A Geochemical Study on the Hot Springs in Peru

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Abstract

Twenty-four hot spring waters collected from five districts, Arequipa, Cajamarca, Cuzco and Lima in Peru were analyzed for chemical constituents as well as isotopic compositions of hydrogen and oxygen to present geochemical characteristics of these hot spring and to discuss the origins of chemical constituents. Excepting the Lima district located in the coastal region, these hot springs are situated in the cordilleran region at elevation of 2000 to 3000 meters. Three hot spring waters in Lima district are concluded to be formed by evaporation of sea water. It can be concluded that the chemical constituents of hot spring waters in the cordilleran region are originated from the interaction of CO_2 bearing meteoric water with rocks and the dissolution of salt such as halite.

Introduction

In Peru, about 300 hot springs are registered by the government agency[1)], most of which are situated in the cordilleran zone as shown in Fig. 1, if Peru is roughly devided into three topographic zones from east to west, i. e. coastal zone along the Pacific Ocean, cental cordilleran zone and Amazon jungle[2)]. These hot springs are mostly located in close vicinity to Andean volcanoes in the Cenozoic[3)]. Few researches have been performed about the Peruvian hot springs, and about 80 % of the hot springs lack reliable chemical data. Although Yano[4)] reported the outlines of hot springs in South America, his report did not include Peruvian hot springs. The authors (Imahashi and Takamatsu) had an opportunity for investigating some hot springs in Peru and collected 23 water samples from 5 districts; one is in the coastal zone and the others in the

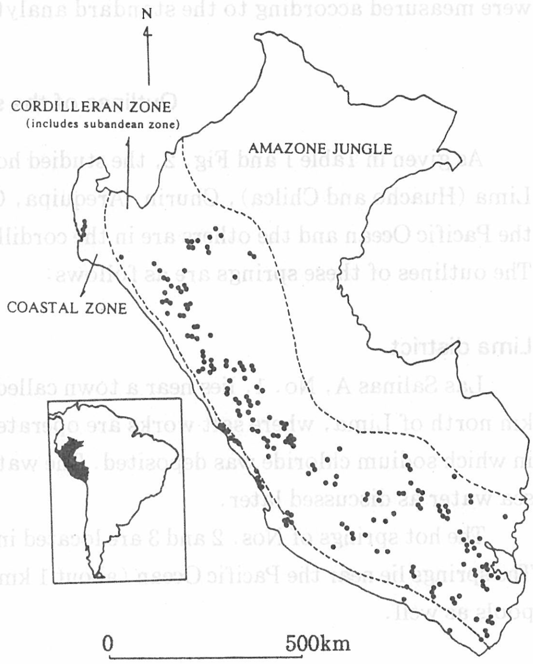

Fig. 1 Locations of main hot springs in Peru

cordilleran zone. The purpose of this study is to present geochemical characteristic of these hot springs and then the origins of dissolved constituents as well as the water are briefly discussed.

Analytical methods

Sampling locations are given in Fig. 2 and the numbers of the samples coincide with those in Table 1. Twenty-three water samples were collected in the summer of 1990 and one sample of No. 24 was collected in the fall of 1990 by a Professor of Cajamarca University and sent to us.

The measurement of water temperature, pH, alkalinity and dissolved carbon dioxide were carried out in the fields. Precipitates and odor were inspected as well. Temperature and pH were measured with a thermister thermometer and a glass electrode pH-meter, respectively. Some water samples were filtered through No. 1 paper filters before storing in plastic bottles.

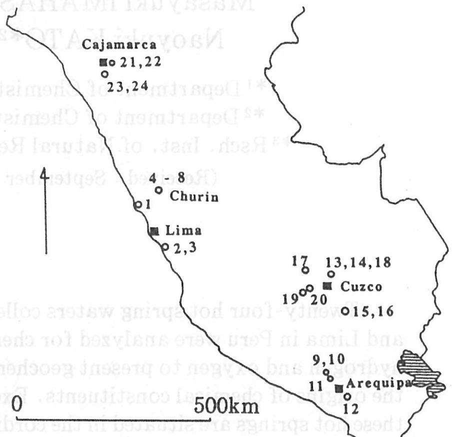

Fig. 2 Map and numbers of sampling locations

The amounts of alkalinity (bicarbonate ions) and dissolved carbon dioxide were determined by titrating with hydrochloric acid and sodium hydroxide solutions, respectively. Some waters contained slight amounts of hydrogen sulfide, though it is not discussed in this paper. The major and minor chemical components of the hot spring waters were measured according to the standard analytical method of hot spring water.

Outlines of the studied springs

As given in Table 1 and Fig. 2, the studied hot spring waters are collected from five districts; Lima (Huacho and Chilca), Churin, Arequipa, Cuzco and Cajamarca. The first is in desert near the Pacific Ocean and the others are in the cordilleran region at elevation of 2000 to 3000 meters. The outlines of these springs are as follows:

Lima district

Las Salinas A, No. 1, lies near a town called Huacho located in the coastal region about 100 km north of Lima, where salt works are operated. The spring water formed several large pools in which sodium chloride was deposited. The water is considered to be formed by evaporation of sea water as discussed later.

The hot springs of Nos. 2 and 3 are located in the town of Chilca about 70 km south of Lima. The springs lie near the Pacific Ocean (about 1 km to the coast). The spring waters formed several pools as well.

Table 1 Name, locations, temperature and pH of the hot spring waters

No.	Name	Location	District	Date	Tw ℃	pH
1	Las Salinas A	Huacho	Lima	July 18,90	21.3	7.28
2	Las Salinas B, No.1	Chilca	Lima	Aug. 6,90	19.1	8.60
3	Las Salinas B, No.2	Chilca	Lima	Aug. 6,90	19.3	9.21
4	Banos de la Esperanza	Churin	Churin	July 20,90	33.7	7.02
5	Banos de la Cabanita	Churin	Churin	July 20,90	34.1	6.71
6	Banos de la Juventud	Churin	Churin	July 20,90	31.9	6.75
7	Banos del Fierro	Cabra Cancha	Churin	July 21,90	49.5	6.08
8	Banos del Cobalt	Churin	Churin	July 21,90	31.1	6.91
9	Agua Mineral de Socosani 1	Socosani	Arequipa	July 26,90	26.0	6.27
10	Agua Mineral de Socosani 2	Socosani	Arequipa	July 26,90	31.2	6.32
11	Banos de Yura	Yura	Arequipa	July 26,90	32.5	6.56
12	Agua Mineral de Jesus	Jesus	Arequipa	July 27,90	23.3	5.83
13	Minas Mocco	Calca	Cuzco	July 29,90	18.0	6.51
14	Banos de Machacancha	Calca	Cuzco	July 29,90	36.8	6.34
15	Agua Medicinal Marcani	San Pedro	Cuzco	July 30,90	18.2	6.33
16	Banos de Caylla	San Pedro	Cuzco	July 30,90	22.6	6.41
17	Aguas Calientes	Urubanba	Cuzco	July 31,90	42.7	6.30
18	Banos de Qaqato Lamay	Lamay	Cuzco	Aug. 2,90	21.6	6.58
19	Banos de Qonoc	Curahusi	Cuzco	Aug. 3,90	33.0	7.28
20	Aguas Termales de Saucera	Limatambo	Cuzco	Aug. 3,90	36.5	6.34
21	Banos del Inca	Cajamarca	Cajamarca	Aug. 8,90	74.2	6.68
22	Banos de Jesus	Jesus	Cajamarca	Aug. 8,90	28.8	6.70
23	Agua Mineral de Yumagual	San Juan	Cajamarca	Aug. 9,90	51.7	6.54
24	Aguas Calientes de la Grama	San Marcos	Cajamarca	——	42.3	6.3

Churin district

The hot springs of Nos. 4, 5, 6 and 8 are in the town of Churin located about 200 km away from Lima (Fig. 2) at elevation of about 2200 meters. There are several hot springs in the town. The hot spring of No. 7, Banos de Fierro, is separately located about 4 km west of the center of Churin. A large amount of iron precipitates was deposited in a small pond of the No. 7 hot spring. The temperatures of the hot springs in this area were relatively high and the highest value of 57.7℃ was recorded in a spring named Banos de Salud about 1 km away from Banos de Fierro, though that hot spring was not studied this time.

Arequipa district

The city of Arequipa is about 1000 km south of Lima (Fig. 2) at elevation of about 2300 meters. There are some volcanoes in the district, for instance, Mt. Misti which is 5822 meters high. The hot springs of Nos. 9 and 10 are located at Socosani in the town of Yura. These springs are in the factory of drinking mineral water. The distance between No. 9 and No. 10 is ten odd meters. The hot spring of No. 11 lies near Yura and No. 12 is located at Jesus about 9 km away from the city of Arequipa, respectively.

Cuzco district

The hot springs of Nos. 13 to 20 are scattered over a wide area around the city of Cuzco located at elevation of about 3400 meters. The hot springs of Nos. 13 and 14 are located in the town of Calca and the water gushed out from a bank of the Vilcanota river. The hot springs of Nos. 15 and 16 are located at San Pedro about 100 km away from Cuzco. Iron precipitate was deposited at the edge of pool of No. 15. The hot spring of No. 17, Aguas Calientes, is located at Machu Picchu about 100 km away from Cuzco. The water flowed into pools from a bank of the Urubanba river. The hot springs of Nos. 18 and 19 are located in the town of Lamay and Curhuasi about 70 odd kilometers away from Cuzco, respectively. The hot spring water of No. 19 gushed out from a bank of the Apurimac river. The hot spring of No. 20 is located in the town of Limatambo and the water flowed into a small pond from the foot of a mountain. Some salt, NaCl and the like, was deposited at the edge of pond and iron precipitate was deposited along the stream flowing out of the pond.

Cajamarca district

Cajamarca lies about 860 km north of Lima at elevation of about 2000 meters. The hot spring of No. 21 is located in the town of Banos del Inca about 6 km away from the center of Cajamarca city. The hot spring of No. 22 is located in the town of Jesus about 20 km far from Cajamarca city. The water flowed into a pond leading to the bath in a small cabin surrounded by the woods. The hot spring of No. 23 is located at San Juan about 30 km away from Cajamarca. The water gushed out from a bank of the river of Jequetepeque and flowed down the river. A small amount of iron precipitate was observed. Little is known about the location of hot spring water of No. 24, because the water was not collected by us.

Results

The temperatures of spring water range from 18.0 to 74.2℃ as given in Table 1. The highest was Banos del Inca (No. 21) at Cajamarca. Fairly high temperatures were also observed at Churin and Cuzco. The pH values range from 5.83 to 9.21, though most of the values are between 6 and 7. The hot springs of high salinity and low dissolved carbon dioxide content at Lima as well as at Cuzco are of relatively high pH values.

The major chemical compositions are given in Table 2, and the equivalent percentages of cations (Na, K, Ca and Mg) and anions (Cl, SO_4 and HCO_3) are shown in Table 3. The chemical type of water is also shown in Table 3 as a combination of dominant cations and anions. Three hot springs in Lima district are highly saline and of Na-Cl type. In the cordilleran area, Aguas Termales de Saucera (No. 20) in Cuzco district is highly saline, and most of the others (Nos. 13, 15, 16 and 17) in Cuzco district as well as Agua Mineral de Jesus (No. 12) in Arequipa district are rather saline. Those hot springs are also of Na-Cl type. On the contrary, hot springs of low salinity in Churin, Arequipa, Cajamarca as well as Cuzco districts are of Na-Ca (Mg) -HCO_3 or Na-Ca (Mg) -SO_4-HCO_3 types as given in Table 3.

The Li, Br and Sr contents as well as their ratios to Na, Cl and Ca, respectively, are shown in Table 4. The highly saline hot springs in Lima (Nos. 1 to 3) and also Cuzco districts (Nos. 19 and 20) have Li/Na ratios almost the same as sea water, while the others have ratios about 100-

Table 2 The amounts of major chemical constituents of the hot spring waters (mg/L)

No.	Na	K	Ca	Mg	Cl	SO_4	HCO_3	CO_2
1	91200	6050	218	20130	187000	20000	268	241
2	30500	1440	55.8	892	40000	11200	1037	0.0
3	8560	488	46.7	481	11700	4110	625	0.0
4	108	12.0	281	35.2	130	510	463	138
5	109	12.8	279	32.5	132	504	481	164
6	94.1	10.7	271	36.6	109	503	441	159
7	303	50.6	145	63.0	427	470	351	334
8	100	12.0	258	38.5	111	510	410	98
9	134	9.02	113	82.8	78.5	160	799	620
10	270	23.2	160	130	192	108	1574	810
11	204	19.1	140	93.4	139	2.6	1235	790
12	443	44.1	120	46.7	765	151	308	565
13	3570	147	563	137	5730	634	1552	893
14	485	47.2	374	84.1	350	715	1410	396
15	1510	45.5	546	116	2880	234	1458	768
16	1510	48.5	432	124	2570	266	1193	805
17	943	94.6	144	16.5	1560	145	323	171
18	146	27.3	335	97.2	132	579	1003	348
19	519	11.1	321	84.8	806	926	319	22
20	29000	147	2664	283	47500	1760	134	52
21	93.6	8.62	46.8	5.29	89.2	74.4	186	66
22	3.29	0.78	2.0	0.71	1.50	4.46	12.5	22
23	12.3	2.92	4.6	0.62	6.55	4.23	41.5	22
24	87.3	9.44	5.0	0.54	106	65.9	0.0	8.5

Table 3 The equivalents of major chemical constituents of the hot spring waters

No.	Cation (meq%)				Total (meq/L)	Anion (meq%)			Total (meq/L)	Type
	Na	K	Ca	Mg		Cl	SO_4	HCO_3		
1	69	2.7	0.2	29	5790	93	7.3	0.1	5695	Na-Mg-Cl
2	92	2.6	0.2	5.1	1440	82	17	1.2	1378	Na-Cl-SO_4
3	87	2.9	0.6	9.3	426.7	78	20	2.4	425.8	Na-Cl-SO_4
4	21	1.4	64	13	21.94	17	49	35	21.88	Ca-Na-SO_4-HCO_3
5	22	1.5	64	12	21.64	17	48	36	22.09	Ca-Na-SO_4-HCO_3
6	20	1.3	65	14	20.88	15	50	35	20.77	Ca-Na-SO_4-HCO_3
7	49	4.8	27	19	26.89	44	36	21	27.57	Na-Ca-Cl-SO_4
8	21	1.5	62	15	20.70	15	52	33	20.47	Ca-Na-SO_4-HCO_3
9	32	1.2	31	37	18.52	12	18	70	18.63	Mg-Na-HCO_3
10	38	1.9	26	35	31.05	17	0.7	82	31.44	Na-Mg-HCO_3
11	37	2.0	29	32	24.03	16	0.2	84	24.21	Na-Mg-HCO_3
12	64	3.8	20	13	30.24	73	11	17	29.77	Na-Ca-Cl
13	78	1.9	14	5.7	198.4	81	6.6	13	200.3	Na-Cl
14	44	2.5	39	15	47.88	21	31	48	47.87	Na-Ca-HCO_3-SO_4
15	65	1.1	25	8.9	108.0	74	5.7	20	110.0	Na-Ca-Cl-HCO_3
16	67	1.3	22	10	98.64	74	5.7	20	97.58	Na-Ca-Cl-HCO_3

17	79	4.7	14	2.6	51.98	84	5.8	10	52.31	Na-Cl
18	20	2.2	53	25	31.75	12	37	51	32.21	Ca-Mg-HCO_3-SO_4
19	49	0.6	35	15	45.87	48	41	11	47.24	Na-Ca-Cl-SO_4
20	89	0.3	9.4	1.6	1421	97	2.6	0.2	1379	Na-Cl
21	58	3.1	33	6.2	7.07	35	22	43	7.12	Na-Ca-HCO_3-Cl
22	44	6	31	19	0.32	12	27	61	0.33	Na-Ca-HCO_3-SO_4
23	61	8	26	5	0.89	19	9	72	0.95	Na-Ca-HCO_3
24	88	5.5	5.8	9	4.33	69	31	—	4.36	Na-Cl-SO_4
SW	77	1.7	3.4	18	609.2	91	9.3	—	612.7	Na-Cl

SW = Sea water

Table 4 The Br, Li and Sr contents, weight ratios of the elements and values of δD and δ^{18}O

No.	Li (mg/L)	Br (mg/L)	Sr (mg/L)	Li/Cl ($\times 10^3$)	Li/Na ($\times 10^3$)	Br/Cl ($\times 10^3$)	Sr/Ca ($\times 10^2$)	δD (per mill)	δ^{18}O (per mill)
1	2.73	1060	4.26	0.015	0.030	5.67	1.95	−7.7	+1.6
2	0.458	133	1.19	0.011	0.015	3.33	2.13	−3.4	+2.1
3	0.166	39.5	0.61	0.014	0.019	3.38	1.31	−2.7	+2.4
4	1.11	0.269	4.48	8.54	10.3	2.07	1.59	−94.4	−13.5
5	1.11	0.270	4.90	8.41	10.2	2.05	1.76	−97.1	−13.5
6	0.930	2.19	5.15	8.53	9.88	2.19	1.90	−98.5	−13.6
7	3.79	0.985	2.49	8.88	12.5	2.31	1.72	−90.5	−12.3
8	0.990	0.258	4.34	8.92	9.90	2.32	1.68	−98.3	−13.7
9	0.170	0.276	0.850	2.17	1.27	3.52	0.750	−96.3	−13.9
10	0.389	0.684	1.52	2.03	1.44	3.56	0.948	−97.2	−14.1
11	0.266	0.489	1.29	1.91	1.30	3.52	0.922	−97.6	−13.9
12	1.62	1.57	2.06	2.12	3.66	2.05	1.71	−73.2	−10.7
13	7.82	4.55	11.9	1.36	2.19	0.794	2.11	−113.7	−15.2
14	2.28	1.26	6.33	6.51	4.70	3.60	1.69	−120.1	−16.5
15	2.82	1.28	7.04	0.979	1.87	0.444	1.41	−122.1	−15.9
16	2.87	1.14	6.09	1.12	1.90	0.444	1.41	−122.1	−15.9
17	4.19	1.88	5.77	2.69	4.44	1.21	4.01	−94.1	−13.6
18	0.840	0.361	4.14	6.36	5.75	2.73	1.24	−114.5	−15.4
19	0.191	0.286	4.08	0.237	0.368	0.355	1.27	−109.3	−14.9
20	2.03	13.7	67.8	0.043	0.070	0.288	2.54	−105.1	−13.8
21	0.268	0.273	0.83	3.00	2.86	3.06	1.77	−78.7	−11.4
22	—	—	—	—	—	—	—	−78.1	−10.7
23	0.043	0.026	0.099	6.56	3.50	4.00	2.15	−69.7	−9.7
24	0.305	—	—	2.88	3.49	—	—	—	—
SW	0.15	73.4	7.28	0.0076	0.016	3.73	1.75	—	—

SW = Sea water

1000 times higher than the sea water value. The Br/Cl ratios are nearly the same as or little lower than the sea water value, except for No. 1 in Lima district, of which ratio is higher than the sea water value, and also the Na-Cl type ones in Cuzco district (Nos. 15, 16, 19 and 20), of which ratios are much lower than the sea water value (Table 6). The Sr/Ca ratios are mostly similar to the sea water value, except for three hot springs in Arequipa district (Nos. 9, 10 and 11), characterized

Table 5 Values of δD and $\delta^{18}O$ for some surface waters in Peru (per mill)

Name	δD	$\delta^{18}O$
Oyon River, Churin	−103.1	−14.2
Stream, Yumina, Arequipa	−68.6	−10.2
Vilcanota River, Cuzco	−109.1	−14.7
Stream, Tambomachai, Cuzco	−119.7	−16.2
Jequetepeque River, Cajamarca	−65.6	−9.3

Table 6 Equivalent ratios of some elements for NaCl-type hot spring waters

No.	Na/Cl	K/Cl ×100	Ca/Cl ×100	Mg/Cl ×100	Mg/K	Br/Cl ×1000	SO_4/Cl ×100	Na/K
1	0.752	2.9	0.21	31.4	10.7	2.52	7.89	25.6
2	1.18	3.3	0.25	6.51	1.99	1.48	20.7	36.1
3	1.13	3.8	0.71	12.0	3.17	1.50	25.9	29.8
12	0.893	5.2	27.8	17.8	3.40	0.91	14.5	17.1
13	0.961	2.3	17.3	6.96	2.99	0.35	8.17	41.3
15	0.808	1.4	33.5	11.7	8.24	0.20	5.99	56.4
16	0.906	1.7	29.7	14.0	8.21	0.20	7.63	52.9
19	0.993	1.2	70.5	30.7	24.6	0.16	84.7	79.5
20	0.942	0.28	9.93	1.74	6.19	0.13	2.73	335
SW	0.863	1.8	3.73	19.6	10.8	1.51	10.3	47.4
DS	0.160	2.6	15.2	68.3	25.6	12.9	0.07	6.01
GL	0.957	0.29	0.77	15.5	53.2	0.32	8.23	328

SW=Sea water, by Sonnenfeld[14].
DS=Dead Sea (Israel), determined by the present authors.
GL=Great Salt Lake (USA), determined by the present authors.

by Mg-rich HCO_3 type.

In Table 4, hydrogen and oxygen isotopic ratios of water (δD and $\delta^{18}O$ relative to SMOW) are also given, and their relationships are shown in Fig. 3. Excepting three hot spring in Lima district, the relationships well fit the meteoric water line[5], and the range of δ values coincides with the range of meteoric water in the studied areas (Table 5). The δD values of three hot springs at Lima are fairly close to that of sea water, while the $\delta^{18}O$ are about 2 per mills higher than that of sea water as shown in Fig. 3.

Discussion

From the hydrogen and oxygen isotopic ratios of hot spring waters in the cordilleran area, the origin of water is considered to be local meteoric water (Fig. 3 and Tables 4 and 5). On the contrary, the hot springs in Lima district are highly saline and their δD and $\delta^{18}O$ are similar to those of sea water. These facts suggest their sea water origin. Las Salinas A (No. 1) is characterized by Cl content about 10 times as high as that of sea water, and the chemical composition is lower in Na/Cl and Ca/Cl ratios, while higher in K/Cl and Mg/Cl than those of sea water (Table 6). According to the experimental study on salt precipition during evaporation of sea water by

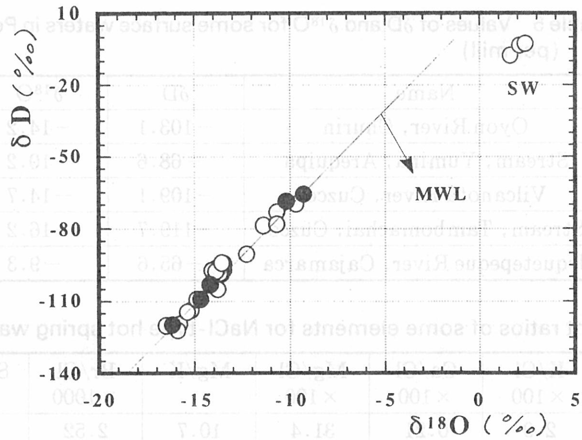

Fig.3 Relationship between δD and $\delta^{18}O$
SW=Sea water, MWL=Meteoric water line by Craig[8].
○=hot spring water, ●=Surface water.

MaCaffrey et al.[6], following the precipitation of calcium carbonate and calcium sulfate, sodium chloride (halite) starts precipitating when the chloride concentration reaches 10.6 times the concentration of sea water. And in the progress of evaporation, Na/Cl ratio is decreasing as the result of removing of NaCl, while K/Cl and Mg/Cl ratios are increasing, or Mg/K ratio is unchanged, till the start of Mg and K bearing salts precipitation. The chemical composition of No. 1 can be explained as a result of such evaporation of sea water, for instance, Mg/K ratio of the water is 10.7 and agrees with the value of sea water (10.8). The value of Na/Cl ratio (0.752) of the hot spring water corresponds to the value when about 50 % of the orginal Na ion are precipitated. Moreover, the Br/Cl ratio of the hot spring water is higher than that of sea water (Table 6), and consistent with the fact that Br is enriched in the residual sea water durig evaporation of sea water, because Br ions can be slightly incorporated into halite[7]. Much more progress of this process can be seen in the Dead Sea (Israel), which has a very high Br/Cl ratio as given in Table 6. The hydrogen and oxygen isotopic ratios of hot spring water should be controlled by evaporation accompanied with isotopic exchange with atmospheric moisture[8], as observed in Antarctic saline lakes[9] or in crater lakes in Japan[10].

The other two hot springs (Nos. 2 and 3) in Lima district are also saline, and the Cl concentration of No. 2 is about twice as high as sea water, while that of No. 3 is about two thirds of sea water concentration. Although the concentrations of both hot springs are different from each other, their compositions are quite similar. The Br/Cl and Li/Na ratios of these hot springs are almost the same as those of sea water (Table 4). From these facts, it is inferred that No. 2 is a concentrated sea water by evaporation and the No. 3 is a dilution of concentrated sea water as No. 2. However, the cation compositions of these waters are fairly different from that of sea water, and enriched in Na and K and slightly in Ca and Mg. This may be ascribed to some modification of cation composition by dissolution of sodium sulfate as well as removal of calcium carbonate, calcium sulfate and magnesium carbonate, because the hot springs are relatively higher in SO_4, HCO_3 and pH than sea water. The isotopic ratios of these water are quite similar to those of No. 1, and may be controlled by the same evaporation process mentioned above.

In the cordilleran area, No. 20 in Cuzco district is highly saline and the Cl content is little higher than that of No. 2 in Lima district (Table 2). The composition of No. 20 are that almost all of anion is Cl, and 90% of cation is Na and the rest is Ca and also that the Br/Cl and Li/Na ratios are much lower than those of sea water. Because such a chemical composition is typical of saline water formed by dissolution of halite deposit[11] as observed at Great Salt Lake (Table 6 and Fig. 4), the salts of No. 20 are considered to come from halite deposit.

The other hot springs of Na-Cl type (Nos. 13, 15, 16 and 19) have also low Br/Cl ratios, and the origin of Cl should be of halite deposit (Fig. 4). However, Li/Na ratios ($1.9-3.7\times10^{-3}$) are much higher than that of sea water and in the range of crustal rocks ($0.5-3.5\times10^{-3}$)[12]. This strongly suggests that the cation compositions of these hot spring waters are controlled by interaction with rocks. Although it is not obvious why No. 20 only has not been subjected to the interaction with rocks, it is possible that meteoric water is quickly circulating.

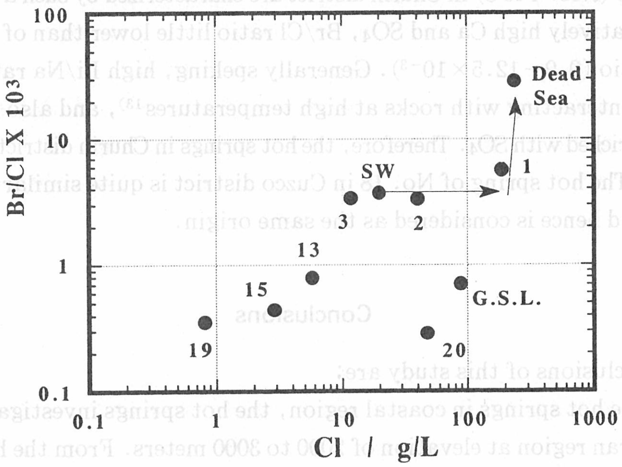

Fig.4 Relationship between Cl contents and Br/Cl ratios
SW=Sea water, G.S.L.=Great Salt Lake (USA).
The arrow indicates the evaporation process of sea water.

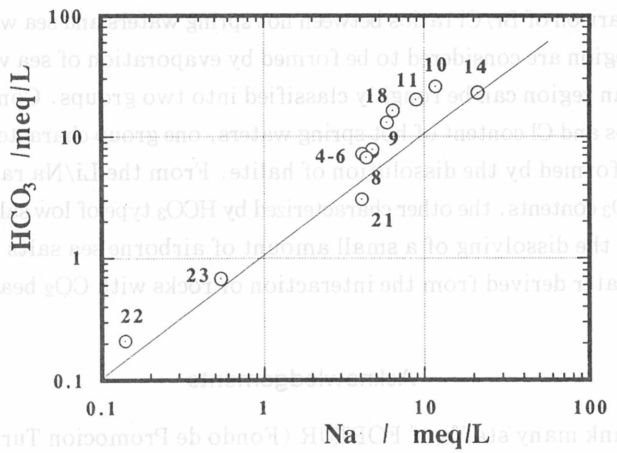

Fig.5 Relationship between Na and HCO_3 contents of HCO_3-type hot spring water

In the case of HCO_3 type in Arequipa (Nos. 9 to 11), Cajamarca (Nos. 21 to 23) and also Cuzco (Nos. 14 and 18) district, the Br/Cl ratios are close to the sea water value, and the sea salts origin is inferred. The Li/Na ratios, however, are in a range of $1-5\times10^{-3}$, and with in the range of crustal rocks. This Li/Na ratio may be ascribed to some reaction between CO_2 bearing meteoric water and rocks. Figure 5 shows the correlation between Na and HCO_3 (alkalinity) contents of the HCO_3 type waters including Churin district. Generally the reaction of rocks or aluminosilicates with a CO_2 bearing water causes a sodium or calcium hydrogen crabonate solution. Hence, the HCO_3 type waters are considered to be formed as follows: a large amount of HCO_3 type water is derived from the interaction of rocks with CO_2 bearing meteoric water and then a small amount of airborne sea salts is dissolved in the water, because the Cl content of these waters is less than one third of total anions. Fairly high saline hot springs (Nos. 12 and 17) have intermediate Br/Cl ratios and a part of Cl may be of the halite origin.

Five hot springs (Nos. 4 to 8) in Churin district are characterized by such a chemical composition as low salinity, relatively high Ca and SO_4, Br/Cl ratio little lower than of the sea water value, and high Li/Na ratio ($9.9-12.5\times10^{-3}$). Generally speking, high Li/Na ratio is expected about geothermal water interacting with rocks at high temperatures[13], and also geothermal water of volcanic origin is enriched with SO_4. Therefore, the hot springs in Churin district are possibly involved volcanic activity. The hot spring of No. 18 in Cuzco district is quite similar to the hot springs in Churin district, and hence is considered as the same origin.

Conclusions

The major conclusions of this study are;

(1) Excepting three hot springs in coastal region, the hot springs investigated in this study are situated in cordilleran region at elevation of 2000 to 3000 meters. From the hydrogen and oxygen isotopic ratios of hot spring waters in the cordilleran region, the origin of water is considered to be local meteoric water. The isotopic ratios for the spring waters in the costal region suggest their sea water origin.

(2) From the comparison of Br/Cl ratios between hot spring waters and sea water, three hot spring waters in coastal region are considered to be formed by evaporation of sea water. The hot spring waters in cordilleran region can be roughly classified into two groups. Considering the relation between Br/Cl ratios and Cl content of hot spring waters, one group characterized by high salinity is considered to be formed by the dissolution of halite. From the Li/Na ratios and the relation between Na and HCO_3 contents, the other characterized by HCO_3 type of low salinity can be concluded to be originated by the dissolving of a small amount of airborne sea salts with a large amount of local meteoric water derived from the interaction of rocks with CO_2 bearing waters.

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