Geochemical Characteristics of Hot Springs in Bulusan Volcanic Complex, Southern Luzon, Philippines

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Abstract

Bulusan Volcano located in the southernmost part of the Bicol Peninsula is one of the active volcanoes in the Philippines. This paper reveals geochemical characteristics of hot springs in the Bulusan Volcanic Complex (BVC).

All of the hot springs except Buhang show the HCO_3-SO_4 and/or HCO_3 types, and also are plotted within the immature water area in the Na-K-Mg diagram, suggesting no strong outflow of neutral Cl-rich deep waters in the BVC. Isotopic compositions(δD and $\delta^{18}O$) of the hot springs indicate the local meteoric water origin. On the other hand, Buhang hot spring shows the Cl-HCO_3 type formed by mixing of meteoric origin CO_2-rich hot fluid and sea water.

Acidic pH of river water was observed during a small lahar caused by heavy rain. Probably this is due to erosion of newly sedimented pyroclastics by the rain and dissolving of the volcanic gases absorbed by the surface grains of the pyroclastics.

San Benon hot spring was monitored for chloride and sulfate ions to detect any precursors of volcanic eruption. The variation of chloride and sulfate ions was directly proportional with each other, ranging from 81 to 168mg/l and 270 to 601mg/l, respectively. This suggests that these ions are strongly affected by the mixing of groundwater in the area. Therefore, chemical monitoring using chloride and sulfate ions at San Benon is not recommended.

Key Words: Bulusan Volcanic Complex, hot spring, geochemical characteristics, monitoring

Introduction

Bulusan Volcano is one of the active volcanoes in the Philippines, and located in the southernmost part of the Bicol Peninsula (Fig. 1). The 2010 – 2011 eruption started in 6 November 2010 and ended on 13 May 2011(e.g. Okuno *et al*., 2011). The southern part of the peninsula is also one of the active geothermal fields in the Philippines.

The Philippines is the world's second largest producer of geothermal energy for power generation, with an installed capacity of about 1900MW, accounting for 12% of the nation's total electric power supply (Bertani, 2010). Among the seven operating geothermal fields (Ogena *et al*., 2010), two geothermal fields are located in the southern part of the Bicol volcanic arc; Tiwi (234MW installed capacity), and Bacon-Manito (BacMan; 152MW) (Fig. 1).

In the Bulusan Volcanic Complex (BVC), geothermal manifestations such as hot spring, fumarole and hydrothermal alteration zone were reported (McDermott *et al*., 2005; Delfin, 1993; JICA and MMAJ, 1999). Although the chemistry of hot springs in the area has been discussed by many authors, but is reported only internally. Delfin *et al*. (1993) briefly discussed the Bulusan hydrothermal system, but no chemical data on the springs in the field were shown.

The purpose of this paper is to reveal the geochemical characteristics of hot springs in the BVC area. Typical hot spring water samples from the nearest geothermal field, Bacon-Manito were also obtained to correlate the chemistry. One of the hot springs was monitored for its chemical composition with an aim to find any precursor of Bulusan Volcano eruption.

Geology and Thermal Manifestations

The volcanic rocks of the BVC are divided into three groups; pre-caldera, caldera, and post-caldera rocks (Delfin *et al*., 1993). The 1.1 Ma old pre-caldera volcanic rocks are exposed to the south and north sectors of Irosin Caldera (Fig. 2). The emplacement of Irosin Ignimbrite was 41 ka (Mirabueno *et al*., 2007), and resulted in the formation of Irosin Caldera.

According to Delfin *et al*. (1993), 11 hot springs are distributed mainly in the Irosin Caldera, including two fumaroles, a superheated solfatara at the summit of Bulusan Volcano and hot to warm springs on the flank of Bulusan Volcano (Fig. 2). A steaming ground also exists at Nag-aso near the southeastern rim of the Irosin Caldera. The hot

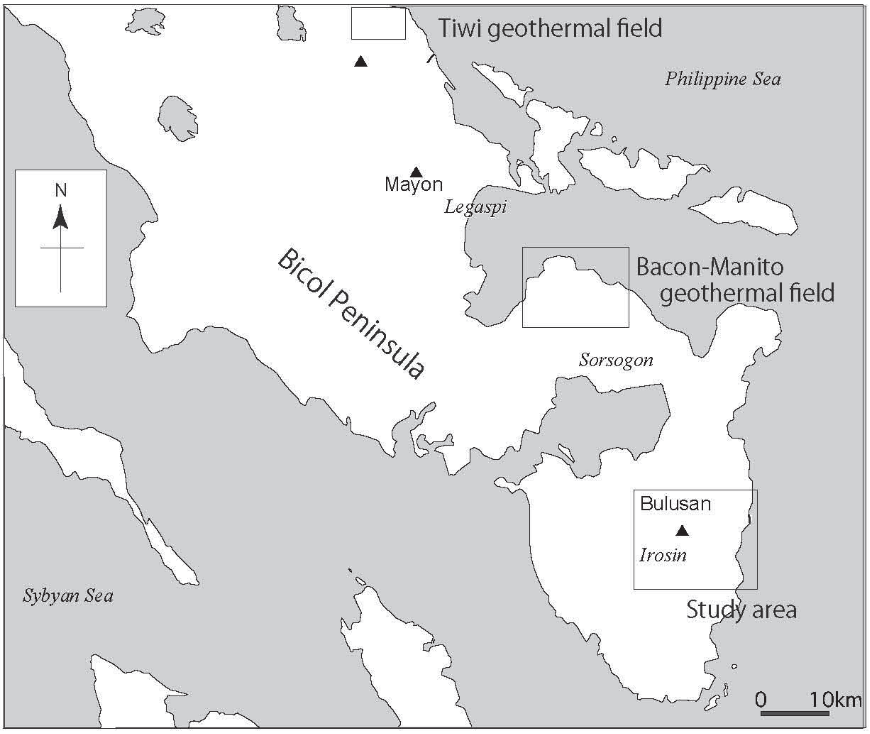

Fig.1 Location of Bulusan volcanoic area with showing two geothermal fields, Tiwi and Bacon-Manito in the Bicol Peninsula, Luzon.

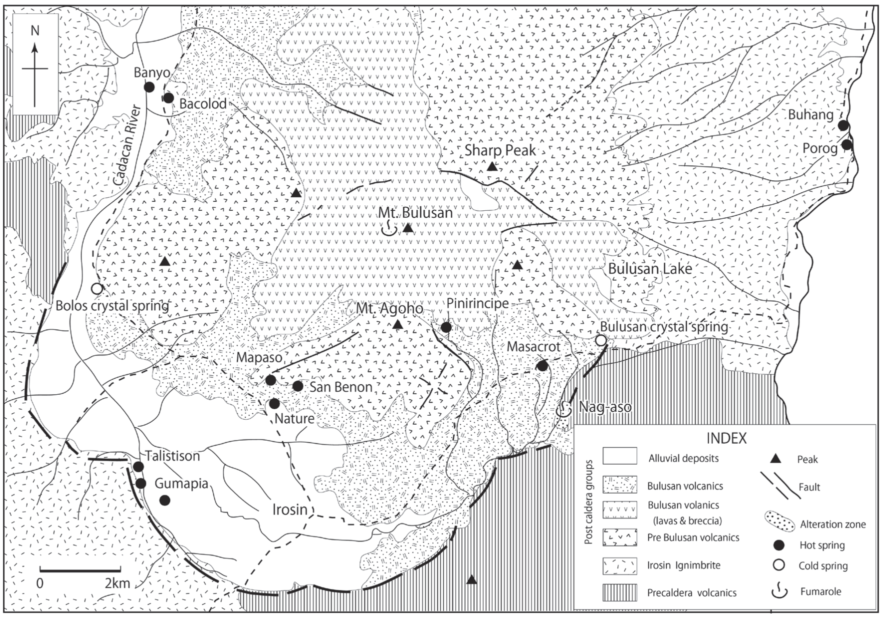

Fig. 2. Geologic map of the Bulusan volcanic area with showing the thermal manifestations (Simplified Delfin et al., 1993).

springs were classified into three main types based on the relative amounts of Cl, SO_4, and HCO_3. Banyo, Buhang and Porogo are classified as Cl-HCO_3 type and located at the lowest elevation and farthest (7-11 km) from Bulusan Volcano. Bacolodo, Talistison, and Gumapia are of the HCO_3 type and are distributed at slightly higher elevation with a distance of 6-9 km from Bulusan Volcano. The SO_4-HCO_3 type is discharging from Pinirincipe, Mapaso, San Benon, and Masakrot which are located at higher elevation and at a distance of 2-3.5 km distant from the volcano. All these hot springs show near neutral pH at temperatures <65°C.

Hot Spring Samples

Seven hot springs samples were collected from the Bulusan Volcanic Complex area (Fig. 3) namely: San Benon (Appendix-1), Mapaso (Appendix-2), Nature, Gumapia, Pinirincipe (Appendix-3), Masakrot (Appendix-4), and Buhang (Appendix-5). Other seven surface waters were also collected from the same area; two from the cold springs of Bolos (Appendix-6) and Bulusan Crystal springs, one sample was seawater from Buhang, and three were river water from Malunoy (Fig.4, Appendix-7 and 8) and Malacata Rivers. Three hot spring samples were also collected from the Bacon-Manito geothermal field (Appendix-9, 10 and 11).

Temperature and pH of water samples were measured in the field. All the samples were filtered using 0.45 micrometer membrane filter, and HCO_3 measurements were done by acid titration in laboratory. Chemical analysis was performed using ion chromatography in laboratory. Measurements of isotopic ratio of water samples were carried out by Delta Plus® with the isotopic gas equilibration method.

Hot Spring Chemistry

1. Geochemial characteristics of hot springs

Chemical data of the hot springs distributed in the investigated area are shown in Table 1. One of the significant features of the hot springs in the area is the absence of boiling water with neutral pH and the steam-heated acid sulfate water which suggest an strong indication of up flowing of neutral deep water. Although San Benon and Buhang hot springs showed relatively high temperatures, the measured temperature were only 45.7 and 45.2°C, respectively (Table 1). Moreover, the Cl contents of most of the hot springs are less than 100 mg/l; San Benon and Buhang hot springs contain only 115 and 613 mg/l, respectively. There are no any acid hot springs. The pH values of the hot springs are almost neutral ranging from 5.77 (Masakrot) to 7.27 (Pririnincipe).

Relative Cl, SO_4 and HCO_3 contents of thermal water samples are plotted on Fig. 5. The results show that the hot springs from the area are classified into three types; HCO_3-SO_4, HCO_3 and Cl-HCO_3 types. As mentioned by Delfin *et al.* (1993), the HCO_3-SO_4 types are discharging at San Benon, Mapaso, Nature, Pirinincipe, and Masakrot hot springs; these are the springs located closer to the Bulusan volcanic vent

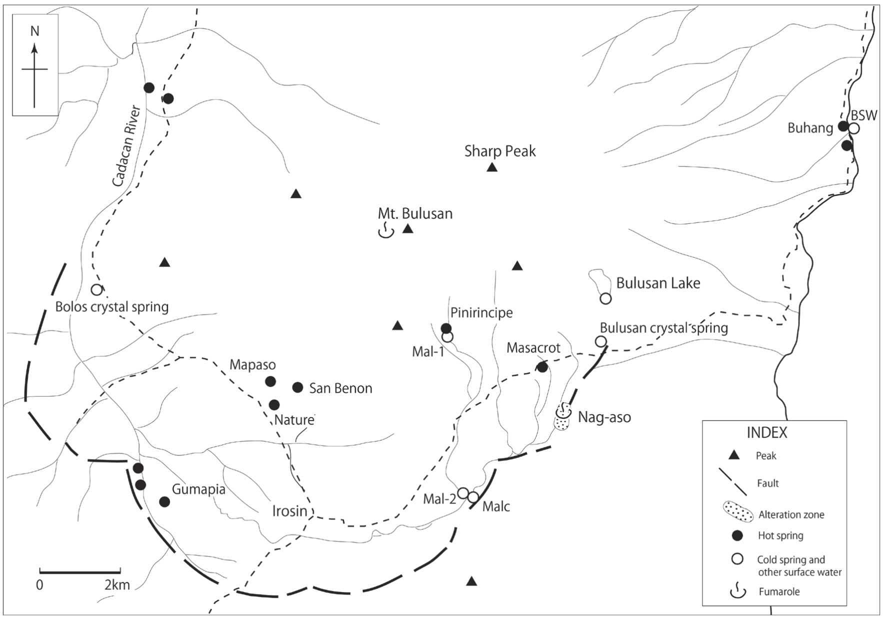

Fig. 3 Sample location of hot/cold spring, and river/lake/sea waters surrounding Bulusan Volcano. Sampling sites are shown with the name and abbreviations. Abbreviations are the same in Table 1.

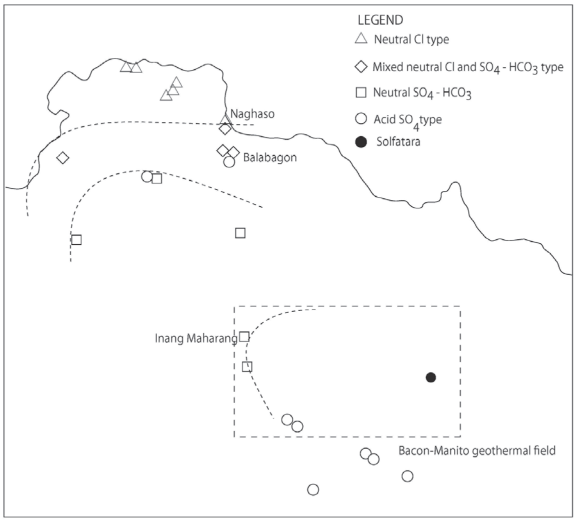

Fig. 4 Sampling locations in the Bac-Man geothermal field. Chemistry of hot springs shows a zonation according to deep fluid flows (Partly modified Leach et al., 1985) . Three samples were taken from the chemical zones, those sites are showing with names.

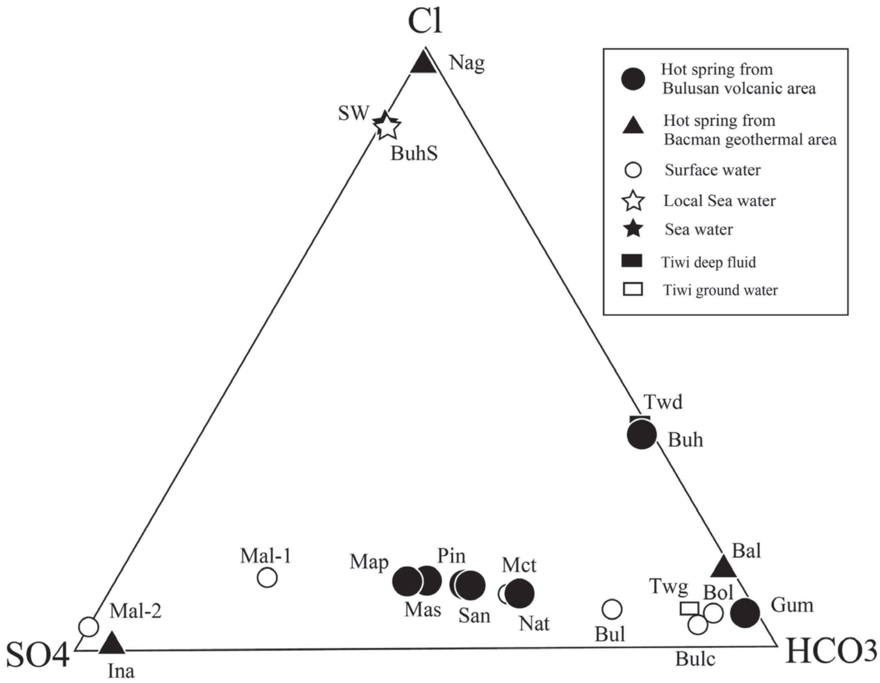

Fig. 5 Cl-SO_4-HCO_3 diagram of water from Bulsan volcanic area. The other geothermal waters from Bac-Man and Tiwi are also shown. Abbreviations are the same in Table 1. Twd and Twg are deep water and ground water, respectively, in Tiwi geothermal field by Sugiaman et al.(2004).

Table 1 Chemical compositions of hot spring and surface waters from Bulusan volcanic area. Samplig sites are shown in Figs. 3 and 4.

Sp. No.	T110302-6	T110303-1	T110303-2	T110303-3	T110302-5	T110303-7	T110302-2	T110303-8	T110302-1	T 110302-4	T110303-4	T110303-5	T110303-6	T110302-3	T110304-1	T110304-2	T110304-3
Location	San Benon HS	Nature HS	Mapaso HS	Pinirincipe HS	Masacrot HS	Gumapi HS	Buhang HS	Bolos Crystal Spring	Bulusan Lake	Bulusan Crystal Spring	Malunoy River	Malunoy River	Malacata River	Buhang SW	Inang Mahareng HS	Naghaso Hot Pool	Balbagon HS
I.D.	San	Nat	Map	Pin	Mas	Gum	Buh	Bol	Bul	Bulc	Mal-1	Mal-2	Malc	BuhS	Ina	Nag	Bal
Field	Bulusan	Bulsan	Bulusan	Bulusan	Bulusan	Bulusan	Bulusan	Bulusan	Bulusan	Bulusan	Bulusan	Bulusan	Bulusan	Bulusan	Bac-Man	Bac-Man	Bac-Man
Temp.(℃)	45.7	37.9	36.1	29.7	27.0	34.3	45.2	25.4	24.9	25.2	25.2	25.7	25.4	31.1	98	56	63.1
pH	6.42	6.36	6.03	7.27	5.77	7.25	6.24	6.77	7.06	6.11	7.4	<4.8		6.72	6.39	4.69	7.14
Elevation(m)	60	43	47	415	292	30	1	20	347	300	390	90	90	0	291	5	15
Li^+(mg/l)	0.1	0.1	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	1.3	0.0
Na^+(mg/l)	125	96.5	66.2	41.3	43.2	142	397	12.7	7.4	6.0	26.8	4.0	18.1	9730	3.3	664	104
NH_4^+(mg/l)	0.1	0.7	1.4	0.0	0.5	0.2	0.3	0.0	0.1	0.1	0.0	0.1	0.0		102	2.3	0.0
K^+(mg/l)	13.2	10.5	14.1	13.6	10.8	12.9	79.9	1.6	2.6	0.7	8.2	1.3	4.3	365	1.1	87.5	28.5
Ca^{2+}(mg/l)	118	106	72.3	39.4	54.6	39.3	192	12.3	13.8	8.0	38.9	10.0	23.5	384	9.6	48.0	35.2
Mg^{2+}(mg/l)	110	78.8	70.5	37.5	40.4	25.2	86.3	4.4	2.5	2.5	27.7	1.4	12.1	1221	2.0	1.6	18.2
F^-(mg/l)	0.4	0.3	0.3	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.2	1.2	0.1	0.5	0.2
Cl^-(mg/l)	115	77.3	71.6	39.6	47.6	33.5	613	5.1	4.8	4.8	31.8	2.5	14.8	16714	3.0	1145	62.6
Br^-(mg/l)	0.2	0.1	0.1	0.1	0.1	0.1	1.8	0.0	0.0	0.0	0.1	0.0	0.0	59	0.0	4.0	0.2
NO_3^-(mg/l)	1.1	n.d.	0.8	0.4	0.7	15.7	0.0	1.6	0.0	0.1	0.9	0.0	0.9	0.0	0.0	0.5	0.0
HCO_3^-(mg/l)	539	486	299	141	184	531	1075	87	54.9	43.8	56	0.0	94	211	15	7	397
SO_4^{2-}(mg/l)	406	268	265	174	184	10.2	23.2	6.4	15.1	1.8	172	60	56	2375	303	22.4	6.2
$\delta^{18}O$(‰)	-5.6	-5.6	-5.6	-5.7	-5.5	-5.9	-4.7	-5.5	-5.0	-5.3	-6.3	-6.6	-5.6	-0.8	1.6	-3.6	-5.2
δD(‰)	-31	-30	-29	-30	-28	-34	-26	-30	-23	-26	-35	-39	-30	1	8	-21	-26
	HS: hot spring, SW: Seawater																

and at relatively higher elevations. The HCO_3 type appears at Gumapia located at the southwestern rim of the Irosin Caldera far from the vent. The occurrence of this water type is also reported in the Bacolod and Talistison hot springs (Delfin *et al*., 1993). On the other hand, the Cl-HCO_3 type of hot springs occurs at Buhang located at the lowest elevation near the beach. Buhang hot spring contains 613 mg/l, the largest amount of Cl in the hot springs in this area.

Cation is also remarkable according to the type of anions. Mg ion is dominant in the HCO_3-SO_4 type of hot springs on meq/l basis as shown in Fig.6, while Na is dominant in the HCO_3 type and Cl-HCO_3 type. Both HCO_3-SO_4 and HCO_3 types of hot springs are arranging on the same line of the distribution of meteoric waters such as spring, river and lake (Fig. 5). This suggests that the origin of these types of hot springs has a strong affinity with meteoric waters; probably degassing gases such as CO_2 and/or H_2S are absorbed in the shallow ground waters resulting in these types of fluids. But Buhang hot spring of the Cl-HCO_3 type has a different origin.

The degree of chemical equilibration between geothermal fluids and rocks can be estimated using Na-K-Mg diagram (Giggenbach, 1988). All the hot springs from the BVC are plotted within the immature water region in Fig. 7. This means that there is no strong outflow of neutral Cl-rich deep waters in the area. Thus, it is difficult to estimate subsurface temperature using the hot springs from the area. On the other hand, a neutral and Cl-rich Naghaso hot spring from the

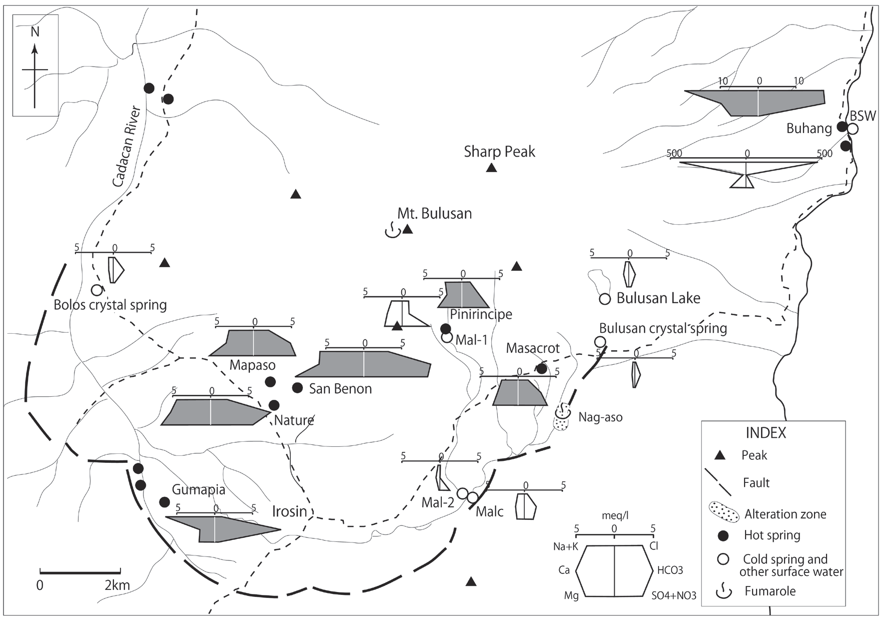

Fig. 6 Distribution of geochemical characteristics in and around Bulusan volcanic area, showing with hexadiagram. The abbreviations are the same in Table 1.

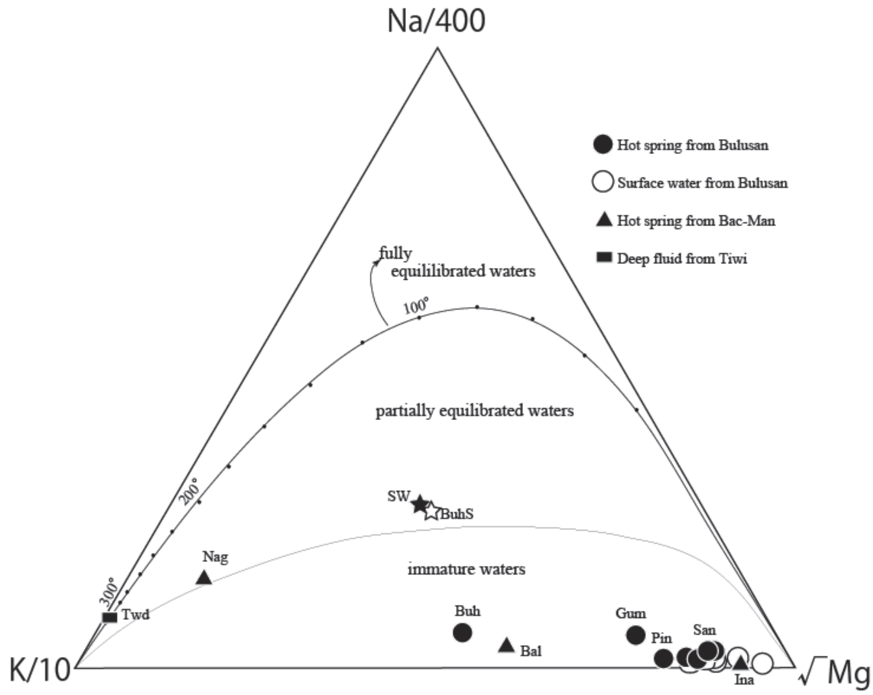

Fig. 7 Giggenbach's Na-K-Mg diagram of hot springs from the Bulusan volcanic area. Abbreviations are the same in Table 1. Samples from the Bac-Man and Tiwi geothermal fields are also shown.

BacMan geothermal field is plotted in a partially equilibrated water region suggesting reservoir temperature of about 260 ºC. This seems to be reflected by equilibration under the maximum reservoir temperature of 320 ºC reported by Ramos (2002). A deep water sample from the Tiwi geothermal field has almost the same relative Cl-SO_4-HCO_3 composition (Fig. 5) as the Buhang Hot spring. However, it suggests a very high reservoir temperature above 300°C as shown in Fig. 7; the value is concordant with reservoir temperature (Sugiaman, 2004). By comparing the Bulusan hot springs to the exploited geothermal fields in the Bicol volcanic arc, it is revealed that the lack of mature waters is one of the characteristics of hot springs from the BVC.

Isotopic composition of the hot springs from the BVC area is shown in Fig. 8. All of the hot springs with the HCO_3-SO_4 and HCO_3 types except Buhang (Cl-HCO_3 type) are on the same trend as the local meteoric waters such as spring, river and lake. This indicates that both types of water are largely originated from the surface or very shallow ground waters. This is concordant with the distribution of both types of hot springs and meteoric waters in the same area on Fig. 5. The hot spring from Buhang seems to be shifted slightly heavier in δ^{18}O. Delfin *et al*. (1993) also pointed out that the small oxygen shift (1 per mil) was found in the high Cl hot springs from the Bulusan area. However, there is another possibility in the formation of the Buhang hot spring, which is a mixing of CO_2-rich water of local meteoric origin and seawater as indicated in Fig. 8. The hot springs of higher Cl contents from the Bulusan volcanic area are Buhang (Cl=613 mg/l), and Naghaso (Cl=1145 mg/l) in the BacMan geothermal field (Table 1). These two hot springs clearly contain Br; 1.8 mg/l and 4.0 mg/l for Buhang and Naghaso, respectively. As shown in Table 2, seawater contains 67 mg/kg of bromide (Drever, 1988). Since the both hot springs are located very close to the shoreline, most of the Cl contents for Buhang and Naghaso can be explained as derived from seawater, provided that all of the bromide of the hot springs were supplied from seawater. Table 2 shows the concentration factors of major ions of the hot springs of Buhang, Naghaso and seawater collected from the hot spring beach at Buhang. The factor is defined by $(M/Cl)_{sp}/(M/Cl)_{sw}$, where M are ion species in sample (sp) and/or sea water (sw). The obtained concentration factors suggest that most of the components of Buhang hot spring are derived from seawater, to which CO_2-rich waters were added during circulation. Bubbling of CO_2 was observed everywhere along the Buhang hot spring beach, which resulted in a low pH=6.72 of local sea water, and also in a shift to lower δ^{18}O (Fig. 8). Probably calcium and potassium were also added by the same processes at Buhang. Similar circulation occurred at Naghaso hot pool in the BacMan geothermal field, but magnesium and sulfate were almost depleted. Such depletion was reported to occur during sea water

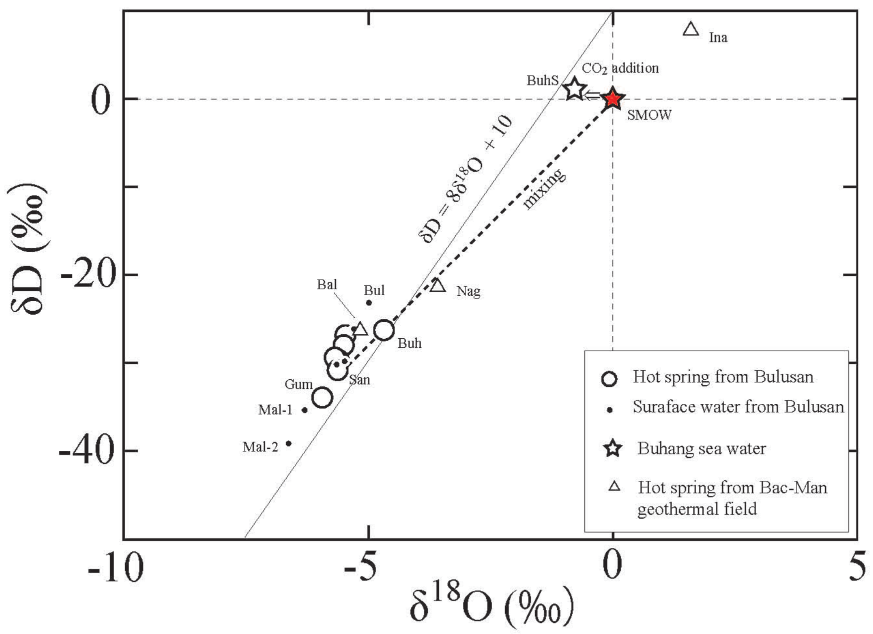

Fig. 8 δD and δ^{18}O compositions of hot springs from the Bulusan volcanic area. Abbreviations are the same in Table 1. SMOW: standard mean ocean water.

Table 2 Concentration factors of high-Cl hot spring and sea water from Bulusan volcanic area. The similar hot spring from the Bac-Man geothermal field are also shown.

Sp. No.	Seawater*	T110302-3	T110302-2	T110304-2
Location	(mg/kg)	Buhang SW	Buhang HS	Naghaso H P
Na^+(mg/l)	10760	1.05	1.16	1.04
K^+(mg/l)	399	1.06	6.32	3.71
Ca^{2+}(mg/l)	411	1.08	14.8	1.97
Mg^{2+}(mg/l)	1290	1.10	2.11	0.02
Cl^-(mg/l)	19350	1.00	1.00	1.00
Br^-(mg/l)	67	1.01	0.87	1.01
HCO_3^-(mg/l)	142	1.72	239	0.88
SO_4^{2-}(mg/l)	2710	1.01	0.27	0.14
*:averagdge seawater by Drever(1988), HS : hot spring, SW : seawater				
HP: hot pool				

circulation at higher temperatures (Bischoff and Dickson, 1975). Circulation at Naghaso is probably undergoing at higher temperatures compared to Buhang as indicated by large magnesium depletion.

Thus, the chemical characteristics and isotope data of Buhang hot spring suggest that the bicarbonate-rich chloride water (the Cl-HCO_3 type) was formed by mixing of sea water and CO_2-rich water which is of meteoric origin.

2. Acid river water

At the upstream of Malunoy River, river water (Mal-1) was sampled at an elevation of 390 m near Pirinincipe hot spring. At the Mal-1 sampling location, the water colored pale brown, and the pH was almost neutral at 7.4, but SO_4 was dominant in anion (Fig. 6). After sampling Mal-1, it began to heavy rain, and Malunoy river water (Mal-2) was collected as samples during a heavy down pour at a 90 m elevation. The heavy rain caused a small lahar at the upper stream, and rapid increased level of water, showing brown coloration (Appendix-8), and sounds of colliding boulders were heard. The Mal-2 sample is characterized by SO_4-rich water with acidic pH. This suggests that rain water dissolved volcanic gases which are absorbed on the surface of volcanic ashes, and resulted in acid river water. However, river water showed a neutral pH when the river was flowing smoothly at the time of Mal-1 sampling. Acidic pH of river water may occur when heavy rain erodes new pyroclastics, and waters may dissolve the volcanic gases which were in turn absorbed on the surface of grains of pyroclastics.

3. Monitoring of hot spring chemistry at San Benon

Bulusan volcano erupted from 6 November, 2010 to 13 May, 2011. We monitored the hot spring at San Benon to detect any precursor of the volcanic eruption of the volcano. The temperature, pH, chloride, sulfate ions, and isotopic composition of the water were monitored on 9 March, 2010 and 10 December, 2011. But unfortunately, we lack data for the early stage of 2010 eruptive activity; data during from 9 March, 2010 to 2 March, 2011). Rainfall was measured at the old Bulusan Volcano Observatory of PHIVOLCS at San Benon. The results of the chemical analyses are shown in Table 3 and rainfall data in Table 4, and are plotted on time scale in Fig. 9. Chloride and sulfate ions vary from 81 to 168 mg/l and 270 mg/l to 601 mg/l, respectively, and are directly proportional with each other. The variation seems to be due to rainfall; for example the maximum rainfall was

Table 3 Changes of chemical and physical properties of San Benon hot spring.

Date	Temp.(℃)	pH	Cl^-(mg/l)	SO_4^{2-}(mg/l)	δ ^{18}O(‰)	δ D(‰)
9-Mar-10	47.6	6.52	168	601	-5.5	-29
2-Mar-11	45.7	6.42	117	408	-5.6	-31
16-Mar-11	43.6	6.84	86.5	301	-5.4	-31
4-Apr-11	41.8	6.46	81.0	270	-5.4	-31
15-Apr-11	43.8	6.53	102	350	-5.5	-32
25-Apr-11	44.1	6.46	118	415	-5.5	-32
18-May-11	42.1	6.53	107	367	-5.5	-30
4-Jul-11	45.1	6.60	158	553	-5.5	-30
16-Jul-11	45.5	6.04	164	571	-5.5	-30
1-Aug-11	40.2	6.18	133	472	-5.6	-31
13-Sep-11	45.7	6.44	114	410	-5.9	-34
18-Oct-11	46.6	6.42	114	407	-5.9	-34
14-Nov-11	44.5	6.58	157	541	-5.5	-31
10-Dec-11	46.3	6.49	114	405	-5.9	-34

Table 4 Rainfall data at San Benon hot spring. Data was collected by PHIVOLCS.

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
2010	306	26	93	73	61	88	155	148	221	293	424	737
2011	1008	290	721	244	673	188	421	283	205	280	475	622
2012	660	494	Unit: mm									

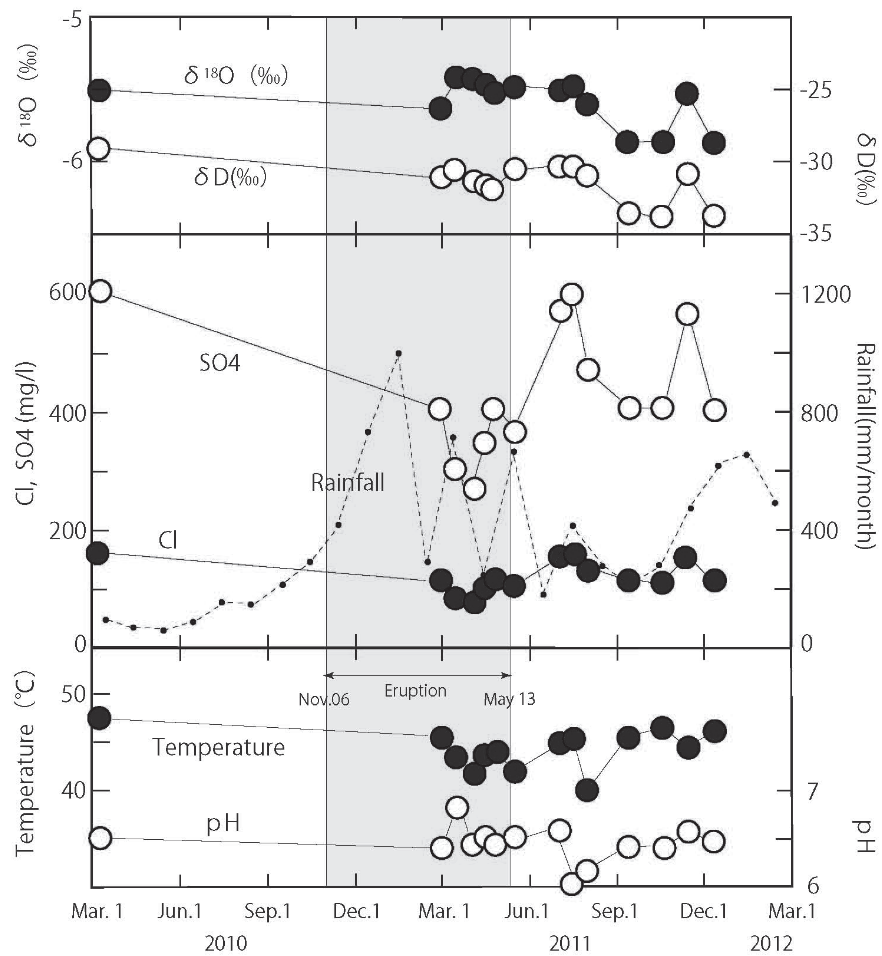

Fig. 9 Changes of physical and chemical characteristics of the San Benon hot spring.

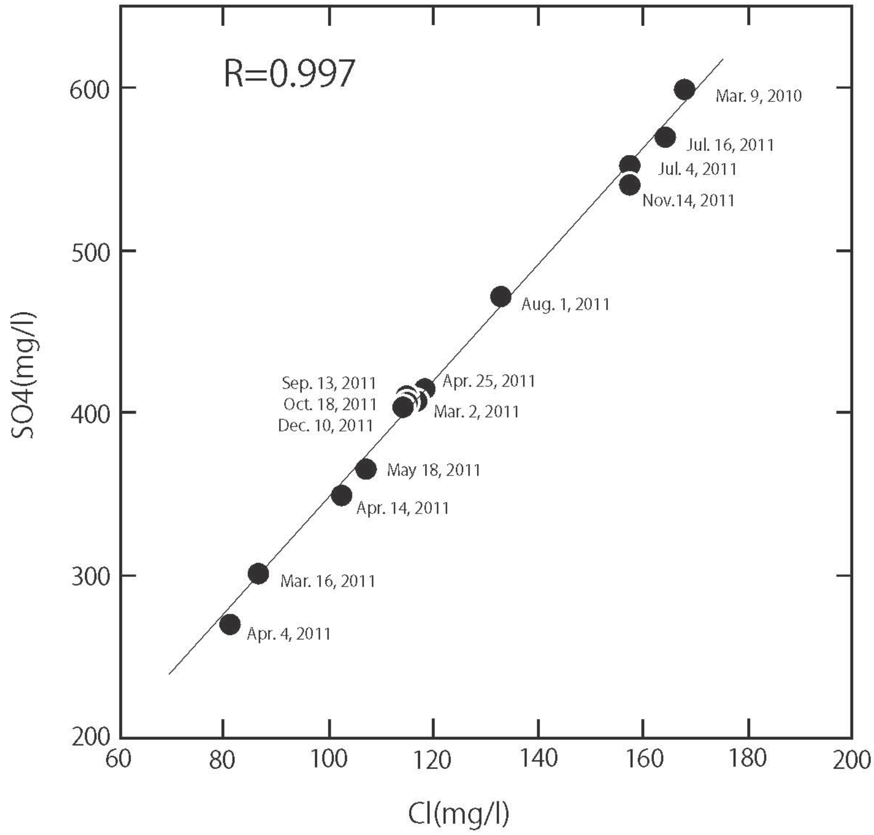

Fig. 10 Relation between the chloride and sulfate ions of hot spring from San Benon.

recorded in February 2011, and lower values of the components were measured on 4 April 2011. The Cl and SO_4 concentrations seem to have decreased two months later. Small rainfall in September 2011 appears to be responsible for increase of the chemistry in November 2011. But, temperature, pH, δD, δ^{18}O are sometimes dependent on the variations of chloride and sulfate ions. It is likely that these four parameters are affected by groundwater conditions, such as volume, residence time, evaporation, degree of reaction with rocks, and so on. The concentrations of chloride and sulfate ions are directly proportional with each other (Fig. 10). Both ions remarkably plot on the same regression line suggesting that the concentrations of chloride and sulfate ions are strongly affected by the mixing of groundwater in the area. Moreover, any deviation from this regression line was not observed during the latter half of the 2010 eruption. Although Aligan (2010) reported that the 2006-2007 phreatic explosion of Bulusan volcano brought changes on the Buhang, Masakrot, San Benon, and Mapasohot springs, we did not detect any variations in the volcanic activities. Based on these findings, chemical monitoring using chloride and sulfate ions at San Benon is not recommended.

Conclusion

The most of hot springs from the Irosin Caldera are of the HCO_3-SO_4 type with near neutral pH, maximum chloride content of 170 mg/l and the maximum temperature of 45°C, whereas hot springs of the remote from the volcanic center are of HCO_3 type. The Na, K, and Mg compositions of the all hot springs suggest immature water, and isotopically are of meteoric origin. Therefore, evaluation of subsurface temperature using chemical compositions is hard. On the other hand, Buhang hot spring is of Cl-HCO_3 type, and formed by mixing of CO_2-rich water with meteoric origin and sea water.

Acid pH of river water is formed by rain water dissolving volcanic gases originated from volcanic ashes on the surface.

Monitoring of chloride and sulfate ions was done at San Benon hot spring. The variation of the both ions is proportional with each other keeping the constant ratio of SO_4/Cl. This suggests the variation was caused by mixing of groundwater in the area. Moreover, any big change of the ratio was not observed during that the latter half of the 2010 eruption. Thus, chemical monitoring for precursor of eruption at San Benon is not recommended.

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（要　旨）

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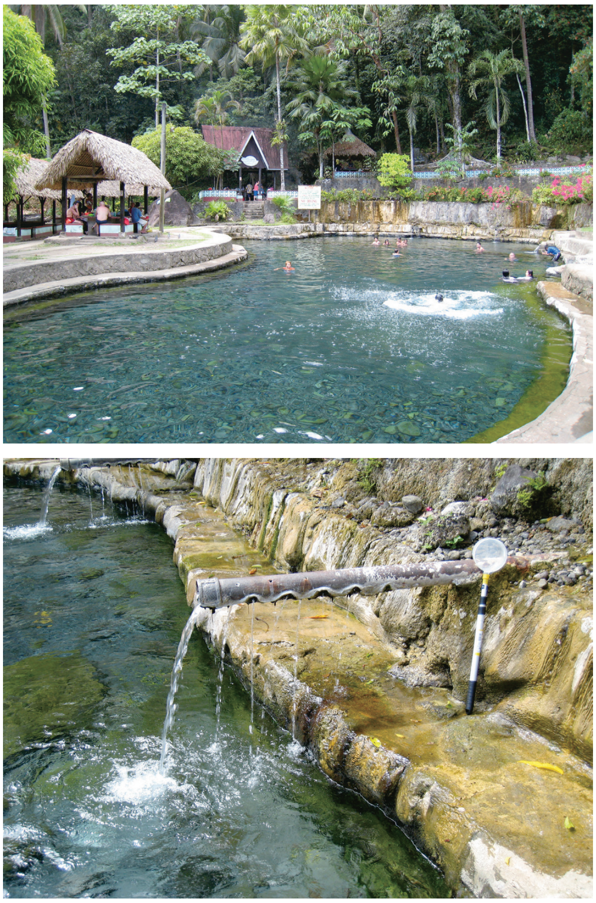
ブルサン火山はルソン島ビコール半島の最南端に位置する活火山である．フィリッピンは火山活動に伴う鉱物資源，すなわち斑岩銅鉱床や浅熱水性金鉱床に富んでいる．また，地熱発電も盛んで世界 2 位の地熱発電国である．地熱発電は全国で 7 か所で行われており，その設備容量は1900MWに達し，フィリッピンの電力供給の12%を占めている重要なエネルギー源である．ブルサン火山の北方の Bac-Man 地熱帯や Tiwi 地熱帯ではそれぞれ設備容量152MW，234MW の発電所が稼働している．

ブルサン火山周辺には多くの温泉が知られているが，具体的な化学的情報が報告されていないので，地熱資源の評価が困難な地域である．今回の調査で明らかになったことの一つには，この地域には成熟した中性の沸騰泉や，深部熱水の上昇部の上位にしばしば発達する加熱蒸気型の SO_4型の酸性泉が認められないことである．イロシンカルデラ内に分布する温泉の温度は高くても45℃程度である（San Benon）．また塩化物イオンも高くても170mg/l で，HCO_3型及び HCO_3-SO_4型のほぼ中性の温泉である．これらは，Na-K-Mg 比を用いた地下温度推定法では未成熟と判定される．イロシンカルデラ外の Bulusan 火山の東方の海岸沿いに位置する Buhang 温泉は，塩化物イオンは多いものの（613mg/l），それらの起源は温泉に含まれる Br や水の同位体比から海水と CO_2に富む水（温泉）の混合により生成したと推定され，塩化物イオンもほとんどは海水由来であると考えられる．また，Bac-Man 地熱帯の海岸近くのホットプール（Naghaso）も同様にしてできたものと考えられる．

イロシンカルデラ内で最も Cl 濃度が高い San Benon 温泉の Cl と SO_4についてモニタリングを行った．モニタリング期間中の Cl は81mg/l ～168mg/l と倍程度変動し，これに応じて SO_4も増減する．しかし，その比はほぼ一定で，これらの変動は浅所地下水の水の混入の増減によっていると考えられ，この温泉は噴火の前兆を観測によってとらえるには不向きの温泉であることが明らかとなった．



Appendix-1 San Benon hot spring. Top: the hot spring has been used for swimming pool. Bottom: sampling site is located at a front wall of the pool in the left photo (Taguchi et al., 2014).

Appendix-2 Mapaso hot spring. Top: Large amount of seeped hot spring water makes a hot spring stream(center in the photo). Local people use the hot spring as a place of bathing and laundry, separating a hot spring site from a hot spring stream with boulders (left half in the photo). Bottom: people are enjoying a private bath, which is easily constructed along the stream, because hot spring is discharging everywhere about 100m along an edge of lava (Taguchi et al., 2014).

Appendix-3 Pinirincipe hot spring discharging from the highest elevation (415 m) among the known hot springs in the Bulusan volcanic area (Taguchi et al., 2014).

Appendix-4 Masacrot warm spring. The spring is discharging from a NW-trending crack in pyroclastics of Bulusan volcanics, and a pool was made by digging the pyroclastics (Taguchi et al., 2014).

Appendix-5 Buhang hot spring. Top: hot spring is discharging from many sites along a shore line more than 100 m in width, and flowing to the sea. Bubbling gas is also observed at many places in the sea along the coast. Along the flow root, orange materials of iron hydrooxisides are precipitated. Bottom: sampling site of hot spring (Taguchi et al., 2014).

Appendix-6 Bolos crystal spring. Local peoples are using as a washing place (Taguchi et al., 2014).

Appendix-7 Malunoy river to the Pinirincipe hot spring, close to the sampling point of Mal-1. Big boulders and trees deposited by newly occurred lahar were distributed on the river bed.

Appendix-8 Brown water of Malunoy River during a small lahar on March, 2012 at a elevation about 90m.

Appendix-9 Inang Mahareng hot spring in a steaming ground, Bacon-Manito geothermal field.

Appendix-11 Balbagon hot spring, Bacon-Manito geothermal field. Hot spring temperature is 63.1°C, and pH 7.14.

Appendix-10 Naghaso hot pool with 70m long and 25m wide, Bacon-Manito geothermal field.