APPLICATIONS OF STABLE ISOTOPES IN GEOTHERMAL EXPLORATION IN THE PHILIPPINES - A REVIEW

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Abstmct *- A review of the isotopic data from geothermal exploration areas in the Philippines indicates that the surface thermal waters and well discharges are enriched in heavier isotopes and deviate from the local meteoric water line defined by δ^2H = $8\delta^{18}O$ + (14 ± 2). This enrichment is commonly due to: 1) near surface evaporation; and 2) mixing between meteoric waters and isotopically enriched deep magmatic waters, a phenomenon confirmed by deep wellfluids in developed Philippine geothermal systems, such* as *Tongonan, Palinpinon and Alto Peak. Waters that are isotopically enriched due to the latter are found to be more significant to exploration because in most cases, these are representative offluidsfrom hotter sources. The dominant process forming these waters can be distinguished by the relationship between stable isotopes and Cl compositions.*

1. INTRODUCTION

The Philippines currently has a total installed generating capacity of 1,036.5 MWe from geothermal energy resources. The Philippine National Oil Company-Energy Development Corporation (PNOC-EDC) generates about 36% of these from the following geothermal fields (Fig. 1): Bacon-Manit0 (BacMan) I (1 10 MWe) and II (20 MWe) in Sorsogon in Luzon; Palinpinon I (112.5 MWe) and II (20 MWe), and the 1.5-MWe pilot plant in Southern Negros; and, Tongonan I (112.5 MWe) in Leyte.

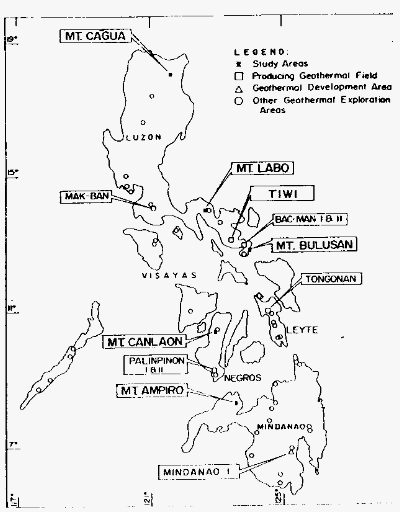


Figure 1: Location map of Philippine geothermal areas.

By 1996-97, the huge geothermal potential of Leyte (additional 640 MWe) shall be developed in line with the plan for the total interconnection of the country into a single grid. The Mindanao 1 (Mt. Apo) geothermal project (40 MWe) shall also be commissioned in 1996 to provide supply diversification in Mindanao.

Despite these, 1,595 MWe is still required to augment the energy demands in the next five years. To meet these needs, PNOC-EDC is exploring and developing 21 geothermal prospect areas, ten in Luzon, six in the Visayas and five in Mindanao, from where a total of 1,090 to 2,550 MWe is expected.

These programs imply greater demand for geoscientific investigations, for which isotopic techniques play an important role. Isotopic investigations have been conducted in Philippine geothermal exploration areas since 1989 under the International Atomic Energy Agency (IAEA) assistance with the following objectives: a) to establish the baseline isotopic data of thermal and meteoric waters in the geothermal exploration areas; and b) to determine the hydrological characteristics of geothermal areas through the use of ^{18}O, ^2H and ^3H.

This paper aims to review and summarize the results of these isotopic investigations. It defines the local meteoric water line, illustrates the common phenomena affecting the thermal and non-thermal fluids in geothermal exploration areas, and identifies the possible origin of fluids. The review is focussed on Mts. Cagua, Labo and Bulusan in the island of Luzon, Mt. Canlaon in the Visayas region, and Mt. Ampiro in the island of Mindanao (Fig. 1).

2. SAMPLING AND ANALYSIS

Meteoric water samples were collected at different elevations (20 to 1100 m asl) from headwaters of rivers, groundwaters tapped by wells and cold springs found in the different study areas (Figs. 2 to 6). The thermal fluids were collected mainly from springs,

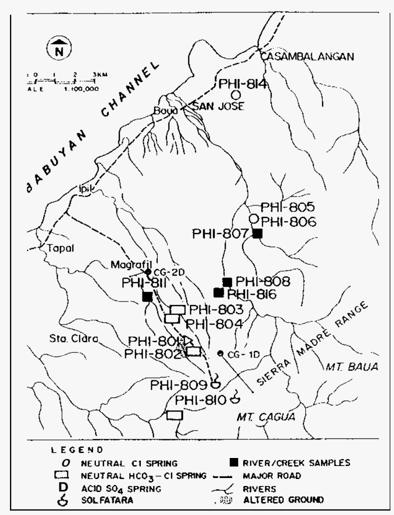


Figure 2: Map of the Mt. Cagua geothermal project showing the sampling location of the thermal and surface meteoric waters. The well tracks of CG-1D and CG-2D are shown.

geothermal wells and solfataras. Where exploratory wells were drilled, as in Mts. Labo and Cagua, samples were collected at stable conditions during discharge testing by using a Webre separator to separate the steam and liquid phases. The number of samples were, however, limited by the short duration of the tests, but are sufficient to characterize the deep geothermal fluids. The analytical results were corrected to their total discharge compositions (Gerardo et al., 1993; Alvis-Isidro et al., 1993).

All samples were stored in polyethylene bottles and analyzed at the Isotope Hydrology Laboratory of IAEA in Vienna for ^{18}O, ^{2}H and ^{3}H. The corresponding chemical samples were analyzed at the PNOC-EDC Head Office Chemical Laboratory in Manila. The isotopic results were reported in ‰ deviation from the Vienna Standard Mean Ocean Water (VSMOW) with uncertainty ranges of ±0.1 ‰ and ±1.0 ‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively. Tritium results were reported in tritium units (TU), where 1 TU has a ratio of $^{3}H/^{1}H = 10^{-18}$. The average analytical error is ±0.4 TU.

3. DESCRIPTION OF THE STUDY AREAS

3.1 Mt. Cagua

Mt. Cagua is associated with an active magmatic hydrothermal system. It is underlain mainly by andesite lava flows, tuffs and breccias, with minor layers of basalts and sediments. The heat source is associated with microdiorites (Bayrante et al., 1989).

This area is characterized by a solfatara (Maasok) which discharges superheated steam at 96°C (Fig. 2) . A neutral pH chloride-bicarbonate spring with a temperature of 42°C is found beneath the crater. The hydrothermal system is postulated to outflow towards the northwest.

Two wells drilled in this area, CG-ID and CG-2D, yielded a maximum measured temperature of 340°C at the well bottom. It is hypothesized that the system consists of a two-phase shallow liquid dominated reservoir and a deeper gas rich zone with magmatic characteristics (Tebar et al., 1991).

3.2 Mt. Labo

Mt. Labo is an inactive Quaternary volcano. It is underlain by the Upper Miocene volcanics consisting of andesitic to dacitic lava flows, agglomerates and tuffs. This is overlain by a Pliocene sedimentary sequence. The youngest and most widespread units are the Pleistocene volcanics which are the products of the volcanism to which the hydrothermal activity is associated (Geoscientific staff, 1993).

The geothermal system is manifested at the surface by neutral pH chloride springs (1700-2700 ppm Cl) which discharge at temperatures of 45-88°C (Fig. 3). These are found at lower elevations (90-205 m asl) southwest of the prospect. Some acid-sulfate springs with temperatures of 30-50°C and Cl of 130-450 ppm are found at higher elevations (565-590 m asl) at the central portion of the volcano (Geoscientific staff, 1993).

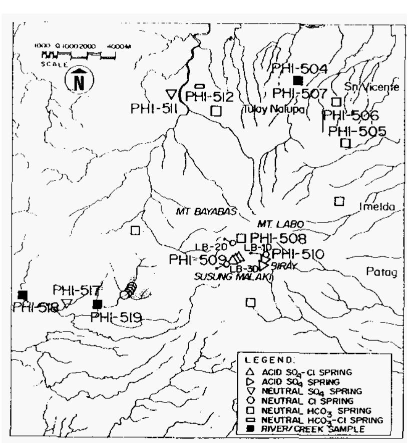


Figure 3: Sampling location map of the Mt. Labo geothermal project. The well tracks of LB-1D, LB-2D and LB-3D are also shown.

Among the three exploration wells drilled, only two were successfully discharged. Well LB-ID, however, discharged acidic fluids (pH = 3.4) with measured temperature of 270°C at well bottom. Well LB-3D initially had a neutral pH discharge which subsequently became acidic. It has a well bottom measured temperature of 264°C (Geoscientific staff, 1993).

3.3 Mt. Bulusan

Mt. Bulusan is a caldera-hosted hydrothermal system which is associated with andesitic volcanism and minor rhyolitic intrusions (Delfin et al., 1993). The thermal manifestations are confined within the caldera, mainly in the form of warm springs having temperatures up to 63°C (Fig. 4). The neutral pH chloride-bicarbonate springs are found at lower elevations (0-20 m asl) (Ramos and Baltasar, 1991).

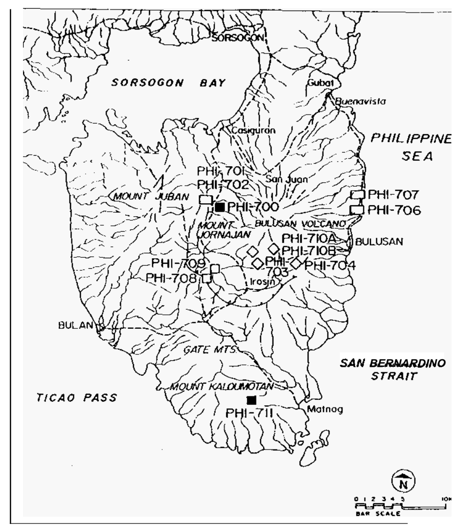


Figure 4: Structural and sampling location map of the Mt. Bulusan geothermal prospect. The SO_4-HCO_3 waters are denoted by ◊ . All other symbols used are the same as in Figs. 2 and 3.

3.4 Mt. Canlaon

Mt. Canlaon is a volcanic complex consisting of four eruption centers. The youngest crater is characterized by minor and periodic eruptions of ashes. The hydrothermal system is associated with the oldest and extinct eruption crater at the southwest. It is underlain by Pleistocene andesite lavas that are intercalated with minor sedimentary layers (Pamatian et al., 1992).

Neutral pH chloride springs, which are manifestations of the

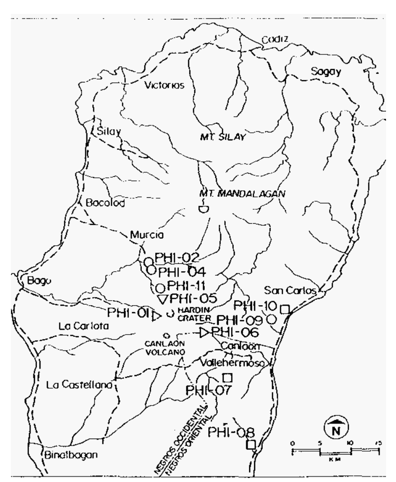


Figure 5: Map showing the sampling location of thermal waters in Mt. Canlaon geothermal project. Symbols used are the same as in Figs. 2 and 3.

outflowing geothermal fluids, are found at the northwestern slope of the volcano (Fig. 5) at an elevation of 340 m asl and with a maximum temperature of 64°C. The acid-sulfate springs are situated at higher elevations (340-870 m asl). A 265°C neutral pH chloride reservoir is postulated to upflow beneath the northwestern part of the volcanic complex (Gerardo, 1990, 1992).

3.5 Mt. Ampiro

Mt. Ampiro, another caldera-hosted hydrothermal system, is underlain predominantly by basaltic rocks with minor andesitic units. A few thermal manifestations consisting of springs with maximum temperature of 53°C, are confined within the caldera (Fig. 6). The heat source of the hydrothermal system is associated with intracaldera domes (Pagado and Camit, 1992). A reservoir with temperature of 275°C is postulated (Clemente, 1992).

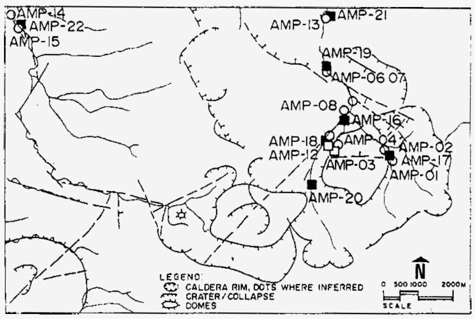


Figure 6: Map of the Mt. Ampiro geothermal prospect showing the major structures and the sampling location of surface thermal and meteoric waters, Symbols used are the same as in Figs. 2 and 3.

4. METEORIC WATERS

The meteoric waters collected from the study areas have a compositional range of -7.59 to -4.73 ‰ in $\delta^{18}O$, -44.8 to -26.8 ‰ in $\delta^{2}H$ and 7 to 25 ppm in Cl (Table I). It may be noted that meteoric waters which are more enriched in the heavy stable isotopes are found in the northern part of the Philippines and the depleted ones in the south (Fig. 7). This behavior may be a reflection of the latitude effect on the isotopic composition (Nuti, 1992).

Table I: Stable isotopic composition of meteoric water samples from the various study areas

Code	Source	DATE	Elevation (m asl)	Cl (ppm)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	Deuterium excess [1]	Tritium (TU)
MT. CAGUA								
PHI-807	Rapa Creek	16-Feb-91	60	17	-5.38	-26.8	16.3	
PHI-808	Baua River	16-Feb-91	25	18	5.72	-30.6	15.2	
PHI-811	Tapel River	19-Feb-91	270	11	-6.48	-38.7	13.2	
PHI-812	Pad-A coldspring	19-Feb-91	700	18	-6.44	-35.8	15.7	
PHI-813	Main Dam	19-Feb-91	400	7	-6.80	-40.7	13.8	
PHI-815	Pateng River	20-Feb-91	10	14	4.X	-35.5	14.1	
PHI-816	Bulawan River	20-Feb-91	140	25	4.X	-39.2	14.4	
	Average						*14.7*	
MT. LABO								
PHI-502	Magana coldspring	10-May-90	202	8.51	-4.73	-28.2	9.6	3.0
PHI-504	CNWD 6 test well	10-May-90	120		-5.15	-28.6	12.6	
PHI-505	Alinao coldspring	11-May-90	253	8.86	-5.05	-31.0	9.4	2.7
PHI-506	Bamban coldspring	11-May-90	207	9.40	-5.51	-34.5	9.6	3.3
PHI-507	CNWD1 well	14-May-90	120	9.57	-5.24	-31.5	10.4	2.2
PHI-508	Hagdan coldspring	15-May-90	850	9.93	-5.80	-35.4	11.0	1.9
PHI-518	Layaton River	18-Jan-93			-5.60	-30.6	14.2	
PHI-519	Bakoko River	18-Jan-93			-5.41	[illegible]	[illegible]	
	Average						*11.1*	
MT. BULUSAN								
PHI-700	Bacolod	07-Jun-90	20	13	-5.27	-27.5	14.7	
PHI-711	Bolocawe	08-Jun-90	20	12	-5.93	-33.7	13.7	
	Average						*14.2*	
MT. AMPIRO								
AMP-03	Sibucal 1	23-Nov-91	920	12	-4.63	-41.7	11.3	
AMP-16	Sabinit River	21-Jan-92	780		-6.89	-41.2	13.9	
AMP-17	Manimatay River	22-Jan-92	950		-6.72	-40.0	13.8	
AMP-18	Sabinit River	22-Jan-92	960		-6.13	-36.1	12.9	
AMP-19	Tuminawan River	22-Jan-92	750		-5.12	-28.7	12.3	
AMP-20	Upper Sabinit	23-Jan-92	1100		-7.35	-44.2	14.6	
AMP-21	Nunganga	25-Jan-92	650		-6.18	-36.2	13.2	
AMP-22	Onidos	27-Jan-92	450		-7.59	-44.6	16.1	
	Average						*13.6*	

[1] Deuterium excess = $\delta^2H - 8\delta^{18}O$ (Dansgaard, 1964)

The average deuterium excess (Dansgaard, 1964), **d**, calculated assuming an a priori slope of 8, is 13.4 for all areas (Table 1). This is consistent with the value calculated for Palinpinon (**d** = 14±2) (Gerardo et al., 1993), for Leyte (**d** = 13.7) (Alvis-Isidro et al., 1993) and for Bacon-Manit0 (**d**= 13.7) (Ruaya et al., 1993).

The deuterium excess for Metro Manila is equal to 10, computed from the weighted means of the monthly average rainfall in Manila Station (average elevation is about 40 m asl) from 1963-76 (Gerardo, 1990; Environmental Management Bureau; 1990). This is consistent with the global meteoric water line (Craig, 1963). The differences, however, in **d** between the study areas and Metro Manila may he attributed to the effect of mean relative humidity of the air masses overlying the oceans (Merlivat and Jouzel, 1979). It may also be due to the contribution **of** the ocean vapor and vapor from terrestrial evaporation and transpiration (Ingrahams and Matthews, 1990). These factors were also postulated to be the causes for the larger **d** in Palinpinon and Leyte. Considering the similarity of **d** in all geothermal areas, it may be pragmatic to consider that the local meteoric water line (LMWL) has the equation $\delta^2H = 8\delta^{18}O + (14\pm2)$. Figure 7 illustrates the isotopic relationship of the meteoric waters at a correlation coefficient, $r^2 = 0.97$, for 25 samples.

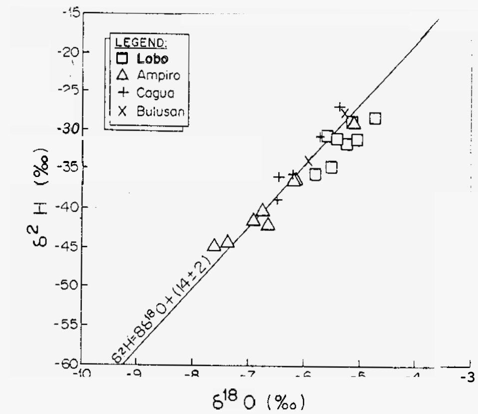


Figure 7: Stable isotope concentrations of meteoric waters in the study areas.

5. THERMAL WATERS

5.1 Chemistry of thermal waters

The thermal waters are classified according to their major anion compositions as reflected on the Cl-SO_4-HCO_3 triangular diagram (Fig. 8). Table II also includes a summary of that classification. The mature neutral pH chloride waters which are the best

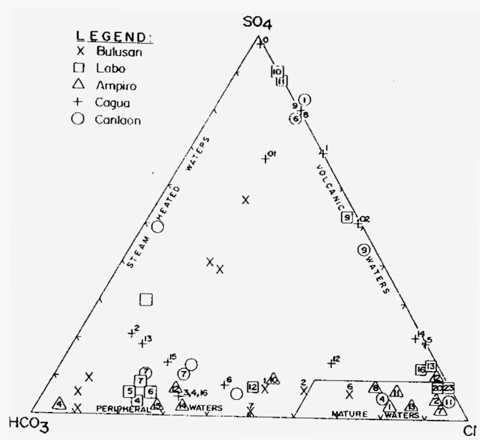


Figure 8: Classification of thermal waters in the study areas, based on anions (Giggenbach, 1988). The numbers in the symbols correspond to the last digits of the sampling codes as presented in Table II.

representative of the deeper geothermal brine for all study areas, except Mt. Cagua, are indicated. Most samples are mixtures of bicarbonate, chloride-rich geothermal fluids or sulfate-rich volcanic vapors. A few samples are volcanic in nature and are mixtures of sulfate-rich vapor and mature geothermal waters.

As illustrated in the Na-K-Mg diagram (Giggenbach, 1988) (Fig. 9), most of the partially equilibrated fluids are neutral pH chloride discharges from geothermal wells. In areas such as Mts. Labo and Ampiro, where more data are available, dilution trends are defined. This triangular diagram also suggests that the possible temperatures of the deep geothermal brine are about 220°C for Mt. Cagua, 230°C for Mt. Labo and 260°C for Mt. Canlaon.

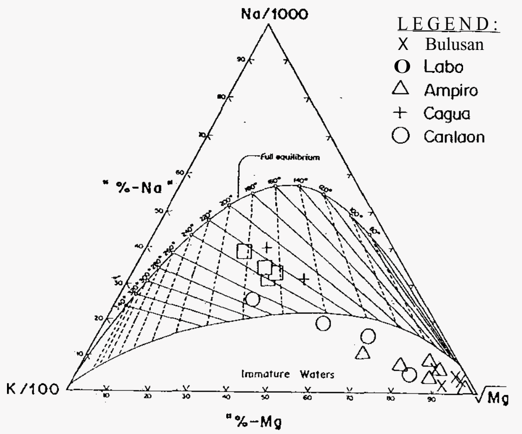


Figure 9: Na-K-Mg diagram (Giggenhach, 1998) showing the relative maturity of the neutral pH chloride waters in the study areas, the mixing trends, and the corresponding estimated reservoir temperatures.

Table II: Isotopic composition of thermal waters in the various study areas

Code	Source	Date	Temp C	Elevation (m asl)	pH	Type of waters, by anion content	Cl (ppm)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	Tritium (TU)
MT. CAGUA										
Thermal springs										
PHI-801	Magrafil A	15-Feb-91	32	400	3.3	SO4	11	-7.44	-46.3	
PHI-802	Magrafil B	15-Feb-91	50	400	7.5	HCO3	18	-7.10	-41.5	
PHI-803	Kabinlangan A	15-Feb-91	41	280	7.9	HCO3-Cl	198	-6.16	-38.6	
PHI-804	Kabinlangan B	15-Feb-91	48	280	7.8	HCO3-Cl	198	-6.20	-38.8	
PHI-805	Manaring A	16-Feb-91	62	25	7.9	Cl	1278	-4.50	-24.1	
PHI-806	Manaring B	16-Feb-91	58	25	8.0	Cl	1313	-4.50	-24.2	
PHI-809	Maasok Pool 1	18-Feb-91	94	760	2.2	SO4-Cl	354	12.78	9.7	
PHI-810	Maasok Pool 2	18-Feb-91	84	760	2.3	SO4-Cl	354	15.12	12.4	
PHI-814	San Jose	20-Feb-91	38	40	7.2	Cl	867	-4.70	-21.9	
Well waters										
PHI-800	CG-1D							1.24	-21.5	1.4
PHI-801	CG-1D							0.61	-32.8	
MT. LABO										
Thermal springs										
PHI-509	Mabahong Labo	15-May-90	50	565	2.6	SO4	484	-5.13	-33.6	2.0
PHI-510	Wala	15-May-90	19	780	3.1	SO4	11	-5.59	-34.6	2.0
PHI-511	Natuldocan	15-May-90	30	80	6.2	SO4	15	-5.06	-30.1	0.5
PHI-512	Baay	16-May-90	30	100	6.7	HCO3	320	-4.92	-29.9	1.4
PHI-517	Makbok	18-Jan-93	38		6.0	SO4	22	-5.77	-31.6	
Well waters										
PHI-513	LB-1D, 1800 m bsl	01-Dec-90	119		7.8	Cl	1142	-3.69	-30.5	
PHI-514	LB-1D, 2500 m bsl	01-Dec-90	127		4.7	SO4	79	-5.55	-30.1	
PHI-515	LB-1D, 1800 m bsl	02-Sep-92	154		6.1	Cl	1547	-3.18	-28.6	
PHI-516	LB-1D, 2500 m bsl	02-Sep-92	154		6.5	SO4	1682	-2.96	-30.2	
PHI-520	LB-3D	29-Nov-92	254		4.5	Cl	4386	-1.10	-29.6	
PHI-522	LB-3D	11-Dec-92	273		4.3	Cl	4399	-0.75	-31.8	
PHI-523	LB-3D	13-Nov-92	263		6.8	Cl	3799	-1.23	-28.1	
MT. BULUSAN										
PHI-701	Banyo	07-Jun-90	63	20		Cl-HCO3	271	-5.05	-28.2	
PHI-702	Banyo	07-Jun-90	53	20		Cl-HCO3	532	-5.13	-30.2	
PHI-703	San Benon	07-Jun-90	55	60		HCO3-SO4	184	-5.62	-30.5	
PHI-704	Masakrot	07-Jun-90	35	285		HCO3-SO4	89	-5.55	-29.8	
PHI-706	Porog	07-Jun-90	45	0	8.0	Cl-HCO3	1845	-4.25	-26.8	
PHI-707	Buhang	08-Jun-90	46	0		Cl-HCO3	640	-4.56	-27.8	
PHI-708	Gumapia	08-Jun-90	43	35		HCO3	56	-5.58	-30.5	
PHI-709	Talistison	08-Jun-90	45	55		HCO3	52	-5.59	-31.8	
PHI-710A	Pinirincipe	08-Jun-90	45	450	2	SO4-HCO3	212	-5.42	-29.8	
PHI-710B	Pinirincipe	08-Jun-90	48	450		SO4-HCO3	197	-5.44	-28.0	
MT. CANLAON										
PHI-01	Hagdan	09-Nov-89	44	870		SO4	96	-8.88	-56.1	
PHI-02	Hda. Montilla	08-Nov-89	25	190		HCO3	140	-7.82	-49.6	
PHI-04	Hda. Paz	08-Nov-89	36	220		Cl	396	-7.62	-49.5	
PHI-05	Kinabkahan	09-Nov-89	38	920		SO4	11	-8.72	-52.7	
PHI-06	Maluyong	17-Nov-89	24	840		SO4	40	-8.42	-52.0	
PHI-07	Bucalan	17-Nov-89	52	320		HCO3	90	-7.46	-46.8	
PHI-08	Kinayan	11-Nov-89	36	20	7	HCO3	97	-6.54	-42.3	
PHI-09	Mabato B	11-Nov-89	64	78		Cl	200	-6.94	-43.1	
PHI-10	Hda. Florida	11-Nov-89	30	10		HCO3	186	-6.43	-41.4	
PHI-11	Aquapool	28-Jun-91	64	340		Cl	1530	-6.35	-48.1	
MT. AMPIRO										
AMP-01	Manimatay 1	23-Nov-91	35	950	7.6	Cl	590	-5.21	-33.5	
AMP-02	Manimatay 2	23-Nov-91	53	950	7.6	Cl	1585	-4.34	-35.2	
AMP-04	Sibucal 2	24-Nov-91	37	920	7.1	HCO3	108	-7.71	-45.8	
AMP-06	Tuminawan 1	26-Nov-91	56	750	7.5	Cl	2130	-4.26	-34.1	
AMP-07	Tuminawan 2	26-Nov-91	49	750	7.2	Cl	1975	-3.83	-31.4	
AMP-08	Lawayan 1	27-Nov-91	45	780	8.1	Cl	2260	-4.91	-36.7	
AMP-11	Sabinit 1	27-Nov-91	45	960	7.9	Cl	4240	-3.39	-36.7	
AMP-12	Sabinit 2	27-Nov-91	40	950	8.2	HCO3	350	-6.89	-43.7	
AMP-13	Nuaganga	30-Nov-91	44	650	8.1	Cl	1600	-4.27	-30.1	
AMP-14	Onidos 1	06-Dec-91	28	450			1429	-6.38	-39.7	
AMP-15	Onidos 2	06-Dec-91	28	450			1007	-6.55	-42.9	

5.2 Isotopic composition of thermal waters

The isotopic composition of thermal waters in the study areas are also tabulated in Table II and plotted in Fig. 10. These waters have $\delta^{18}O$ of -7.82 to -0.75 ‰ and $\delta^{2}H$ of -50 to -28.8 ‰. They generally cluster along the LMWL but are slightly enriched both in ^{18}O and ^{2}H. The enrichment is pronounced for Mts. Labo and Cagua where samples were taken from deep geothermal wells.

The thermal waters also plot to the right of the LMWL on a slope from 1 (in Mts. Canlaon and Labo) to 3 (in Mt. Bulusan). These lines intersect the LMWL at the isotopic composition equivalent to the composition of the local meteoric water which recharges the areas (Table III).

Table III: Stable isotopic composition of local meteoric water recharge in the various study areas

Geothermal area	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
Mt. Cagua	-6.7	-41
Mt. Laho	-6.1	-31
Mt. Bulusan	-5.8	-33
Mt. Canlaon	-8.0	-SO
Mt. Ampiro	-7.2	-44

5.3 Processes affecting the isotopic compositions of thermal waters

The isotopic trends exhibited by Fig. 10 represent at least two processes, namely: a) evaporation of a thermal water having a composition similar to the local groundwater; or b) mixing between two end members, one being an isotopically enriched deep thermal water with the other end member being groundwater. Both these processes result to the enrichment of the heavy stable isotopes. However, these two processes are distinguished by plotting ^{18}O and Cl. Mixing of fluids shows a linear trend while evaporative fractionation gives a logarithmic relationship (Olafsson and Riley, 1978). Evaporation would increase the heavy isotopic and chloride compositions depending on the temperature of fractionation and the fraction of steam removed from the water.

To illustrate, Mt. Ampiro is characterized by neutral pH chloride fluids, with AMP-I 1 having the largest ^{18}O shift (Fig. 10) and considered the best representative of deep thermal waters. Bicarbonate-rich thermal waters also exist. The ^{18}O - Cl diagram (Fig. 11) illustrates two mechanisms: 1) the logarithmic trend of bicarbonate-rich waters which show evaporation with ^{18}O enrichment and no or slight increase in the chloride content; and *2)* linear trend which indicates mixing with isotopically enriched fluids, with the increase in the chloride contents corresponding to an enrichment in ^{18}O.

Similarly, Mt. Canlaon data points lie close to the LMWL (Fig. 10) indicating that the thermal waters are meteoric in origin. There are no indications of an active magmatic water input despite the presence of the active Canlaon volcano nearby. There also exists a mixing trend between the dilute fluids and the neutral pH

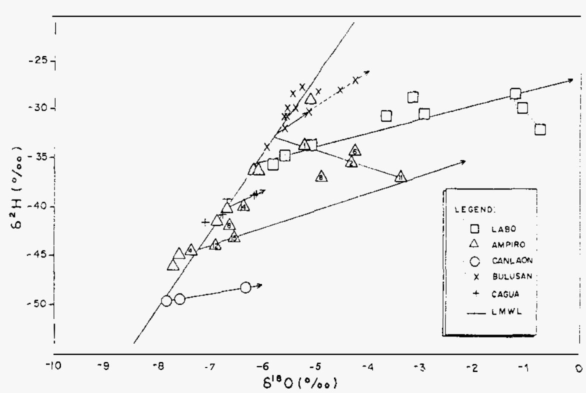


Figure 10: Stable isotope composition of the thermal waters from the study areas. Fine lines indicate the mixing trends. Their respective intercepts with the local meteoric water line represent the isotopic concentration of the meteoric water recharge.

chloride geothermal waters (Fig. 11). The same trend is observed for Mts. Cagua, Labo and Bulusan (Fig. 11). This illustrates that the neutral pH chloride thermal waters define a mixing line with isotopically enriched waters. The secondary waters, on the other

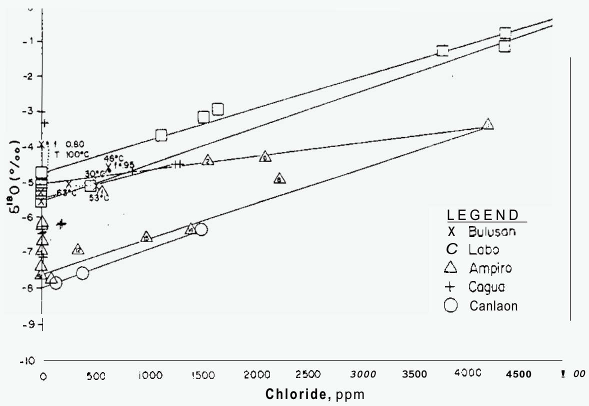
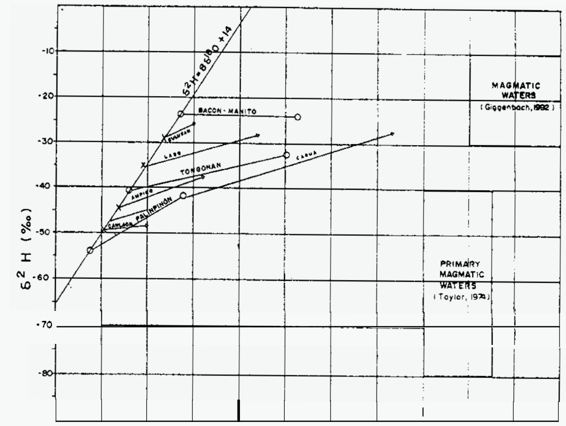


Figure 11: ^{18}O - Cl relation of geothermal waters in the study areas. A mixing trend is illustrated by fine lines which also correspond to those in Figure 10. Evaporation trends are indicated by dots.



hand, like bicarbonate and sulfate waters are logarithmically related and since these waters are produced by the adsorption of H_2S-rich vapors into the groundwater, their isotopic enrichment is due to fractionation at lower temperatures near the surface.

5.4 Origin of geothermal waters

Isotopic data from exploration areas clearly show that the thermal waters are essentially a mixture of meteoric water and isotopically enriched fluids, with meteoric waters contributing a greater proportion. The effect of water-rock interaction to the enrichment of ^{18}O and Cl is however, not discounted. The meteoric water component has the isotopic composition equivalent to the intercept of the δ^2H - $\delta^{18}O$ mixing line defined by the thermal waters with the LMWL.

By extrapolating the composition of the other end-member to the waters having the most enriched composition, the values approach the composition of magmatic waters (Giggenbach, 1992) (Fig. 12). The geothermal waters, in most cases, are isotopically heavier due to mixing with isotopically heavy magmatic waters. This relationship is observed in most Philippine geothermal systems, particularly where a number of wells have been drilled, e.g. Palinpinon (Gerardo et al., 1993), Tongonan (Alvis-Isidro, 1993), and Alto Peak (Reyes et al., 1993). This also holds true for some Italian and Japanese high temperature systems (Mizutani et al., 1986; Bolognesi and D'Amore, 1993; Seki, 1991 and Yoshida, 1991).

6. CONCLUSIONS

The LMWL, as a working requirement for interpreting isotopic data, is defined by $\delta^2H = 8\delta^{18}O + (14\pm2)$. Such equation is common for all geothermal areas. However, with the availability of more data in the future, this line may be further verified.

Two processes generally influence the isotope enrichment of thermal fluids, and these are evaporation and mixing with isotopically heavier magmatic fluids. Both can be distinguished by ^{18}O - Cl relationships. The enrichment of waters with heavier isotopes due to the latter is a strong indication that the fluids are geothermal in nature and, in most instances, come from a hotter source.

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