

INTERPRETATIONS OF THE WATER AND GAS CHEMISTRY  
FROM THREE GEOTHERMAL AREAS IN THE PHILIPPINES -  
MANITO IN ALBAY, BILIRAN ISLAND AND TONGONAN IN LEYTE

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ABSTRACT

Chemical data from three geothermal areas - Manito in Albay and Biliran Island and Tongonan in Leyte, in the Philippines were studied and various geothermometry temperatures calculated.

From the water chemistry of Manito, Albay, the following was recognized: Primary alkaline waters issue from springs in the lowlands. These waters have mixed with cold water of meteoric origin in the upflow. No evidence was found for the influx of sea water (except in the Parong area). The cation geothermometers and a mixing model involving a silica-enthalpy plot indicate the presence of a high temperature reservoir wherein temperatures are probably near 300°C. The low pH and the abundance of carbon dioxide and hydrogen sulfide gases in the secondary springs in the highlands suggest steam heating of local meteoric water from a deep seated high temperature reservoir.

The gas chemistry of Biliran Island, Leyte, gives evidence of the presence of a high temperature geothermal heat source, with gas geothermometry temperatures of 184° to 292°C, but temperatures above 300°C may also be present.

In Tongonan, Leyte, various geothermometry temperatures were calculated and compared with the maximum temperatures measured in the deep drill-holes in the main production zones. The Na/K geothermometer by Arnórs-son (1980) using calculated activities of  $\text{Na}^+$  and  $\text{K}^+$  in the deep water, gives the least average and standard deviations. Anhydrite was found to be in chemical equilibrium with the deep water. A comparison of isochloride and isothermal contours of the deep water indicates heating of the cold meteoric water percolating into the reservoir by the hot rocks in the production zones.

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## 1. INTRODUCTION

### 1.1 Scope of work

Since 1962, the Philippines has embarked on an intensive program to harness geothermal energy as an ingenious power source. A part of this program is to send Filipinos abroad to train in specialized fields in the leading countries engaged in geothermal exploration, development and utilization. In line with this, the author was accepted as a United Nations University Fellow in the 1980 UNU Geothermal Training Programme at the National Energy Authority in Iceland in the field of Chemistry of thermal fluids.

After a four week introductory lecture series, the author received specialized training in: water sampling and analysis (3 weeks), chemistry and chemical thermodynamics (3 weeks), geothermometry (3 weeks), and water/rock interaction (4 weeks). This report represents a research project carried out mainly during the last 2 1/2 months of the training.

Chemical data from three geothermal areas in the Philippines (Fig.1) were studied to assist in their overall evaluation. These areas were selected to train the author in the application of various geochemical interpretation methods commonly used during both the exploration stage (Manito, Albay (water chemistry) and Biliran Island (gas chemistry)) and during the development phase (Tongonan, Leyte, water and gas chemistry) of geothermal fields.

### 1.2 Regional setting

The Philippines is one of the island arcs that circumscribe the Pacific seismic zone. Trenches can be found on the southwestern, northwestern and eastern edges and a left-lateral transcurrent fault (the Philippine fault) traverses the country for a distance of 1000 km where it curves its way from Central Mindanao northeastwards towards Luzon (Fig.2). Dacitic to andesitic volcanoes line the inner side of the trenches and it is with such volcanic clusters of Plio-Quaternary age that the Philippine geothermal areas are associated (Alcaraz, 1974).

### 1.3 Method of collection and analyses

All the analyses used in the present report were made at the chemical laboratories of the geothermal Division of PNOC-EDC in Tongonan (Leyte) and Manila. A short description will be given below of the methods of collection of water and gas samples and the analytical methods used.

Water samples from the springs and streams were collected and stored in polyethylene bottles. Acidified samples (using 50% nitric acid) were also taken to preserve constituents in solution that might be precipitated or adsorbed onto the walls of the vessel.

Gas samples from the fumaroles or steam vents or steam were collected using glass tubing into 330-400 ml evacuated glass flasks containing a 70% sodium hydroxide solution closed by teflon stopcocks. Triplicate gas samples were also collected into locally fabricated glass flasks closed by a piece of butyl rubber with aluminium clips.

Figure 3 shows the discharge test assembly of drillholes in Tongonan, Leyte. Water samples were collected from the weirbox at atmospheric pressure and stored in polyethylene bottles and a glass bottle with an 8" long piece of butyl rubber with aluminium or steel clips attached to it. An acidified sample was also collected and stored in a polyethylene bottle. Steam samples were collected under pressure into evacuated thin-walled borosilicate flasks (Ellis et al. 1968) from the high pressure and low pressure sampling points in the horizontal bypass pipe leading to the silencer. Condensed steam samples were collected into empty 5 liter flasks and the noncondensable gases were collected into 2-3 liter flasks containing about 30% sodium hydroxide solution.

A summary of the methods used in the analysis of steam and water samples is presented in Table 1.

Table 1

Analytical methods for steam and water samples

	Element	Method
Steam Phase	CO <sub>2</sub>	Potentiometric titration from pH 8.25-3.80 using 0.1 N-hydrochloric acid <sup>1a</sup>
	H <sub>2</sub> S	Back titration with 0.01N sodium thiosulfate in acid solution (2N sulfuric acid) after the addition of 0.01N iodine <sup>1a</sup>
	NH <sub>3</sub>	Specific ion electrode
	Cl <sup>1a</sup>	Mohr titration using 0.025N silver nitrate <sup>1a</sup>
	CH <sub>4</sub>	gas chromatography <sup>2</sup>
	H <sub>2</sub>	- do -
	N <sub>2</sub>	- do -
	O <sub>2</sub>	- do -
Water Phase	pH	Glass electrode
	Li	Atomic absorption spectrophotometry
	Na	- do -
	K	- do -
	Ca	- do -
	Mg	- do -
	Cs	- do -
	Rb	- do -
	Cl	Mohr titration using 0.10 N AgNO <sub>3</sub> <sup>1a</sup>
	SO	Spectrophotometry using barium chromate <sup>1b</sup>
	CO <sub>2</sub>	Double potentiometric titration from pH 8.25-3.80 using 0.02N hydrochloric acid <sup>1</sup>
	SiO <sub>2</sub>	Spectrophotometry using ammonium molybdate <sup>1b</sup>
	As	Spectrophotometry through the evolution of arsine gas from a hydrochloric acid solution using silver dichthyl-dithiocarbamate dissolved in chloroform with 1-ephendrine <sup>3a</sup>
	NH <sub>3</sub>	Specific ion electrode
	B	Potentiometric titration with 0.025N sodium hydroxide to pH 7.30 after adding an excess of mannitol <sup>1a</sup>
H <sub>2</sub> S	Same method as for the steam phase <sup>1a</sup>	

<sup>1</sup> outlined in Ellis et al. (1968)

<sup>2</sup> outlined in Galia (1980)

<sup>3</sup> Kopp (1973)

<sup>a</sup> with modifications to adapt to local conditions (Barnett pers. comm.)

<sup>b</sup> with modifications to adapt to local conditions (Glover pers. comm.)



## 2. INTERPRETATION OF WATER ANALYSES FROM THE MANITO GEOTHERMAL FIELD, ALBAY

### 2.1 Introduction

Manito is one of several geothermal areas in the Philippines presently being explored and investigated for its geothermal potential. The PNOC-EDC Geothermal Division has estimated the areal extent of the field to be about 190 km<sup>2</sup>.

The area lies in the southeastern part of the province of Albay and is bounded to the south by Sorsogon, the southernmost province of the Bicol Region. The investigated area is linked to Legazpi City, the center of trade and industry in the region, via a 42 km partly asphalted and partly macadamized road. There is a network of feeder roads linking Manito to some of its barrios. The highlands are, however, not passable to motor vehicles.

Geoscientific investigations consisting of geological, geochemical and electric (Schlumberger array) surveys were conducted in the area in 1977 and 1978. Similar surveys were conducted in the early part of 1979 including a dipole-dipole resistivity survey and vertical electric soundings on several selected locations. The encouraging results gave PNOC-EDC grounds to recommend exploratory drilling and two wells were sunk in 1979, wells Manito-1 (M-1) and Manito-2 (M-2).

### 2.2 Geological and geophysical features

The Manito geothermal area lies along the volcanic belt traversing the entire Bicol peninsula and it is associated with the Pocdol mountains volcanic complex of two or more overlapping cones.

The rock formations are predominantly lava flows in the central region, while pyroclastic deposits of mainly lahars and sedimentary formations cover the northern tip of the geothermal system. As deduced from the regional geology, this volcanic complex is probably resting over the Pre-Cretaceous basement complex composed of peridotite, chlorite and sericite schists, later intruded by diorite (Española et al., 1980). A tentative stratigraphy of the area is shown in Table 2.

Three principal tectonic systems appear to meet in the area (Fig.4). The major and oldest structure is a strike-slip fault, a NW-SE extension of the Philippine fault. Close to this fault are volcanic domes of basaltic and andesitic composition with well preserved craters, lakes and steep country that develops the west-east trending volcanic complex. Acid-sulfate springs and extensive acid hydrothermal alteration products coincide with this structure. The other two tectonic systems are younger and have N-S strikes and form the Manito Graben. These secondary faults formed by divergent wrenching along the regional fault are the Buyo and the Manitohan Faults (Espiritu, 1979). The northern portion of the Manito Graben contains the greatest number of thermal manifestations of mainly alkali-chloride and bicarbonate springs, geysers and bubbling mud pools.

A Schlumberger resistivity survey in the area detected contrasts between the physical properties of the rocks in the geothermal area and those of surrounding areas. The results (Fig.4) show an elongated area of low resistivity coinciding with the major structural lines and over the known thermal manifestations. Obusan (1979) postulates that the reservoir fluids move out as a major flow tongue along the NW-SE fault and finally along the permeable zones of the Manito graben.

A dipole-dipole resistivity survey was also undertaken to obtain resistivity information at greater depths to about 1.3 km or more. The results correlated well with the results obtained using the Schlumberger array, except for a deep seated (900-1200 m) resistivity low of less than 3 ohm-meters at the northern portion (Espanola et al., 1980).

Vertical electric soundings were carried along with the dipole-dipole survey using the same equipment. In Inang Maharang, the lowest values were recorded nearest the thermal manifestations. Other soundings in the southern part indicated increasing resistivity at depth. In the northern portion of the geothermal reservoir, results are in the order of 100 ohm meters followed by decreasing resistivity at depth where values approach 1 ohm-meter (Espanola et al., 1980).

Table 2

Tentative stratigraphy of Manito and vicinity (After Espiritu 1979)

<u>Rock unit/Description</u>	<u>Probable thickness</u>	<u>Age</u>
Alluvium and associated lahar includes recent hot springs deposits as sinter and travertine	10 m	Quaternary
Maharang sedimentary formation interbedded calcarenite and calcisiltite with conglomeratic base. Transgressive over older formation.	50 m	Late Pleistocene
Minaturon basaltic andesite Upper member: Coarse-grained, porphyritic 2 pyroxene andesite with fracture sheetings and silification.	250 m	Plio-
Lower member: Fine-grained 2 pyroxene basaltic andesite with extensive hydrothermal alteration.	150 m	Pleistocene
Maharang basalt - fine grained dark grey pyroxene basalt	200 m	Pliocene
Probable rock unit - andesitic (?)	?	
Basement complex - assemblage of peridotite, chlorite and sericite schist intruded by diorite	?	Pre-Cretaceous

### 2.3 Geochemistry of the springs

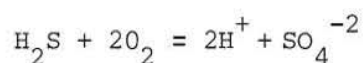
The physical data of thermal springs in Manito, Albay is shown in Table 3. The distribution of thermal springs is shown in Fig. 5.

Obusan (1979) classified the thermal springs in the area as:

- a. Low-lying near neutral ALKALI CHLORIDE SPRINGS of Naghaso, Pawa, Parong, and Buyo (also called Buang),
- b. Moderately elevated to low-lying BICARBONATE SPRINGS of Balabagon, Banao and Inang Maharang, and
- c. Steam heated ACID SULFATE SPRINGS at moderate and high altitudes.

The present author suggests that springs can also be divided into two groups on basis of their chemical composition. The primary springs or the alkali chloride springs, and the secondary springs which are the bicarbonate and the acid sulfate springs. The primary springs may give information about underground hydrothermal conditions and the composition of the deep fluid of the hydrothermal system, while the secondary springs are local meteoric water heated with steam that is flashed at depth and have very minor geochemical significance. The chemical results are presented according to this classification (Tables 4 & 5).

The secondary springs in the highlands are considered to be steam heated surface waters. This can be seen from their low chloride concentrations. The low pH in the samples matches with the high sulfate concentrations and can be quantitatively explained through the oxidation of hydrogen sulfide in the steam to sulfuric acid:



The neutral pH waters are identified by their total carbonate concentrations ( $\text{H}_2\text{CO}_3 + \text{HCO}_3^- + \text{CO}_3^{-2}$ ). It is postulated that  $\text{H}_2\text{S}$  but not  $\text{CO}_2$  had been lost through reactions underground producing steam heated carbonate-rich water. The abundance of carbon dioxide and hydrogen sulfide gases (Table 3) in these areas indicate that the steam heating is from a high temperature reservoir.

The alkali chloride waters in the lowlands are considered to have mixed with cold waters in the upflow. This can be seen from the positive relationship between the silica and sodium concentrations in the samples. And this is also suggested by their low measured temperatures, high flow rates and high geothermometry temperatures.

Table 3

Physical data of thermal areas in Manito, Albay (after Galia 1979, and Obusan 1979)

	Location	Elevation (masl)	Temperature range (°C)	Flow (l /sec)	Gas	Deposits
A. Primary springs	Parong	0	88-105		absent	SiO <sub>2</sub> sinter+Fe oxide
	Pawa	~20	43-67	0.5	little H <sub>2</sub> S	Fe oxide
	Naghaso	5	61-86	100	little H <sub>2</sub> S	SiO <sub>2</sub> sinter+Fe oxide+NaCl salt
	Buang/Buyo	0-5	43		absent	none
B. Secondary springs	Inang Maharang	300	48-96	100	abundant H <sub>2</sub> S, CO <sub>2</sub>	silica sinter
	Puting Bato	430-540	23-49	6	abundant H <sub>2</sub> S, CO <sub>2</sub>	sulfur
	Tinapian	70	25-27		abundant H <sub>2</sub> S, CO <sub>2</sub>	sulfur
	Damoy	680-720	25-29		abundant H <sub>2</sub> S, CO <sub>2</sub>	sulfur
	Balabas	20-25	41-72	5	moderate H <sub>2</sub> S, CO <sub>2</sub>	
	Banao	180-200	39-42		little H <sub>2</sub> S	none
	Malangto	30	77-95		moderate H <sub>2</sub> S, CO <sub>2</sub>	Fe oxide
	Balabagon	5-10	55-66		little CO <sub>2</sub>	none
	Azufre	60-100	37-40		little H <sub>2</sub> S	Fe oxide+sulfur
Salvacion	400-700	22		abundant H <sub>2</sub> S, CO <sub>2</sub>	sulfur	

Table 4

Chemical analyses in ppm of the "primary springs" (alkali chloride springs) in Manito, Albay

Sample no.	Location	Measured temperature C°	pH (at 25°C)	Li	Na	K	Ca	Mg	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	B	SiO <sub>2</sub>	NH <sub>3</sub>	Geothermometers in °C					Na-K-Ca <sup>f</sup> = 1/3	
															Silica			Na/K			
															a	b	c	d	e		
623	Parong	88	7.70	0.104	1586	117	160	329	5496	390	79.1	0.813	15.9	-	48	55	21	157	162	186	
624		89	4.27	3.43	1352	312	194	105	4928	344	9.88	15.9	232	-	178	190	170	300	275	253	
1263		103	6.79	2.69	4630	360	628	412	7512	663	185	7.91	210	36	172	183	162	167	169	199	
194	Pawa	48.2	-	-	329.7	53.57	24.59	3.24	659.5	-	-	-	-	-	-	-	-	247	232	220	
195		65	-	-	7045	166.04	42.8	8.31	1489	-	-	-	68.76	-	117	117	87	71	93	165	
196		66.8	-	-	6992	156.4	45.04	11.7	1447	-	-	-	76.39	-	122	123	93	68	93	160	
197		-	-	-	60.85	11.75	6.33	3.18	107.43	-	-	-	76.39	-	122	123	93	271	254	210	
198		-	-	-	44.71	7.38	9.62	2.74	67.37	-	-	-	-	-	-	-	-	-	249	234	190
675		65	6.44	1.49	361	98.6	50.5	7.01	1241	51	79.1	6.30	110	-	138	143	115	329	300	249	
676		65	6.32	1.71	383	133	55.3	8.70	1454	49	118	6.91	127	-	145	151	125	377	350	268	
1260		42.5	6.14	1.07	407	75.3	39.7	7.25	766	34.3	20.5	3.2	68.9	0.14	117	117	89	265	247	228	
1261		50	6.61	1.79	843	153	68.7	9.09	1461	28.8	116	6.8	175	1.55	162	171	149	262	245	237	
1262		66	6.59	1.73	914	147	68	8.87	1418	37.5	118	1.86	182	1.26	164	173	152	245	231	231	
131	Naghaso	66	3.73	4.9	3271	732	150	4.09	5084	-	-	26.7	444	-	218	241	232	294	271	276	
132		27	6.60	0.05	18.2	8.5	5.6	5.4	13.6	-	90	0.108	90.1	-	131	134	106	447	406	243	
133		62.5	3.70	5.03	3230	787	148	3.86	5092	-	-	27	401	-	211	232	222	309	283	283	
190		85.5	-	-	1421	267	111	10.48	3351	-	-	-	168	-	160	168	145	267	249	246	
670		55	3.57	5.41	1236	306	201	3.34	4503	75.7	-	23.2	248	-	181	195	176	311	285	255	
671		61	3.58	5.24	1224	304	202	3.24	4450	79.1	-	22.8	123	-	144	149	123	312	285	255	
1256		62	3.05	6.15	2860	365	197	4.38	4976	47	-	24.6	328	6	203	216	201	215	207	229	
1257		65	3.12	5.95	2890	360	200	3.39	4907	42.4	-	24.5	328	8	203	216	201	212	205	227	
129		Buang/ Buyo	43.3	6.55	0.08	1025	115	64.5	64.1	1048	-	106	1.62	99.3	-	134	137	109	200	195	209
683			37	6.46	-	184	44.8	72.8	43.5	7.1	68.3	109	1.52	69	-	117	118	89	309	283	222
1265	44		6.84	-	470	56.1	92.8	59.4	936	74	116	1.40	83.4	0.047	125	127	99	212	204	197	

- Analysis not available  
a Quartz, adiabatic cooling (Truesdell 1975)  
b Quartz, conductive cooling (Truesdell 1975)  
c Chalcedony, conductive cooling (Truesdell 1975)  
d White & Ellis (see Truesdell 1975, White 1970)  
e Arnórsson 1979  
f Fournier & Truesdell (1973)  
(Refer to Table 6 for geothermometer formulas)

Table 5

Chemical analyses in ppm of the "secondary springs" (bicarbonate and acid sulfate springs) in Manito, Albay  
(after Galia 1978, 1979)

Samples no.	Location	Measured temperature °C	pH (at 25°C)	Li	Na	K	Ca	Mg	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	B	SiO <sub>2</sub>	NH <sub>3</sub>
134	Inang Maharang	96	6.98	0.03	23.1	12.0	7.27	4.83	5.4	-	26.3	0.108	153	-
135		93	6.82	0.03	23.1	11.9	6.52	5.43	5.4	-	3.66	0.539	95.9	-
136		51.5	6.75	0.03	115	41.2	23.8	19.0	10.6	-	268	0.108	162	-
137		95	-	0.03	16.6	3.01	5.56	3.77	14.9	-	-	-	184	-
640		88	2.05	-	5.39	1.64	7.52	3.02	10.6	-	-	0.103	47	-
1242		92	5.02	-	14.0	5.35	16.4	5.46	7.44	282	495	2.0	132	62.4
1243		60	2.24	-	10.0	3.30	18.1	9.96	6.74	441	-	1.4	179	89
1244		59	5.29	-	8.0	2.71	7.8	6.35	7.09	46.9	211	0.4	52	0.86
1247		51	6.71	-	56.3	20.0	45.3	17.5	9.97	87.3	307	0.6	190	0.04
191		Puting Bato	29	-	-	57.26	10.15	24.59	20.5	17.73	-	-	-	76
192	23		-	-	32.17	12.19	18.17	14.67	24.82	-	-	-	-	-
193	32		-	-	-	-	18.17	1.76	8.51	-	-	-	-	-
634	49		2.95	-	13.0	7.23	28.4	10.9	10.6	280	-	0.394	99	-
635	29		3.68	-	8.64	3.70	41.6	6.14	8.57	143	-	0.388	63	-
636	23		1.74	-	5.11	2.08	8.94	3.06	7.09	455	-	0.314	40.9	-
637	32		2.43	-	26.4	8.33	37.4	13.4	12.2	436	-	0.368	60.3	-
1219	35.5		5.14	-	56.3	0.30	37.8	16.1	9.22	417	77.4	0.4	62	0.56
1246	50		5.22	-	24	6.54	25	11.7	8.19	268	60.7	0.4	105	1.65
138	Tinapian		25.8	4.22	-	15.0	6.35	9.01	3.56	1.78	-	-	0.108	57.9
139		25.8	5.25	-	17.0	7.8	9.25	3.63	1.78	-	-	0.108	93.1	-
673		25	3.56	-	8.04	3.27	17.1	4.16	9.22	95.3	-	0.448	72.9	-
674		25	3.58	-	7.39	3.08	16.1	3.24	8.86	93	-	0.396	43.7	-
1266		26.5	5.15	-	7.86	2.01	14.7	4.05	8.35	69.3	5.67	0.20	76.9	0.026
1267		26.5	3.34	-	7.60	2.90	12.8	3.50	8.33	73.9	-	0.30	41.2	0.011
653		Damoy	25	3.41	-	3.98	1.51	3.71	1.31	8.27	59.8	-	0.461	32
1249	25		2.52	-	4.67	1.34	13.9	7.77	8.16	562	-	0.20	69.3	0.03
1270	29		2.12	-	12.7	4.18	17.2	7.80	11.3	334	-	0.30	112	0.03

Table 5 continued

Samples no.	Location	Measured temperature °C	pH (at 25°C)	Li	Na	K	Ca	Mg	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	B	SiO <sub>2</sub>	NH <sub>3</sub>
127	Balasbas	41	4.85	0.05	9.26	2.29	2.4	2.0	88.8	-	54.6	0.216	52.1	-
128		35.9	3.48	0.05	5.56	3.26	1.94	1.8	88.8	-	-	0.108	51.7	-
672		40	5.11	-	4.52	1.09	4.16	2.0	9.22	-	9.88	0.407	18.6	-
1259		71.5	3.37	-	6.53	1.74	4.72	3.07	7.62	26.1	-	0.2	28	2.25
186	Banao	41.5	-	-	33.96	11.0	15.59	8.47	22.69	-	-	-	115	-
1252		39	6.48	-	24.9	6.7	19.4	9.96	8.06	10	201	1.4	133	0.04
177	Malangto	87	-	-	42.92	7.25	8.73	4.72	23.05	68.2	-	-	92	-
178		93	-	-	50.09	7.50	7.98	4.31	87.93	80.65	-	-	84	-
179		77	-	-	238.29	31.62	24.94	5.75	425.48	82.95	-	-	99	-
185		25.6	-	-	-	-	3.67	2.82	14.8	48.85	-	-	61	-
1253		95	7.33	-	65.2	14.4	21.9	12.6	19.8	19.7	283	0.2	133	4.5
1254		87.5	7.13	-	79.1	15.5	22.5	12.7	41.7	21	289	0.2	133	2.3
140	Balabagon	55.2	7.48	0.111	198	58.3	18.8	9.0	68.3	-	362	0.431	197	-
669		66	7.33	-	93.1	25.7	31.2	18.2	54.1	11.3	395	0.742	126	-
1255		59	7.16	-	103.2	30	29.7	19.5	63.8	20.4	425	0.5	182	0.23
182	Azufre	40	-	-	51.88	7.66	53.88	2.61	21.27	462.56	-	-	76	-
682		37	5.29	-	23.2	4.81	59.4	3.26	7.98	228	19.8	0.476	52.3	-
1258		36.5	5.60	-	40	4.26	50.3	4.05	8.91	218	21.7	-	55.9	0.023
627	Salvacion	22	3.58	-	4.66	1.55	6.99	2.83	8.42	44.7	-	0.433	53.1	-

- Analysis not available



Because of the proximity of these waters to the shore, it might be expected that the cold water component during mixing is sea water, as suggested by Obusan (1979) and Española et al. (1980). However, low magnesium and sulfate concentrations and the positive relationship between silica and sodium indicate that there is no sea water influx except in the Parong area (suggested strongly by high magnesium results). Therefore, the cold water component during mixing is meteoric water. A probable explanation is that a high water table in the highlands produces a pressure gradient towards the lowlands and prevents sea water infiltration.

To test this hypothesis further a mixing model was attempted to estimate underground reservoir temperatures and the fraction of hot water involved in the mixing. The Naghaso area was chosen as the basis because of its high silica concentrations (168-444 ppm) and its high mass flow (100 liters/sec.).

Following the procedure of Truesdell and Fournier (1977) assuming steam loss from an adiabatically cooled liquid before mixing with cold water and that the steam escapes at 100°C (or boiling occurs at 100°C), minimum underground temperatures from a silica plot were found to be in the range 226-254°C, and the fraction of hot water after steam loss in the warm spring ranges from 39-53%. The weight fraction of the original hot water lost as steam before mixing is 26-33%. The results can be read from Figure 6.

From the chloride content of the mixed water and the fraction of the hot water component in the mixture, the unmixed deep water was calculated to contain about 10.000 ppm of chloride.

The calculated Na/K temperatures ranged from 213-309°C (White and Ellis, see Truesdell 1975, White 1970) and 205-285°C (Arnórsson, 1979). The Na-K-Ca temperatures range from 227-283°C (Fournier and Truesdell, 1973).

The presence of silica sinter deposits in the Naghaso area (Table 3) suggests that silica precipitates on the way of the hot water to the surface. The silica precipitation occurs because of the relatively fast rate of reaction at these temperatures and because supersaturation with respect to amorphous silica is attained as the solution cools (Fournier

1979). This would mean that the temperatures calculated from the silica geothermometer would be too low because the method assumes that no further solution or deposition of silica occurs before or after mixing. The cation geothermometers will therefore give more accurate results.

#### 2.4 Exploratory wells

Two exploratory wells were sunk in an area characterized by altered ground with acid sulfate and bicarbonate springs (secondary springs according to the classification used here). Both wells were within the 30 ohm-meter contour outlined by the resistivity survey. The location of the wells is shown in Fig. 4 and Fig. 5. Manito-1 (M-1) at about 320 meters above sea level is about 2 km SW of the Inang Maharang thermal area and is 1372 meters deep. Manito-2 (M-2) at about 500 meters above sea level is in the Puting Bato thermal area and is 1637 meters deep. M-2 is approximately 2.2 km SW of M-1.

M-2 encountered more circulation losses during drilling (Table 5) and a maximum temperature of 248°C at the bottom compared to M-1, which only has a maximum temperature of 218°C at the bottom. Temperature measurements made three weeks after drilling (Obusan, 1979) show nearly linear thermal gradients of approximately 150°C/km for M-1 and 180°C for M-2. Attempts to flow the wells by stimulation have all been unsuccessful.

Downhole samples of the well fluids were collected using a Kuster down-hole sampler. The results are shown in Table 5. The downhole samples do not represent the reservoir fluids postulated from the geochemistry of the primary springs. This is inferred from the low chloride, low silica and high sulfate concentrations in the wells. This indicates that the wells have not reached the main geothermal reservoir and the hot water in the wells represents secondary water just like the surface springs in the drilling areas. The recorded downhole temperatures are below those estimated by the chemical geothermometers for the drillhole water and for the primary springs. This clearly indicates that equilibrium has not been reached between water and the bedrock.

## 2.5 Model of the Manito field

The chemistry of the alkali chloride (or primary) springs in the lowlands of Manito indicate the presence of a high temperature reservoir of probably near 300°C near this area. From a mixing model made from the Naghaso area, this primary deep water is expected to contain chloride in concentrations of the order of 10.000 ppm.

The present chemical evidence in the highlands is not yet conclusive to identify a major upflow zone in the area as suggested by Galia (1979). The bicarbonate and acid sulfate springs and the well fluids are considered to be secondary waters produced by heating of cold groundwater by steam flashed at depth and have no major geochemical significance. Gas sampling in the highland area may possibly help in identifying upflow zones, but conclusive evidence can only be obtained by deep drilling.

## 2.6 Conclusions

On the basis of the available chemical data from Manito, Albay, the following conclusions are drawn:

- a. The alkali chloride springs are considered to be primary thermal waters, whereas the bicarbonate and acid sulfate springs are secondary waters formed by the heating up of local ground water by steam flashed from primary thermal water at depth.
- b. Evidence was found for the mixing between hot water and meteoric water in the alkali chloride springs which are located in the lowlands. No evidence was found for the infiltration of seawater into the thermal system in the lowlands, except in the Parong area.
- c. A mixing model made on the alkali chloride springs in the Naghaso area, indicates the presence of a reservoir wherein estimated temperatures from the cation geothermometers are probably near 300°C. The presence of silica sinter deposits in Naghaso suggests that the silica geothermometry temperatures estimated from the mixing model are too low. The cation geothermometers are believed to give more accurate results.
- d. The mixing model results indicate that the unmixed water may contain about 10.000 ppm chloride.

Table 6

Downhole results of well chemistry in Manito, Albay

Well	Depth (meters)	pH (25 °C)	All concentrations in ppm									Temperatures (°C)					Na-K-Ca <sup>f</sup>	measured <sup>+</sup>	
			Na	K	Ca	Mg	Cl	SO <sub>4</sub>	HCO <sub>3</sub>	B	SiO <sub>2</sub>	Silica			Na/K				
												a	b	c	d	e			
M-1	200	2.40	10	3.6	7.9	2.20	-	-	ND	-	10								
	500	3.30	343	31.8	108.0	3.30	133	270	ND	1.66	185	175	164	148	179	182	173	95	
	1000	3.70	339	32.7	82.6	7.60	110	288	ND	0.83	331	217	198	192	183	186	176	150	
	1180	1.60	330	28.6	78.8	4.70	113	278	ND	ND	235	191	177	165	172	177	170	173	
	1300	2.70	356	29.2	18.4	1.60	177	575	ND	0.83	335	218	199	193	167	173	181	198	
M-2	600	5.85	24	8.3	17.7	2.26	11	82	11	0.78	ND							74	
	750	2.78	178	15.1	20.0	2.05	83	663	ND	2.94	76	122	120	94	170	175	175	144	
	900	5.45	169	12.4	18.5	2.28	43	330	18	1.95	66	115	114	87	156	164	163	180	
	950	7.06	501	23.7	13.8	0.46	132	675	202	5.69	191	177	166	150	119	134	146	199	
	1200	7.12	487	23.2	19.2	0.75	113	625	260	4.70	289	207	190	181	119	134	161	206	
	1350	4.13	477	30.8	16.2	0.90	276	725	156	6.08	257	197	183	172	144	155	178	246	

Loss of circulation zones encountered during drilling

M1: 14 barrels at 1179-1180 m

M2: 30 barrels at 1082 m, 80 barrels at 1173 m

Legend

ND not detected

- analysis not available

+ taken 24 days after the well was shut

Geothermometers

a. Quartz (Fournier 1977)

$$t^{\circ}\text{C} = \frac{1309}{5.19 - \log\text{SiO}_2} - 273$$

(SiO<sub>2</sub> in mg/kg)

b. Quartz after steam loss (Fournier 1977)

$$t^{\circ}\text{C} = \frac{1522}{5.75 - \log\text{SiO}_2} - 273$$

c. chalcedony (Arnórsson 1980)

$$t^{\circ}\text{C} = \frac{1112}{4.91 - \log\text{SiO}_2} - 273$$

(SiO<sub>2</sub> in ppm)

d. Na/K (White and Ellis, see Truesdell 1975, White 1970)

$$t^{\circ}\text{C} = \frac{855.6}{\log(\text{Na/K}) + 0.8573} - 273.15$$

e. Na/K (Arnórsson 1980) based on low albite-microcline equilibria

$$t^{\circ}\text{C} = \frac{1120}{\log(\text{Na/K}) + 1.426} - 273.15$$

(Na, K in ppm)

f. Na-K-Ca (Fournier and Truesdell 1973)

$$t^{\circ}\text{C} = \frac{1647}{\log(\text{Na/K}) + \beta \log(\sqrt{\text{Ca/Na}}) + 2.24} - 273.15$$

where  $\beta = 1/3$  for  $\sqrt{\text{Ca/Na}} < 1$  or  $t > 100^{\circ}\text{C}$

(Na, K, Ca in moles/liter)

e. The chemical characteristics of the springs and well waters in the highlands show them to be secondary waters. Evidence from the water chemistry cannot be used to delineate an upflow zone for the Manito field, as has been suggested by previous workers. Gas sampling will hopefully assist in identifying upflow zones, although conclusive evidence will only be obtained by deep drilling.

### 3. INTERPRETATION OF GAS ANALYSES FROM BILIRAN ISLAND, LEYTE

#### 3.1 Introduction

Biliran Island is located at the northeastern tip of Leyte Island (Fig.7) and is currently being explored and investigated for its geothermal potential.

A reconnaissance survey team by staff from PNOC-EDC and KRTA (New Zealand) visited some thermal areas in the island in May, 1978. The favourable results from this survey prompted further geoscientific investigations in 1979. This consisted of geological (detailed stratigraphic, structural and tectonic mapping), Schlumberger DC resistivity soundings, and geochemical sampling of springs and fumaroles in the areas.

This chapter deals with the interpretation of the gas analyses of fumaroles in the area reported by Galia (1980). The ionic balances of the water analyses reported by Galia (1980) were found to be poor, so interpretation of the water chemistry was not attempted. Resampling of the thermal springs is suggested.

#### 3.2 Gas chemistry

Fig. 7 shows the main structures and the distribution of thermal manifestations in Biliran Island. Espiritu (1980) describes the faults as NE strike-slip faults arranged en echelon almost perpendicular to the Philippine fault, and points out that they coincide with the thermal manifestations in the area.

Gas samples were collected from some of the impressive steam vents in the Libtong and Volcan (also called Upper Cabiran) thermal areas. The results of the analyses and calculated molecular ratios (after Galia 1980) and geothermometry temperatures are shown in Table 7.

The analyses show that CO<sub>2</sub> is the main gas component and comprises 92-98% (by volume) of the noncondensable gases.

Table 7

Analyses of fumaroles, Biliran island

Samples no	Location	CO <sub>2</sub>	H <sub>2</sub> S	Total	Gas	Mole	%			Molecular ratios				Calculated temp. (°C)	
		- mm /100m		CO <sub>2</sub>	H <sub>2</sub> S	CH <sub>4</sub>	H <sub>2</sub>	N <sub>2</sub>	O <sub>2</sub>	CO <sub>2</sub> /H <sub>2</sub> S	CO <sub>2</sub> /CH <sub>4</sub>	CO <sub>2</sub> /H <sub>2</sub>	H <sub>2</sub> CH <sub>4</sub>	a	b
V-1	Volcan	2972	89.81	92.18	2.79	0.02	0.11	4.18	0.73	33.0	4609	836	5.5	292 <sup>+</sup>	>300
V-2		7026	163.87	92.18	2.15	0.06	0.15	4.76	0.77	42.9	1536	614	2.5	286 <sup>+</sup>	>300
V-3		3840	33.52	98.55	0.86	3x10 <sup>-4</sup>	0.001	0.42	0.16	114.0	328500	98550	3.3	184 <sup>+</sup>	>300
L-1	Libtong	4274	80.09	96.40	1.81	0.03	0.001	1.38	0.38	53.3	3213	96400	0.03	161	>300
L-2		2424	72.78	93.88	2.82	0.06	6x10 <sup>-4</sup>	2.75	0.50	33.29	1878	156480	0.012	152	>300

Legend

a. D'Amore and Panichi (1980)

$$t^{\circ}\text{C} = \frac{24775}{\alpha + \beta + 36.05} - 273$$

where

$$\alpha = 2 \log \frac{\text{CH}_4}{\text{CO}_2} - 6 \log \frac{\text{H}_2}{\text{CO}_2} - 3 \log \frac{\text{H}_2\text{S}}{\text{CO}_2}$$

and

$$\beta = - 7 \log P_{\text{CO}_2}$$

(concentrations in % by volume)

<sup>+</sup>calculated using  $P_{\text{CO}_2} = 10 \text{ atm}$  (see text for discussion)

b. Arnórsson (unpublished work)

(only holds up to 300°C)

$$t^{\circ}\text{C} = \frac{3055}{9.23 - \log \text{CO}_2} - 273$$

CO<sub>2</sub> is mg/kg

### 3.3 Gas geothermometry

Gas geothermometers were used to estimate the underground reservoir temperatures (Table 7). The following gas geothermometers were used:

a. D'Amore and Panichi (1980) developed an empirical relationship between  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{H}_2$  and  $\text{CH}_4$ , and reservoir temperatures considering chemical analyses of 34 thermal systems. The calculated temperatures can be expressed by (all concentrations in % by volume):

$$t^{\circ}\text{C} = \frac{24755}{\alpha + \beta + 36.05} - 273$$

where

$$\alpha = 2 \log \frac{\text{CH}_4}{\text{CO}_2} - 6 \log \frac{\text{H}_2}{\text{CO}_2} - 3 \log \frac{\text{H}_2\text{S}}{\text{CO}_2}$$

$$\beta = -7 \log P_{\text{CO}_2}$$

$P_{\text{CO}_2}$  is the partial pressure of  $\text{CO}_2$

The following orders of magnitude for  $P_{\text{CO}_2}$  were assumed based on the statistical differences noted in the gas  $\text{CO}_2$  compositions of the mixtures involved: ( $\text{CO}_2$  in % by volume)

a.  $P_{\text{CO}_2} = 0.1 \text{ atm}$  if  $\text{CO}_2 < 75$

b.  $P_{\text{CO}_2} = 1 \text{ atm}$  if  $\text{CO}_2 > 75$

c.  $P_{\text{CO}_2} = 10 \text{ atm}$  if  $\text{CO}_2 > 75$  and  $\text{CH}_4 > 2\text{H}_2$ ,  $\text{H}_2\text{S} > 2\text{H}_2$

If these assumptions were used in the Volcan samples,  $P_{\text{CO}_2}$  would be 1 atm. However, the high concentrations of  $\text{CO}_2$  in the samples indicate higher partial pressures so 10 atm was used in the computations.

b. Arnórsson (unpubl. work) has developed a provisional geothermometer for  $\text{CO}_2$  in steam which has boiled adiabatically in one stage to  $100^{\circ}\text{C}$ . This is empirical and based on drillhole data from Iceland. The temperatures can be expressed by: ( $\text{CO}_2$  in mg/kg)

$$t^{\circ}\text{C} = \frac{3055}{9.23 - \log \text{CO}_2} - 273$$

This geothermometer only holds up to about  $300^{\circ}\text{C}$  because above this temperature,  $\text{CO}_2$  becomes mobile and is not governed by gas-water-rock equilibria (Arnórsson, pers. comm.).



D'Amore and Panichi's (1980) gas geothermometer gives estimates of 152-161 °C for the Libtong area and 286-292°C for the Volcan area if sample V-3 is excluded. The CO<sub>2</sub> gas geothermometer (Arnórsson unpubl. work) estimates the temperatures in both areas to be above 300°C.

#### 3.4 Conclusions

The gas analyses indicate conclusively that a high temperature geothermal heat source exists in Biliran Island. Different gas geothermometry calculations indicate reservoir temperatures of 184-292°C (D'Amore and Panichi 1980) or temperatures above 300°C. (Arnórsson unpubl. work).

#### 4. GEOTHERMOMETRY OF THE DEEP DRILLHOLES OF TONGONAN, LEYTE

##### 4.1 Introduction

The Tongonan geothermal area is located on the NW part of a geothermal reservation which covers an area of 52km x 2.5 km. Within the boundaries of the reservation (Fig.8) there is a segment of the Philippine fault, a line of Quaternary andesite volcanoes and associated thermal springs.

In the Tongonan geothermal area (Fig. 9) three approximately parallel components of the Philippine fault are found; the West, Central and East faults. A series of cross faults with both horizontal and vertical displacements and thermal springs, which are associated with the three major faults, can also be found in the area (Vasquez and Tolentino 1972, Reyes 1979).

Reyes (1979) suggested three major divisions of the Tongonan geothermal area. These are the Mahiao proven field, which is delineated by a 10  $\Omega$ m resistivity anomaly, the Malitbog area which is southeast of the Mahiao and confined within a 20  $\Omega$ m contour line, and the Bao Valley, south of the Mahiao, which is confined within a second 10  $\Omega$ m anomaly (Fig. 9).

Previous chemical investigations (e.g. KRTA 1976, Abiog 1969) of the thermal springs in Tongonan showed the following: acid sulfate waters were found in the Mahiao area and chemical studies suggested a large steam upflow zone in the area. Chloride springs were found in the Bao valley, and were considered to suggest a deep water outflow which was penetrated by the early shallow wells. To the southeast of the Bao Valley at higher elevations a series of acid sulfate steam heated surface waters were found.

In the early stages of exploration twelve shallow wells were drilled in Tongonan with ten located in the Bao Valley, one in the Mahiao area and one between the two areas. In the Bao Valley, many of the wells penetrated flows of hot (190°C), high chloride (3000 ppm), neutral pH waters with two of the wells discharging a low enthalpy steam and water mixture. However, after several days these wells were found to be blocked by calcite/aragonite deposition. The shallow well in the Mahiao area (4R1) recorded maximum temperature of 251°C, a temperature profile following the boiling point curve, and it discharged a low chloride, high sulfate and ammonia, almost

neutral pH fluid, which was compositionally similar to the spring waters nearby. The shallow well situated between the Mahiao and Bao Valley had a bottom hole temperature of 110°C and well water samples appeared to be local surface waters presumably representing the drilling fluid (KRTA reports 1976, 1977, 1978).

The most favourable results were obtained in the Mahiao area, and the first deep exploratory well (401) was drilled in this area and favourable results were encountered. This success prompted further deep drilling in the Mahiao, and all the wells proved to be successful. The Malitbog area, which has no active thermal springs but is characterized by intense hydro-thermal alteration, was found to be within 20  $\Omega$ m resistivity contour. The combination of the high surface alteration and the relatively low resistivity suggested a possible geothermal reservoir underneath. To test this a deep well (MB-1) was drilled. Results were favourable.

The deep wells in Tongonan (Fig. 10) show two-phase conditions at depth except MB-1 (Whittome and Smith 1979). These wells have a discharge enthalpy of 1300 to 2400 kJ/kg at wellhead pressures of 3 to 15 bars. Most of these wells encountered two main aquifers at depth (KRTA 1980), referred to as the main production zone and the secondary production zone (Table 8).

#### 4.2 Discharge chemistry

The chemical results of the discharge fluids of nine deep wells in the Mahiao (1121 to 1942 m) and one in the Malitbog area (MB-1, 1665 m) are shown in Table 9. The discharge enthalpy was calculated from a measurement of the critical lip pressure and the water discharge at atmospheric pressure (James 1970) taken on the day of sampling. For references to the method of sampling and analysis the reader is referred to section 1.3. As a consequence of the presence of two-phase conditions at depth, corrections for excess enthalpy must also be applied in computing for the composition of the deep water.

The discharge waters are relatively neutral with a total dissolved solids content of 2.4 to 3.0 % (by weight). They contain high concentrations of arsenic, boron, lithium and dissolved silica with relatively low concentrations of bicarbonate, magnesium and sulfate. In the steam

Table 8

Physical measurements data and interpretations of the deep wells in Tongonan, Leyte showing production zones and measured temperatures (After KRITA 1980)

Well	Total depth (m CHF)	Production zones (mCHF)		Measured temperatures (°C)	
		Main	Secondary	a	b
401	1942.1	1450-1800	500-700	314	324
404	1668.2	1500-1600	-	302	313
406	1794.5	1600-1700	850-1100	310	323
407	1605.4	1325-1405	-	302	315
103	1402.0	1220-1300	600-660	280	312
105	1796.0	800-1070	1600-1740	313	317
202	1896.1	1100-1250	-	312	312
209	1121.3	1100-1121	920-970	280	286
213	1597.1	1440-1580	1050-1080	304	308
MB1	1665.1	1410-1661	1200-1300	280	284

CHF: means the central head flange (CHF) is the reference level of depth measurement

a: refers to maximum temperature measured at main production zone before discharge

b: refers to maximum temperature measured in well

Table 9

Chemical composition of the deep well fluids at Tongonan, Leyte  
Concentrations in ppm.

Well No	h* kJ/kg	SP bars abs.	steam phase at SP (mm/100m steam)				water phase (mg/kg at atmospheric pressure and local boiling point)															
			CO <sub>2</sub>	H <sub>2</sub> S	NH <sub>3</sub>	R <sup>1</sup>	pH/T°C	Li	Na	K	Ca	Mg	Cs	Rb	Cl	SO <sub>4</sub>	CO <sub>2</sub> <sup>2</sup>	SiO <sub>2</sub>	As	NH <sub>3</sub>	B	H <sub>2</sub> S
401	1800	8.9	485	19.3	1.23	4.73	6.68/25	39.8	7800	2110	219	0.28	3.5	12.5	14370	32	27.4	995	28	6.4	313	11.8
404	2065	4.5	1220	22.6	1.88	9.26	7.13/25	37.8	7690	2025	210	0.24	3.0	11.5	13805	100	43.3	1010	26	9.6	359	14.9
406	1697	6.9	402	14.8	1.16	0.79	6.80/26	35.8	8623	2579	230	0.39	-	11.5	16339	62	38.2	1079	29	6.3	347	15.0
407	1770	6.1	951	17.8	1.46	4.82	6.77/27	34.0	8634	2666	184	0.28	5.4	11.9	16503	40.6	44.7	1148	34	10.1	399	17.2
103	1582	8.6	290	15.8	1.27	2.84	6.97/30	34.3	7150	2184	255	0.41	4.4	10.1	13550	32	20.2	1010	24	6.0	260	12.5
105	1344	6.5	256	7.8	1.08	0.57	6.76/25	26.8	7137	2016	183	0.25	-	9.5	12816	33.6	23.1	949	21	3.7	242	5.6
202	1395	11.8	250	9.3	1.61	2.99	7.08/25	33.5	6750	1710	211	0.08	3.4	10.8	12390	19	67.1	1034	20	4.8	235	10.0
209	2311	7.2	126	21.4	1.04	1.24	6.68/25	32.5	9549	3000	313	0.98	5.8	13.2	17305	92.5	39.7	1039	28	5.9	382	6.4
213	1705	7.6	160	17.4	1.09	1.52	6.57/26	31.0	7994	2361	126	0.34	-	11.1	15382	30.5	21.8	1213	24	5.0	284	11.6
MB1	1322	8.4	314	11.7	1.82	1.83	7.48/25	17.7	5045	1176	146	0.18	-	7.7	8682	21.1	20.0	895	14	3.2	153	8.2

h\*: discharge enthalpy

SP: sampling pressure

<sup>1</sup>: undifferentiated residual gases (CH<sub>4</sub>+H<sub>2</sub>+N<sub>2</sub>+O<sub>2</sub>)

<sup>2</sup>: total carbonates (HCO<sub>3</sub><sup>-</sup>+ CO<sub>3</sub><sup>=</sup>+ H<sub>2</sub>CO<sub>3</sub>) reported as CO<sub>2</sub>

-: analysis not available

phase, carbon dioxide and hydrogen sulfide comprise about 90% of the noncondensable gases (Barnett 1979, Baltasar 1980).

Water samples from the deep wells have chloride/boron (Cl/B) ratios ranging from 12 to 18 (Barnett, 1979, Baltasar, 1980) and the thermal waters in the wells are presumed to have originated from within a common reservoir. In the Bao Valley, the Cl/B ratio is about 32 in the discharge fluid from the shallow wells (KRTA 1977). Barnett (1979) suggests that this represents a N to S petrochemical trend which can be explained from a consideration of the volatility of boron in steam.

The isochloride contours (Fig. 11) taken from Baltasar (1980) can be compared with the isothermal contours (Fig. 12) at 1000 m below sea level taken from Ablazo (1980). Fig 11 shows a significant decrease in chloride of 3000 ppm, but the temperature drop is small, only 20°C (from 300 to 280°C). The cold surface water is apparently heated up by contact with hot rock which explains the small temperature variation as compared with that for chloride.

#### 4.3 Geothermometry

Table 10 shows the calculated geothermometry temperatures of the deep fluid in nine deep wells in the Mahiao and one in the Malitbog areas.

Since the pH of the discharge waters is less than 8.5, the analysed silica can be taken to represent undissociated silica in the deep water, when the effect of steam loss has been taken into account. The calculated quartz equilibrium temperatures are given in Table 10.

The calibration curves for the Na/K geothermometer used here are based on thermodynamic data between Na- and K- feldspars and solution (e.g. Arnórsson, 1980) and on empirical data using the van't Hoff equation (e.g. White and Ellis, see Truesdell 1975, White 1970). The Na-K-Ca geothermometer by Fournier and Truesdell (1973) was also used to estimate temperatures.

Temperatures based on the gas concentrations of the wells were also computed using a CO<sub>2</sub> gas geothermometer (Arnórsson, unpubl. work).

Table 10

Calculated geothermometers and maximum measured temperatures at the main production zones in Tongonan, Leyte

Well	Temperatures (°C)									CO <sub>2</sub> <sup>h)</sup>
	Measured <sup>a)</sup>	Quartz <sup>b)</sup>	Na-K-Ca <sup>c)</sup>	Na/K <sub>1)</sub>						
				d) <sup>1)</sup>	e) <sup>1)</sup>	f) <sup>1)</sup>	f) <sup>2)</sup>	g) <sup>1)</sup>	g) <sup>2)</sup>	
401	314	264	311	328	325	298	325	289	310	>300
404	302	267	309	323	320	294	305	285	294	>300
406	310	277	323	347	342	314	340	301	320	>300
407	302	289	330	353	348	320	337	305	318	>300
103	280	283	317	351	345	318	318	304	304	285
105	313	268	315	336	332	305	329	294	303	278
202	312	273	302	316	314	290	310	281	295	273
209	280	266	326	356	351	322	322	308	307	256
213	304	299	329	344	340	312	336	300	314	262
MB1	280	272	292	301	301	274	274	271	271	281

## Legend

a) Max. temp. at main production zone before discharge (KRTA 1980)

b) Quartz geothermometer, range 200-370°C (Arnórsson 1979)

$$H_4SiO_4 \text{ (in ppm)} = 1.2 \cdot 10^{-4} \cdot t^{\circ}C^{2.76} - 6.94 \cdot 10^{-24} \cdot t^{\circ}C^{10.2}$$

c) Na-K-Ca geothermometer (Fournier and Truesdell 1973)

$$t^{\circ}C = \frac{1647}{\log(Na/K) + \beta \log(\sqrt{Ca}/Na) + 2.24} - 273.15$$

where  $\beta = 1/3$  for  $\sqrt{Ca}/Na < 1$  and  $t > 100^{\circ}C$ 

and Na, K, Ca in moles/liter

Na/K geothermometers

d) (White and Ellis,  $t^{\circ}C = \frac{855.6}{\log(Na/K) + 0.8573} - 273.15$   
see Truesdell 1975, White 1970) where Na, K in mg/kg

e) (Arnórsson 1980)  $t^{\circ}C = \frac{933}{\log(Na/K) + 0.993} - 273.15$   
where Na, K in mg/kg

f) (Arnórsson 1979) Based on Na- and K-feldspar and solution equilibrium from experimental data by Helgeson (1969). Range 30-300°C

$$\log(Na/K) = -10.96 + 1709/T^{\circ}K + 3.18 \cdot \log T^{\circ}K$$

where Na, K in moles/liter

g) (Arnórsson 1980) Based on low albite - microcline equilibria from data by Helgeson et al. (1978). Range 30-300°C

$$t^{\circ}C = \frac{1120}{\log(Na/K) + 1.426} - 273.15$$

where Na, K in mg/kg

h) Provisional geothermometer for CO<sub>2</sub> in steam which has boiled adiabatically in one stage to 100°C (Arnórsson unpubl. work) - only holds to 300°C

$$t^{\circ}C = \frac{3055}{9.23 - \log CO_2} - 273$$

CO<sub>2</sub> is in mg/kg in steam

1) Na/K ratio from Na, K analysed

2) Na/K ratio from computed Na<sup>+</sup>, K<sup>+</sup> activities

The  $\text{CO}_2$  concentrations at the sampling pressures were computed to 1 atm assuming adiabatic boiling in one stage. For a further discussion of this geothermometer, the reader is referred to section 3.3.

The results show (Table 11) that the silica geothermometer consistently gives lower values than the cation geothermometers and the measured temperatures. The high temperatures and the high salinity of the reservoir cause precipitation of silica as quartz at depth due to the relatively fast rate of re-equilibration at these temperatures. The silica temperatures do therefore not reflect underground temperatures, and the cation geothermometers are considered to give more accurate results.

The Na/K geothermometers used based on empirical data and formulated using the van't Hoff's equation (Arnórsson 1980, White and Ellis, see Truesdell 1975, White 1970) show consistently higher values than the measured temperatures. The average deviation is  $35^\circ\text{C}$  (White and Ellis, see Truesdell 1975, White 1970) and  $33^\circ\text{C}$  (Arnórsson 1980). The reason for this deviation is that the assumption that the standard heat of formation of the reaction  $\Delta H_R^\circ$  is constant does not apply at these high temperatures.

Calibration curves (Arnórsson 1979, 1980) for the Na/K geothermometer based on thermodynamic data from Helgeson (1969) and Helgeson et al. (1978) assuming low albite and microcline equilibrium lie both above and below the empirical calibration curve. Whichever of the two curves is used similar average deviation is found from the measured downhole temperatures, or about  $17^\circ\text{C}$  (Table 11).

Since the reservoir is somewhat saline, the formation of NaCl and KCl complexes can cause the Na/K ratios to deviate significantly from the ratio of the respective cation activities ( $a_{\text{Na}^+}/a_{\text{K}^+}$ ). The  $\text{Na}^+$  and  $\text{K}^+$  activities were computed using a procedure outlined by Arnórsson et al. (1980), and these values were used to compute the Na/K temperatures. They gave average deviations of about  $22^\circ\text{C}$  and  $14^\circ\text{C}$  when using the curves given by Arnórsson (1979) and Arnórsson (1980) respectively, and standard deviations of  $16^\circ\text{C}$  and  $7^\circ\text{C}$  respectively.

The Na-K-Ca geothermometer gives an average deviation of about  $18^\circ\text{C}$  and



Table 11

Table showing deviations of the geothermometers from the measured temperatures (in °C) in the deep wells in Tongonan, Leyte

Well	Quartz	Na-K-Ca <sup>1</sup>	Na/K						CO <sub>2</sub> gas
			d <sup>1</sup>	e <sup>1</sup>	f <sup>1</sup>	f <sup>2</sup>	g <sup>1</sup>	g <sup>2</sup>	
401	+50	+3	-14	-11	+16	-11	+25	+4	NA
404	+35	-7	-21	-18	+8	-3	+17	+8	NA
406	+33	-13	-37	-32	-4	-30	+9	-10	NA
407	+13	-28	-51	-46	-20	-35	-3	-16	NA
103	-3	-37	-71	-75	-38	-38	-24	-24	-5
105	+45	-2	-13	-19	+8	-16	+19	+10	+35
202	+39	+10	-4	-2	+22	+2	+31	+17	+39
209	+14	-46	-76	-71	-44	-42	-28	-27	+24
213	+5	-25	-40	-36	-8	-32	+4	-10	+42
MB1	+8	-12	-21	-21	+6	+6	+9	+9	-1
Ave. deviation (°C)	24.5	18.3	34.8	33.1	17.4	21.5	16.9	13.5	24.3
Standard deviation (°C)	17.7	15.5	24.8	24.5	13.9	15.5	10.1	7.4	17.7

1 based on analysed Na, K

2 based on Na<sup>+</sup>, K<sup>+</sup> activities

- sign refers to degrees C higher than measured temperature

+ sign refers to degrees C lower than measured temperature

NA geothermometer not applicable

Na/K geothermometers (using same nomenclature as table 10)

d White and Ellis (see Truesdell 1975)

e Arnórsson 1980

f Arnórsson 1979, from thermodynamic data of Helgason (1969)

g Arnórsson 1980, from thermodynamic data of Helgason et al. (1978)

a standard deviation of about 15°C.

The results show that Arnórsson's (1980) curve, which is based on thermodynamic data of low albite and microcline equilibrium from Helgeson et al. (1978), is the most suitable chemical geothermometer for the Tongonan reservoir.

The CO<sub>2</sub> gas geothermometer (Arnórsson, unpubl. work) yields on average a temperature which is 22°C below the measured temperatures. This deviation can, at least partly, be explained by the high enthalpy of the well discharges. Surplus steam in the discharge will lower the CO<sub>2</sub> content in the steam.

#### 4.4 Anhydrite equilibrium

The solubility product of anhydrite was calculated assuming distribution of gases between the reservoir water and steam for conditions of equilibrium (maximum degassing) and 1/5 of maximum degassing using a procedure outlined by Arnórsson et al. (1980). The reference temperatures used are the maximum recorded temperatures in the main production zones.

The results (Table 12) indicate saturation of the deep water with respect to anhydrite. The close fit of the values for the two conditions of degassing shows that the distribution of gases between the two phases has no significant effect on the state of anhydrite saturation.

#### 4.5 Conclusions

a. The Na/K geothermometer calibration curve given by Arnórsson (1980) using the calculated activities of Na<sup>+</sup> and K<sup>+</sup> in the deep water compares well with the measured temperatures for this geothermal system.

b. Anhydrite, a common mineral found in geothermal systems, was found to be in equilibrium with the deep water.

c. Meteoric water mixes with the reservoir in the vicinity of the Malitbog area but becomes heated by contact with the hot rock so the dilution effect becomes greater than the temperature drop.

Table 12

Log solubility products of anhydrite in deep water showing theoretical values and measured values in Tongonan, Leyte

Well	Meas. temp. <sup>1)</sup> °C	Log solubility products of anhydrite in deep water		
		theor. <sup>2)</sup>	calc. <sup>3)</sup> (- 100%DG)	calc. (-20%DG)
401	314	-9.316	-9.233	-9.274
404	302	-9.085	-8.698	-8.743
406	310	-9.239	-8.914	-8.936
407	302	-9.085	-9.113	-9.147
103	280	-8.665	-8.647	-8.662
105	313	-9.297	-9.350	-
202	312	-9.227	-9.469	-
209	280	-8.665	-8.558	-8.569
213	304	-9.123	-9.317	-9.334
MB1	280	-8.665	-8.758	-8.775

1) Max. measured temperature at main production zone

2) Theoretical values

3) Calculated values

DG: Degassing

## 5. RECOMMENDATIONS

In the evaluation of chemical data during the course of this research project, results have emerged on the basis of which the following recommendations are made:

- a) Aluminum and iron should be analysed both in spring and well waters. Most of the minerals found in geothermal systems contain these elements and this could allow more mineral/solute equilibria results for study.
- b) Gas samples should be collected in Manito, Albay. This could be a valuable aid in identifying the major upflow zones and the gas chemistry may be used to estimate underground temperatures.
- c) Analyses of some of the primary springs in Manito (Albay) and Biliran Island (Leyte) should be rechecked because of poor ionic balances.
- d) The results based on the gas chemistry in Biliran Island should be compared to the water chemistry results for an interpretation of the geothermal system.
- e) More gas samples should be collected from Biliran Island, Leyte. The results of the five gas samples are not sufficient to identify the major upflow zones.
- f) The study of mineral/solute equilibria is a valuable aid in the overall evaluation of a geothermal system. However, the complicated calculations involved make the use of a computer necessary.

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