1	54	7/11/84	90	6	3.5	50	24	-3.64	-29.4
Balasbas	55	7/1/83	22	5	10			-5.41	-28.7
Lake Rangas	800	8/16/83	28					-8.16	-55.8
Lake Osiao	400	8/30/83						-3.5	-28.7
Balasbas grndwater	55	7/11/84	30					-5.77	-33.7
Stream at CN1 pad	734	7/8/84	22	4.2	14.2	15.9	15	-6.9	-33.1

Table 1b. Isotopic composition of springs, 1990

Name	Elevation m	Date	Temp °C	pH @ 25°C	Cl	SO <sub>4</sub>	SiO <sub>2</sub>	<sup>18</sup> O	<sup>2</sup> H
					mg/kg			permille	
Inang Maharang	285	4/2/90	96	5.98	366	107	127	-0.22	-3.3
Inang Maharang	285	4/5/90	94	3.32	138	150	143	2.54	-0.4
Damoy3	660	4/5/90	26	3.22	17	316	73	-5.3	-28.7
Damoy2	660	4/6/90	26	2.69	26	482	146	-7.31	-27.6
Puting Bato	450	4/16/90	33	4.55	21	171	67	-5.7	-30.3
Calpi	85	4/16/90	40	5.44	19	288	55	-5.29	-30.7
Tinapian 1	75	4/17/90	26	5.21	17	82	82	-4.9	-33.1
Malangto2	35	4/4/90	64	2.97	22	235	71	-0.9	-13.1
Cawayan 4	615	4/17/90	29	3.43	17	113	57	-5.05	-30.1
Naghaso 2	5	4/5/90	89	3.01	1993	56	209	0.24	-10
Naghaso 7	5	4/5/90	94	3.45	2426	87	257	1.72	-5
Pawa	10	4/5/90	69	6.44	1364	48	174	-4.52	-25.3
Buang	5	4/5/90	45	6.38	697	60	76	-5.47	-39
Parong	0	4/17/90	98	5.19	5545	415	230	-2.5	-27.9
Osiao Artesian well	5	5/3/90	31	6.68	518	49	82	-5.13	-28
Malangto 1	35	4/5/90	95	7.14	21	18	149	-5.39	-34.1
Mapaniki	475	4/3/90	40	6.87	19	46	121	-5.54	-31.9
Balading	35	4/4/90	32	6.43	60	9	85	-5.34	-39
Banao	125	4/4/90	41	6.82	19	8	121	-5.54	-38.4
Alinao 1	275	4/19/90	39	6.23	34	107	147	-6.31	-36.6
Salvacion 2	600	5/4/90	22	5.63	19	97	50	-7.54	-44.8
Salvacion 1	600	5/4/90	22	5.34	23	83	57	-4.36	-29.5
San Lorenzo 2	600	5/2/90	37	6.19	35	251	138	-5.47	-29.2
Balabagon	5	11/16/90	64	6.87				-5.29	-29.4
Palhi	5	4/18/90	26	6.49	27	7.3	87	-6.37	-42.7
Puting Bato Creek	450	4/4/90	28	6.5	21	6	31	-5.58	-31.1
Lake Osiao	400	4/3/90	30	6.54	17	5.3		-2.22	-26.1
Lake Rangas	800	4/21/90	27	5.27	17	11.9	138	-0.28	-1.7
Lake Naghaso	5	4/5/90	65	3.8	4379	82	300	0.8	-14.3
Parong Seawater	0	4/17/90	29	8.14	18940	1194	0.9	-0.65	-1.2

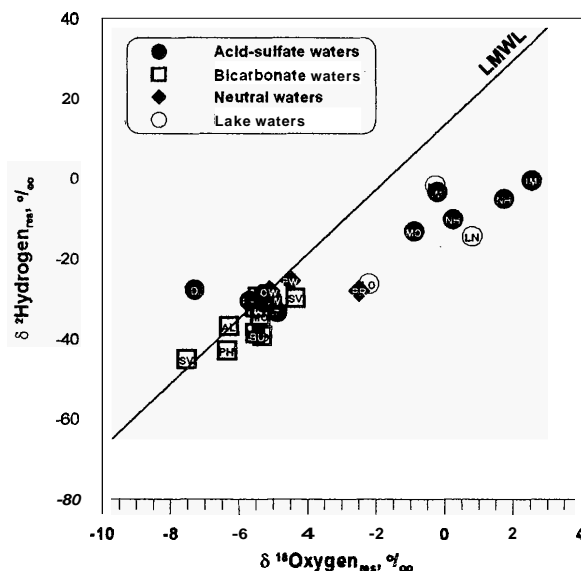


Figure 3. Isotopic composition of springs and lake waters.

Table 2. Isotopic composition of production wells.

Well Name	Sampling Date	T(Quartz) °C	H(TQuartz) kJ/kg	Clres mg/kg	<sup>18</sup> O		<sup>2</sup> H	
					per mille			
PAL3D	17-Apr-00	268	1174	5715	-3.12	-22.93		
PAL4D	23-Sep-93	281	1241	6011	-2.22	-25.00		
	17-Apr-00	265	1159	6022	-2.66	-24.45		
PAL5D	20-Jul-84	261	1139	4748	-3.26	-24.60		
PAL7D	23-Jul-84	269	1179	5338	-3.01	-20.10		
PAL9D	17-Aug-93	275	1210	5781	-1.78	-21.00		
	17-Apr-00	280	1236	5711	-2.62	-22.65		
PAL11D	18-Apr-00	274	1205	7266	-1.16	-24.09		
PAL12D	5-Apr-00	282	1246	6874	-2.14	-24.69		
PAL13D	13-Aug-93	277	1220	5804	-2.01	-24.00		
	10-Apr-00	271	1190	6292	-2.35	-25.15		
PAL14D	7-Oct-93	294	1311	6378	-1.31	-26.10		
	13-Apr-00	283	1252	7117	-2.38	-24.30		
PAL16D	4-Mar-92	245	1061	5154	-1.86	-21.40		
PAL18D	11-Jan-93	260	1134	6354	-0.60	-23.00		
	13-Apr-00	274	1205	7436	-1.24	-26.35		
PAL21	17-Apr-00	262	1144	5612	-3.01	-22.64		
OP3D	27-Aug-91	301	1350	8318	2.26	-28.00		
	20-Apr-00	308	1390	12503	2.93	-26.25		
OP4D	12-Jun-91	316	1437	7186	0.64	-27.00		
OP5D	18-Nov-00	302	1351	11881	0.54	-28.18		
OP6D	4-Sep-91	271	1190	1566	3.97	-27.00		
OP7D	11-Apr-00	250	1085	14397	4.22	-17.72		
CN1	24-Sep-93	267	1169	5286	-2.94	-23.80		
	4-Apr-00	225	967	4213	-2.96	-24.12		
CN3D	1-Oct-93	268	1174	5732	-2.12	-24.4		
CN-4D	4-Apr-00	279	1229	5545	-2.96	-24.12		
CN2RD	7-Jun-91	246	1069	154	-3.37	-24.6		
CN3RD	13-Sep-91	247	1073	186	-3.77	-23.9		
MO2	18-Apr-00	217	930	5635	-2.36	-22.81		
MO3	9-Aug-84	212	908	5729	-2.63	-24.4		
TW-1D	11-Jul-01	274	1207	5999	-1.89	-23.29		
TW-2D	18-Jun-01	251	1089	5529	-1.86	-27.94		

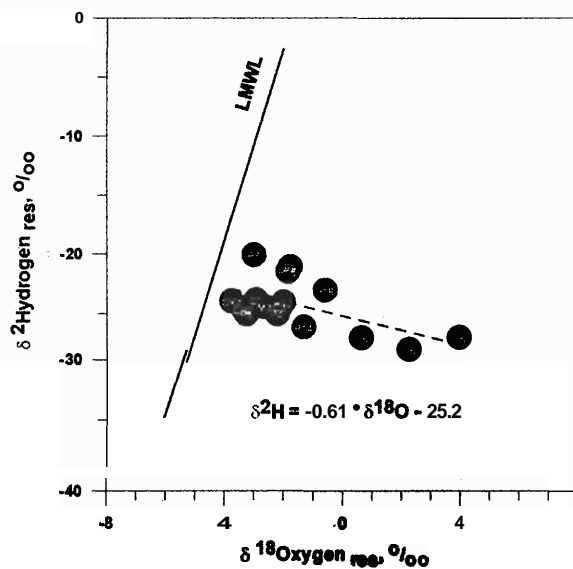


Figure 4. Isotopic composition of production wells.

the homogeneity of the source of these fluids. The extent of the isotopic shift of the well fluids from the LMWL may also be a function of the fluid temperature. Lesser isotopic shift may indicate a cooler well fluid temperature due to its higher meteoric water component. Well fluids that exhibit greater isotopic shifts, like OP-4D, have higher temperatures.

The wells are plotted together with the lake waters and neutral-pH chloride springs (Fig. 5). Parong spring is clustered with the wells denoting a similar source for the spring and wells. Lake Naghaso falls along the boiling path of PAL-14D. The fluids of PAL-14D boiled to 100°C, accumulated in this area and was heated-up by the ascending steam. This explains the high Cl content and the acidic nature of the lake.

### 3.0 PRE-EXPLOITATION CONDITION OF THE FIELD

The  $\delta^{18}\text{O}$  content of all the wells before production was contoured to illustrate isotopic variation across the field (Fig. 6). The most enriched zone is centered across the OP wells in Botong at 0 to +4.0 ‰. It becomes depleted towards Palayang Bayan at -1.0 ‰ and Cawayan sector to as low as -3.26 ‰. This variation is consistent with reservoir chloride (Cl<sub>res</sub>) (Fig. 7) and T(Quartz) (Fig. 8) contours across the field where the highest values are centered at Botong and decreases towards the NW and SW part of the field. This indicates that the center of the resource delineated by the highest chloride and T(Quartz) is isotopically enriched and becomes depleted towards the outflow zone.

The plot of Enthalpy (T<sub>Quartz</sub>) vs. Cl<sub>res</sub> of the wells (Fig. 9) gives a general overview of the different processes occurring in the reservoir. There are three distinct lines that can be drawn along the wells, each representing a reservoir process. A dilution line can be drawn from OP-4D towards the cluster of the wells. This dilution line also indicates the direction of the outflow zone.

Wells OP-6D, CN-2RD and CN-3RD form another line, which also denotes dilution but with another type of fluid. The most probable diluting end-member is steam condensate. Boiling occurs in the reservoir and the steam

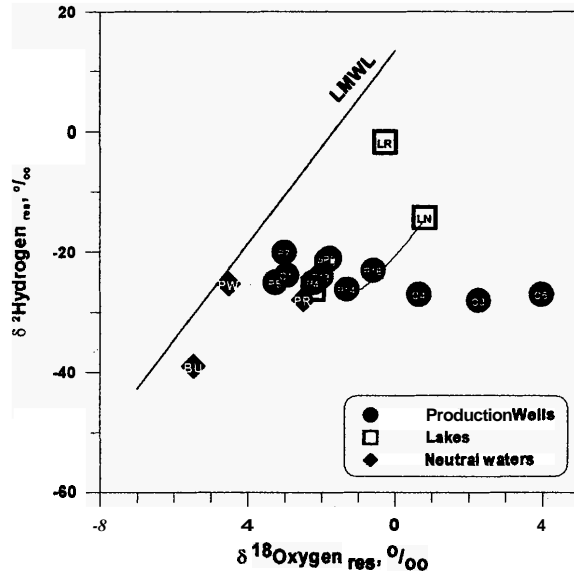


Figure 5. Isotopic content of production wells, neutral-pH waters and lake waters showing boiling path of PAL-14D.

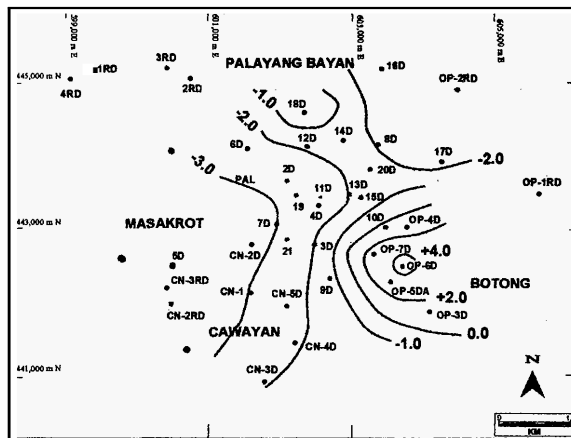


Figure 6. Variations of  $\delta^{18}\text{Oxygen}_{res}$  across the field.

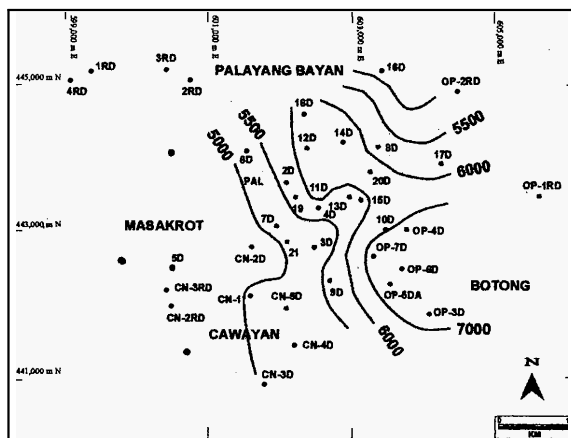


Figure 7. Variations of Cl<sub>res</sub> across the field.

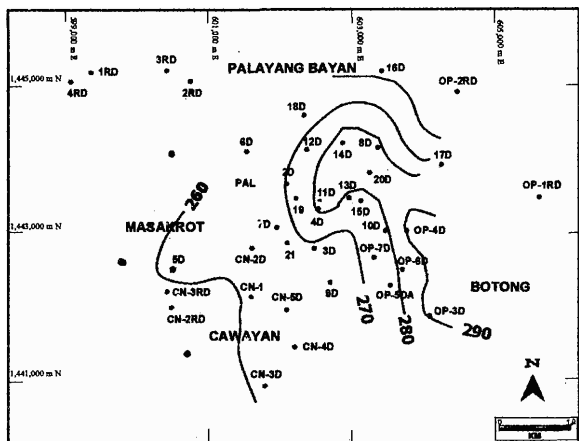


Figure 8. T(Quartz) contour across the field.

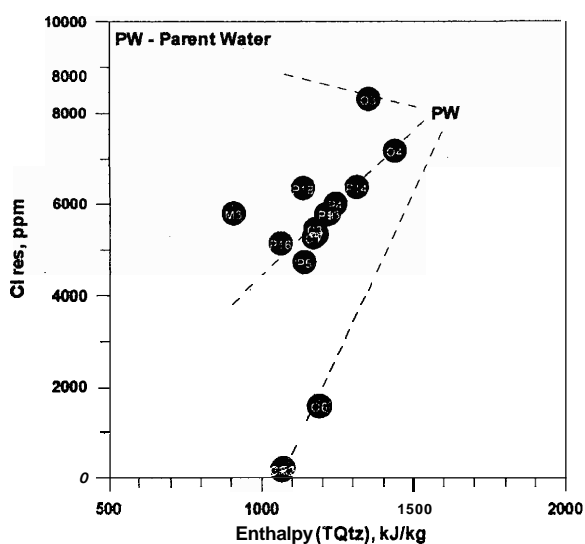


Figure 9. Clres-enthalpy diagram of production wells.

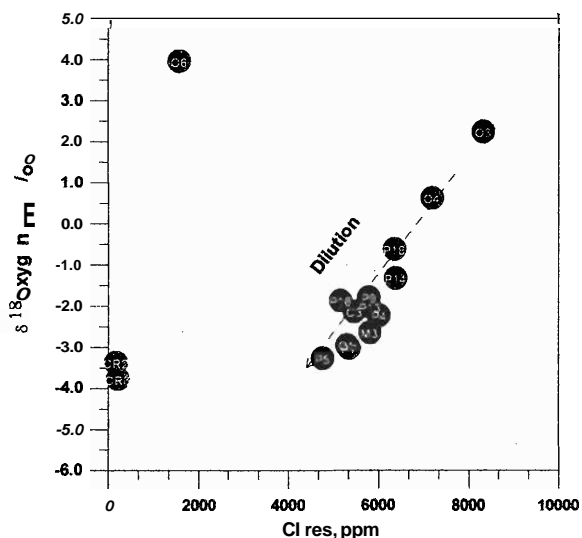


Figure 10. Variations of  $\delta^{18}\text{Oxygen}_{res}$  with Clres of production wells (pre-exploitation).

formed could be tapped by wells producing at shallow levels. This is exactly the case of OP-6D, where the steam zone was tapped by the well (Solis *et al.*, 1994); thus discharging a steam-rich fluid. The Clres and the T(Quartz) represented here is characteristic of OP-6D fluid coming from the shallow horizon (steam-condensate) and not from the deep reservoir. CN-2RD and CN-3RD, both located at the westernmost part of the resource, also discharged steam-condensate type of fluid. Based on the discharge test reports (Solis *et al.*, 1994), CN-2RD is producing from a deep acid zone, while CN-3RD is producing from a shallower steam-condensate type fluid.

The two dilution lines converge to a point with Clres of about 8000 mg/kg and Enthalpy (Tquartz)  $\approx$  1500 - 1600 kJ/kg. This point could very well represent the parent water of the resource. OP-3D defines a distinct line from the parent water. The increased chloride and decreased enthalpy clearly denotes boiling process. This means that the fluids discharged by OP-3D are products of boiled parent water.

These processes are all consistent with the isotope trends. The succeeding figures, which are crossplots of  $\delta^{18}\text{O}$  with different chemical parameters, illustrate the trends in the reservoir.

The relationship of Clres with  $\delta^{18}\text{O}$  is shown in Figure 10. An arbitrary dilution line can be inferred to pass thru OP-3D towards most of the wells, representing the mixing of meteoric waters and the parent water. There is a depletion of heavier isotopes as Clres decreases. This relationship between  $\delta^{18}\text{O}$  and Clres clearly illustrates dilution. This is the behavior of fluids as it flows towards the periphery of the resource.

OP-6D, with its high  $\delta^{18}\text{O}$  content but low Clres, is not consistent with the earlier explanation of it tapping the shallow steam-zone. If it were tapping the shallow steam-zone, we would have expected a depleted isotopic content. Its low Clres, however, is consistent with it tapping the steam-zone. Other explanations would have to be invoked for this. According to earlier reports (Buenviaje *et al.*, 1993), discharge tests indicate that the well is not yet stable during this period, so its chemical and isotopic composition may not yet be stable.

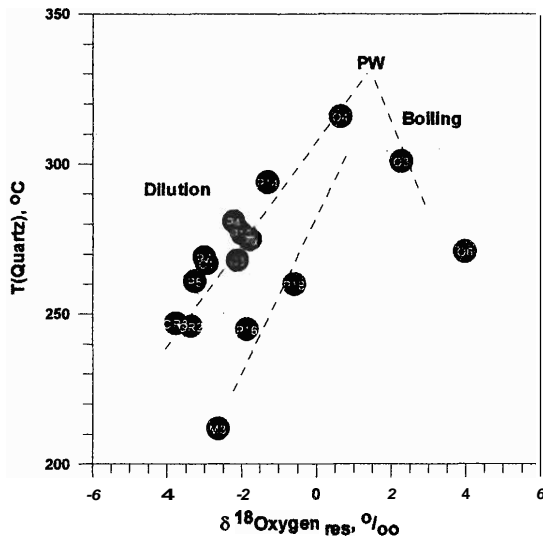


Figure 11. Variations of  $\delta^{18}\text{Oxygen}_{\text{res}}$  with T(Quartz).

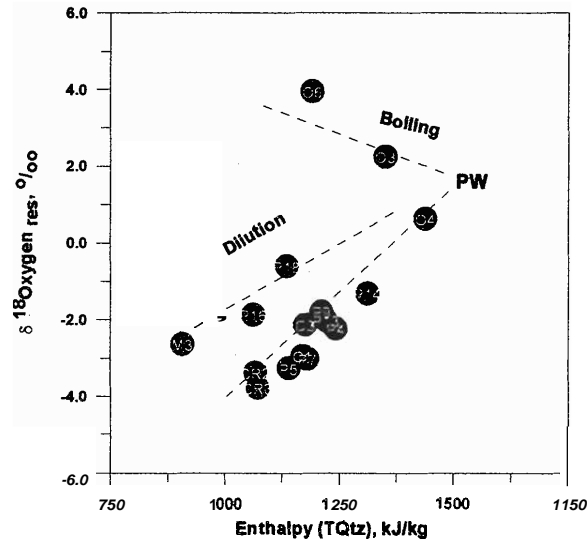


Figure 12. Variations of  $\delta^{18}\text{Oxygen}_{\text{res}}$  with enthalpy.

CN-2RD and CN-3RD show waters with depleted isotope and low Clres characteristic of a diluted water. However, these do not lie along the dilution line of the other wells. This could only mean that these wells have a different diluting end-member. Chemistry would reveal the presence of a sulfate-rich fluid in the discharge, possibly coming from a shallow steam-condensate reservoir within the vicinity. The presence of acid minerals (Solis *et al.*, 1994) within the section of the wells would corroborate with this shallow steam-condensate reservoir.

Based on Figure 10 (Clres vs  $\delta^{18}\text{O}$ ) OP-3D, which is enriched and most mineralized, could be inferred to closely represent the parent water. However, the T(Quartz) vs  $\delta^{18}\text{O}$  plot would show otherwise (Figure 11). OP-4D has the highest temperature among the wells which means that its fluid is nearest the parent water composition. A dilution line can be drawn from OP-4D towards the cluster of the wells with decreasing temperature. As temperature decreases, there is depletion in the isotopic composition of the fluids. Similarly, PAL-18D, PAL-168 and MO-3, which are relatively enriched compared with the other wells, seem to form another dilution line. These wells are located at the northeastern periphery of the resource and possibly have a different diluting end-member coming from the eastern part of the geothermal system. This diluting end-member, however, still has to be identified.

Aside from these dilution lines, OP-3D and OP-6D form a different line on their own. In this case, there is an enrichment of isotope as temperature decreases. This trend denotes boiling. Boiling decreases the temperature of the residual liquid and as the lighter isotope fractionates into the steam phase, the residual liquid then becomes enriched with heavier isotopes. Therefore, OP-3D is only a product of boiling of the parent water and not the parent water itself.

Similarly, the crossplot between  $\delta^{18}\text{O}$  and Enthalpy (Fig. 12) would show that OP-4D has the highest enthalpy among the wells. Two arbitrary lines can be generated towards the cluster of the wells denoting dilution, while another arbitrary line towards OP-3D and OP-6D suggests boiling.

Based therefore on the above discussions, the parent water of the **BGPF** resource is closely resembled by OP-4D and has Clres of about 8000 mg/kg and an isotopic composition of approximately:  $\delta^{18}\text{O} \approx +2.0 \text{ ‰}$  and  $\delta^2\text{H} \approx -26.0 \text{ ‰}$ .

#### 4.0 CHANGES IN ISOTOPIC COMPOSITION DURING PRODUCTION

After seven years of production, there was an observed change in the isotopic content of the fluids. The  $\delta^{18}\text{O}$  contour of the wells for the year

2000 is shown in Figure 13. The most enriched section is still the Botong area and the waters still become depleted towards the Palayang Bayan and Cawayan sectors. However, the -3.0 ‰ contour have already advanced into the central Palayang Bayan sector. Moreover, there is a steep gradient between the Botong sector and the central Palayang Bayan sector. This could mean that the isotopically depleted fluid from the Cawayan sector is encroaching the central Palayang Bayan sector.

This change was also observed in the chemistry of the fluids a few years after Bacman-1 power plant was commissioned in 1993. The most notable were the declining boron of the fluids of the central Palayang Bayan wells resulting to increasing Cl/B ratio (Maturgo, 2000). Moreover,  $TSiO_2$  of these fluids have also been declining. This was attributed to the incursion of the Masakrot fluids coming from the western part to the central part of the resource. Masakrot fluids, typified by PAL-SD, is relatively cooler ( $T_{Quartz} = 240-250^\circ C$ ), has low gas ( $CO_{2gd} = 50 \text{ mmole}/100 \text{ mole } H_2O$ ) concentration, and slightly less mineralized (Maturgo et al., 2000).

Compared to its pre-production values, the fluids of most of the PAL wells have recently become isotopically depleted due to the mixing with Masakrot fluids. OP well fluids, on the other hand, have become more enriched.

Figure 14 shows the  $Cl_{res}$  vs  $\delta^{18}O$  plot of the production wells showing both the 2000 and pre-exploitation data. The central PAL wells have become much isotopically depleted (in open circles) compared to the pre-exploitation data (in closed circles). Most notably, these wells have converged to the area of PAL-SD and PAL-7D, clearly illustrating that their chemistry are becoming similar to the fluids of PAL-SD and PAL-7D fluids.

$T_{Quartz}$  vs  $\delta^{18}O$  plot for the year 2000 (Fig. 15) would also illustrate the effect of the mixing of the Masakrot fluids with that of the fluids of the central Palayang bayan wells. The wells which showed the closest proximity with PAL-SD and PAL-7D are PAL-3D, PAL-4D and PAL-21. The other PAL wells have also become depleted. CN-1 well, which originally plotted very near PAL-5D and could also represent the Masakrot fluids, is observed to have dropped in temperature. Its isotopic content slightly

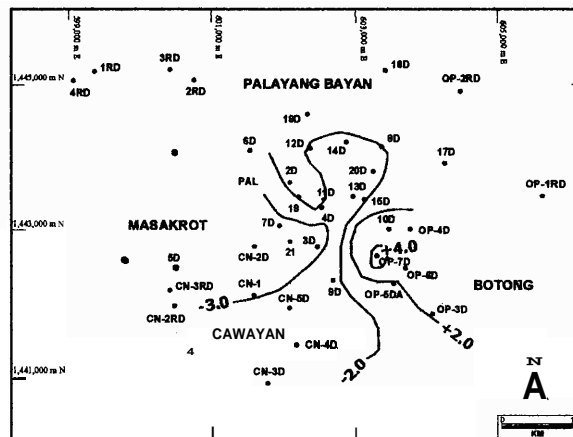


Figure 13.  $\delta^{18}O_{res}$  contour, 2000 data.

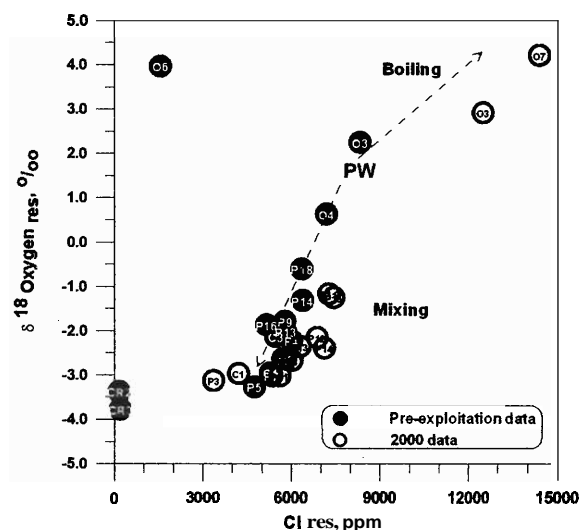
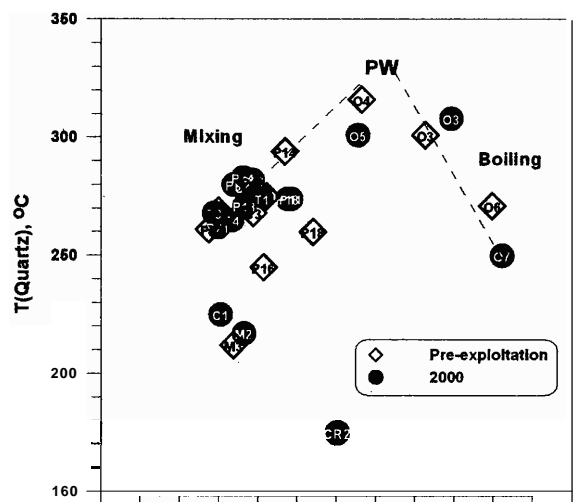


Figure 14.  $Cl_{res}$  vs  $\delta^{18}O_{res}$  plot showing both pre-exploitation and 2000 data.



became depleted also. This behavior suggests that the well have been diluted by another type of fluid, which obviously has lower temperature.

The OP wells still have a separate trend or line on their own. OP-3D has become more enriched, which suggests that the well has continuously undergone boiling. OP-7D seems to be the most enriched among all the wells. Its low temperature, on the other hand, points to it being a boiled fluid. The isotopic signature of the OP wells is in agreement with their chemistry, which indicates a boiling process for these wells.

However, it is not very clear if the depletion of the other PAL wells have been affected by the dilution of the Masakrot fluids or caused by other processes. Based on the crossplots of their isotopic composition, the Central Palayang Bayan (PAL) sector does not seem to be affected by boiling or steam gain. All the wells in this sector have become isotopically depleted. However, this does not imply that there are no other processes occurring in this part of the reservoir. Chemistry of the fluids would indicate the occurrence of boiling in some wells in this part of the reservoir (Maturgo et al., 2000). This could just mean that fluid migration and dilution (i.e. Masakrot fluid) has a greater effect on the isotopic signature of the fluids compared perhaps to boiling in this sector.

On the other hand, the OP wells which are originally enriched, have become more enriched. This clearly suggests that boiling process is actively occurring in this part of the reservoir. Moreover, the OP wells seem to be affected only by boiling process. Since these wells are situated in the hottest part of the resource, this is just expected of these wells.

## 5.0 CONCLUSIONS

Based on the analysis of the available data, most of the thermal waters within the resource were derived from rainwater. The isotopic signatures of the acid-sulfate springs indicate steam-heating and change in composition mainly by evaporation. The lake waters were also affected by evaporation. Lake Naghaso apparently contains deep brine component, and is affected by steam-heating. Similarly, the neutral-chloride springs have deep-fluid signature.

The Bacman Geothermal Production Field is comprised of a single geothermal system which is centered within the Botong area. The Osiao-Pangas (OP) wells tap the center of resource and encounter fluids which are already products of boiling of the parent water closely represented by OP-4D. The fluids at the upflow are isotopically enriched and have  $\delta^{18}\text{O}$  composition as high as  $\approx +2.0$  ‰. The fluids then outflow towards north-northwest in the central Palayang Bayan and towards the southwest in the Cawayan sector. The fluids along the outflow path are products of mixing between meteoric waters and the parent water. Wells situated at the margins, like CN-2RD and CN-3RD tap steam-condensate type of fluids. Although there are limited data, the outflow possibly extends towards the Manito area farther north. Fluids in the outflow are isotopically depleted and have  $\delta^{18}\text{O}$  as low as  $-3.9$  ‰.

The parent water, which closely resembles OP-4D, has an isotopic composition of :  $\delta^{18}\text{O} \approx +2.0$  ‰ and  $\delta^2\text{H} \approx -26.0$  ‰. It is estimated to have a Clres of 8000 mg/kg and enthalpy of 1500-1600 kJ/kg.

After seven years of production, the most prominent processes occurring in the reservoir are boiling and dilution. Isotopic trends confirm that the central Palayang Bayan sector has been diluted by fluid coming from the western part. This fluid, termed as the Masakrot fluid, is isotopically depleted, slightly cooler, less mineralized and has lower gas and boron contents. The effect of dilution is manifested by the depletion of  $^{18}\text{O}$  and  $^2\text{H}$  in the central Palayang Bayan wells. Although not clearly indicated by the isotope data, boiling could also be occurring in this part of the reservoir. Chemical trends, e.g. increasing discharge enthalpy and gas and chloride concentrations, show that boiling does occur in some wells. These mean that the dilution process masks the effect of boiling in the isotopic signatures of the fluids. The OP wells, on the other hand, are showing enrichment in isotope composition. As pressures draw down, these wells experience boiling in the reservoir.

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