

Hydrothermal system of the Papandayan Volcano, West Java, Indonesia and its geochemistry evolution of thermal water after the November 2002 eruption

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ABSTRACT

Papandayan is a strato volcano situated in West Java, Indonesia. After the last magmatic eruption in 1772, only few phreatic explosions have been occurring. At the present time, the activity is centered in the northeast crater manifested by the presence of fumaroles and hot springs. In November 2002 an explosive eruption occurred and ejected ash and altered rocks. Study of the altered rocks revealed that an advanced argillic alteration took place in the hydrothermal system by an interaction between acid fluids and rocks. Four zones of alteration have been formed as a limited extension along faults or across permeable structures at different levels beneath the active crater of the volcano.

Two types of acid fluids are distinguished in the crater of the Papandayan Volcano: (1) acid sulphate-chloride water with pH values between 1.6 and 4.6, and (2) acid sulphate water with pH values between 1.2 and 2.5. The samples collected after the eruption revealed an increase in the SO_4/Cl and Mg/Cl ratios. This evolution is likely explained by an increase in the neutralization of acid fluids which tends to show that water-rock interactions were more significant after the eruption. The changes in chemistry observed in 2003 were the consequence of the opening of new fractures where unaltered or less altered volcanic rocks were in contact with the ascending acid water. The high $\delta^{34}\text{S}$ values (9-17‰) observed in the acid sulphate-chloride water before the November 2002 eruption suggest that dissolved sulphates were mainly formed by the disproportionation of magmatic SO_2 . On the other hand, the low $\delta^{34}\text{S}$ values (-0.3-7 ‰) observed in acid sulphate-chloride water sampled after the eruption suggest that the origin of dissolved sulphates for these waters is the surficial oxidation of hydrogen sulphide.

Keywords: Papandayan Volcano, phreatic eruption, hydrothermal system, fluid geochemistry, advanced argillic alteration

SARI

Papandayan adalah gunung api strato yang terletak di Jawa Barat, Indonesia. Setelah erupsi magmatik terakhir pada 1772, letusan yang terjadi hanyalah bersifat freatik. Pada saat ini, kegiatan vulkanik terpusat pada kawah sebelah timur laut berupa fumarola dan mata air panas. Pada November 2002, terjadi letusan eksplosif yang memuntahkan abu dan batuan alterasi. Studi batuan alterasi menunjukkan bahwa perkembangan alterasi argilik yang terjadi dalam sistem hidrotermal merupakan interaksi antara cairan asam dengan batuan. Empat zona alterasi yang terbentuk terbatas pada rekahan sepanjang sesar, memotong struktur lapisan lolos air yang berbeda-beda lapisan di bawah kawah aktif gunung api ini.

Dua macam cairan asam yang berbeda pada kawah Gunung Api Papandayan, yaitu: (1) air asam sulfat-klorida dengan pH berkisar antara 1,6 dan 4,6, dan (2) air asam sulfat dengan pH

antara 1,2 dan 2,5. Pengambilan percontoh setelah erupsi menunjukkan peningkatan pada rasio SO_4/Cl dan Mg/Cl . Evolusi ini tampaknya mencerminkan peningkatan dalam netralisasi cairan asam yang cenderung menunjukkan bahwa interaksi air-batuan adalah tipe kontak dengan meningkatnya air asam. Tingginya $\delta^{34}S$ (9-17‰) yang teramati di dalam air asam sulfat-klorida sebelum erupsi November 2002 menunjukkan bahwa larutan sulphate terutama terbentuk karena ketidak seimbangan SO_2 dalam magma. Sementara, rendahnya $\delta^{34}S$ (-0,3-7‰) yang teramati di dalam contoh air asam sulfat-klorida setelah erupsi menunjukkan bahwa larutan sulfat yang berasal dari air tersebut merupakan oksidasi permukaan hidrogen sulfida.

Kata kunci: Gunung Api Papandayan, erupsi freatik, sistem hidrotermal, cairan kimia, alterasi argilik lanjut

INTRODUCTION

Papandayan Volcano produced a catastrophic debris avalanche during the brief magmatic eruption in 1772. Afterwards, only small phreatic eruptions had occurred prior to the more explosive eruption in November 2002 which has changed the crater morphology. Today, the volcano activity is reduced to be the presence of fumaroles with sulphur-mud pools and hot springs. The geochemical survey of fumaroles and thermal springs can provide useful information on the state of activity of the volcano, on the relationship between the hydrothermal and the structural systems of the volcano and on the activity evolution with time (Fischer, 1997; Taran, 1998; and Federico, 2002). Changes in the chemical composition of gases and/or hot springs may reflect an interaction more or less important between the deep fluid and the superficial aquifer (Ohsawa, 1993; Valentino, 1999; and Tassi, 2003). But, these evolutions may also be the consequence of an increase in the volcano activity that could generate a phreatic eruption (Nogami, 2000), or a magmatic one (Giggenbach, 1990; Takano and Watanuki, 1990; Arribas, 1995; and Fischer, 1997). The recent activity ejected ash and altered rocks coming from the inside of the hydrothermal system offers an opportunity to improve our knowledge on the alteration processes occurring at depth (Christenson and Wood, 1993). This paper presents the results of chemical and isotopic studies of hot-spring waters sampled from 1994 to 2002. After the phreatic eruption that occurred in November 2002, new hot-spring waters were collected for chemical and isotopic analyses, whilst volcanic ashes and altered rocks were also sampled for mineral analysis. The chemical and mineralogical data serve in having a better under-

standing about the alteration by the acid-fluids on the rocks in the hydrothermal system and allow to observe changes in the activity of the Papandayan Volcano which has already produced a catastrophic magmatic eruption in its historical time.

VOLCANO SETTING AND THE NOVEMBER 2002 ERUPTION

The Papandayan Volcano is a stratovolcano (7°32' S, 107°73' E, 2665 m a.s.l.) located at 180 km to the southeast of the Jakarta (Figure 1). During its historic activity, the eruptive center moved to the northeast with the formation of successive new craters. The deposits in this area consist of Tertiary andesitic lava flows overlain by numerous alternating pyroclastic flows and falls with andesite basaltic lavas. The last magmatic eruption of the Papandayan Volcano occurred in 1772. A debris avalanche created a horseshoe-shaped crater open to the northeast and covered an area of about 250 km², resulted in the destruction of 40 villages and the death of 2957 inhabitants (van Padang, 1951). The last reported activity, during June 1998, consisted of increased seismicity and minor phreatic explosions (USGS, 1998). Until November 2002 eruption, the hydrothermal activity was centred in the crater (1 × 1.5 km) with multiple fumaroles, mud-pools and hot springs.

In Early October 2002, the seismicity of the volcano increased and small phreatic explosions occurred in the crater (USGS Volcanic Activity Report, 2002). On 11 November 2002, a phreatic eruption from the southeast of the crater caused a landslide that became a lahar. On 15 November 2002, a phreatic eruption ejected steam and an ash plume up to

4000 m above the crater. Earth Probe TOMS (Total Ozone Mapping Spectrometer) instrument detected small amount of SO₂ on November 13 (<1500 tons). On November 15, SO₂ was again detected, in a small plume extending west of Papandayan. The estimated SO₂ mass was 7000 tons. Between 16 and 20 November 2002, explosions ejected an ash plume up to 700 m high then followed by landslides and lahars. On 20 November, another major eruption took place at the northwest of the crater. Ash plume reached 1500 m above the vent and the cloud drifted to the northeast. The eruption also produced a directed blast as far as 2 km and left blocks and smaller fragments of altered rocks and 4-8 cm thick deposit of wet ashes. Bread crust bombs with maximum diameter of 50 cm were found. During the next month, the activity decreased and actually only fumarolic manifestations were present (USGS Volcanic activity report, 2003). New vents have been created with one containing a small lake, and another mud-pool and new hot springs appeared (Figure 1).

SAMPLING AND ANALYTICAL METHODS

Water samples were collected from 1994 to 2005 in the crater (Figure 1). The pH was determined in the field after calibration with pH 1 and standard reference buffers. The concentrations of cations were measured by inductive coupled plasma optical emission spectroscopy (ICP-OES) whereas the anions Cl⁻, SO₄²⁻ and F⁻ were analyzed by high performance liquid chromatography (HPLC). Furthermore, the δ³⁴S of sulphates were determined by mass spectrometry. Products of 2002 eruption collected around the new vents consist of grey ashes and altered rocks. Their mineralogy was determined by means of an X-ray micro diffraction instrument equipped with a HISTAR detector. A scanning electron microscopy (SEM) and an energy-dispersive X-ray spectrometer (EDS) were also used to study the ejecta. The EDS detector was equipped with a NORVAR window that enables the detection of elements with atomic number (Z) above 3.

RESULT OF INVESTIGATIONS

Mineralogy of Erupted Products

The altered rocks are derived from highly altered lavas of andesitic compositions. Some samples show a complete silicification. Bread crust bombs come from the eruption of 20 November 2002, the most explosive of this period. Rock and ash alteration mineralogy is summarized in Table 1. The most abundant phases are cristobalite (XRD patterns on Figures 3a and 4a), quartz (XRD patterns on figures 3b and 4b), pyrite (Figures 2a and XRD patterns on Figures 3b and 4) or marcasite (XRD pattern on figure 4a), pyrophyllite (Figure 2b and XRD patterns on Figures 3b and 4b) and alunite (Figure 2c). The alunite phase identified is a natroalunite ((Na_{0.5}, K_{0.5}) Al₃ (SO₄)₂ (OH)₆), based on XRD analysis (Figure 4a). Sometimes some radiating pyrite or marcasite (Figure 2d) has been found in ejectas covered by small crystals of alunite. In experimental studies (Murowchick and Barnes, 1986), the occurrence of marcasite indicates: (1) a fluid relatively acid (pH<4-5), (2) a temperature of deposition below 240 °C and post-depositional temperatures that remain below 160°C and (3) the presence of polysulphides (*e.g.* H₂S₂) that are formed by partially oxidation

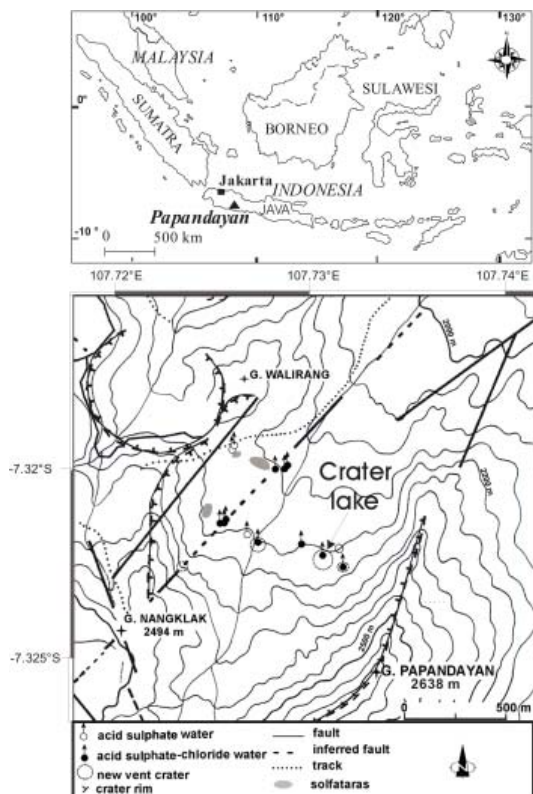


Figure 1. Location map of the Papandayan Volcano. The faults and vents appearing during November 2002 are also highlighted.

Table 1. Alteration Phases in Ejecta from the November 2002 Eruption

Samples	Cristobalite	Opal-CT	Quartz	Pyrite	Marcasite	Native Sulfur	Pyrophyllite	Natroalunite	Kaolinite	Anhydrite	Gypsum
Ejecta											
PAP_01	X		X				X	X			
PAP_02	X		X								
PAP_03		X	X	X	X						
PAP_04	X			X				X			
PAP_05	X			X				X	X		
PAP_06	X			X	X			X			
PAP_07			X	X	X						
PAP_08			X	X			X			X	X
PAP_09	X		X	X		X	X				
PAP_10	X		X				X	X			
PAP_11			X				X	X		X	
PAP_12		X	X	X							
PAP_13		X	X	X							
Ashes											
Ash1	X		X	X		X	X	X	X	X	
Ash2	X		X	X		X	X	X	X		X
Ash3	X		X	X		X	X	X	X		
Ash4	X		X	X			X	X	X		
Ash5	X		X	X			X	X	X		X
Ash6	X		X	X		X	X	X	X	X	
Ash7	X		X	X		X	X	X	X	X	

of sulphides species (*e.g.* H_2S) close to the site of deposition. Marcasite has been found coexisting with pyrite, quartz and/or alunite in high altered rocks. Anhydrite (Figure 2e and XRD pattern on figure 3b) or gypsum and kaolinite (XRD pattern on Figure 4b) are sporadic phases. The accessory minerals are, in altered rocks, rare enargite, rutile or anatase inclusions in pyrite and muscovite. The bread crust bomb shows many phenocrysts of plagioclase, hypersthene and augite in a gangue of glass plus crystals of principally plagioclases and pyroxenes (Figure 2f). This bomb is not altered and is characterized by a fragment of lava without vesicles and contains many phenocrysts.

Four alteration assemblages have been determined in altered rocks. The first assemblage consists of pyrophyllite, quartz $\pm$ cristobalite $\pm$ natroalunite $\pm$ anhydrite $\pm$ pyrite $\pm$ native sulphur and gypsum (PAP-01, PAP-08, PAP-09, PAP-10 and PAP-11). The second assemblage contains kaolinite, quartz, cristobalite, natroalunite, anhydrite and pyrite (PAP-05). The third suite is composed of natroalunite, pyrite, cristobalite and $\pm$ marcasite (PAP-04 and PAP-06). The last assemblage consists of quartz $\pm$ cristobalite $\pm$ pyrite and $\pm$ marcasite (PAP-02, PAP-03, PAP-07, PAP-12, PAP-13).

Composition of Volcanic Gases

Chemical compositions of volcanic gases from the crater of Papandayan Volcano (Figure 1) are presented in Table 2. The crater discharged gases up to 400°C in 1994-1996, and in 2004 after the eruption, the maximum temperature measured was 260°C. The gases collected in the fumaroles consist mostly of H_2O with minor amount of CO_2 and H_2S and very low SO_2 and HCl contents.

Composition of Thermal Water

The analysis result of hot spring water collected since 1994 are shown in Table 4. Several hot springs are present on the west and south sides of the crater with mud pools close to solfataras (Figure 1). Considering the data on Table 3, two groups of springs can be distinguished: acid sulphate-chloride and acid sulphate water. Acid sulphate-chloride water have pH varying from 1.6 to 4.6, temperatures between 17 and 94°C and TDS concentrations between 506 to 8380 mg/l. A crater lake was formed during the November 2002 eruption and belongs to the same type of acid sulphate-chloride water. Acid sulphate (or steam condensates) water containing high sulphate concentration but low amounts of chloride, have pH values between 1.2 to 2.5, temperatures between 23

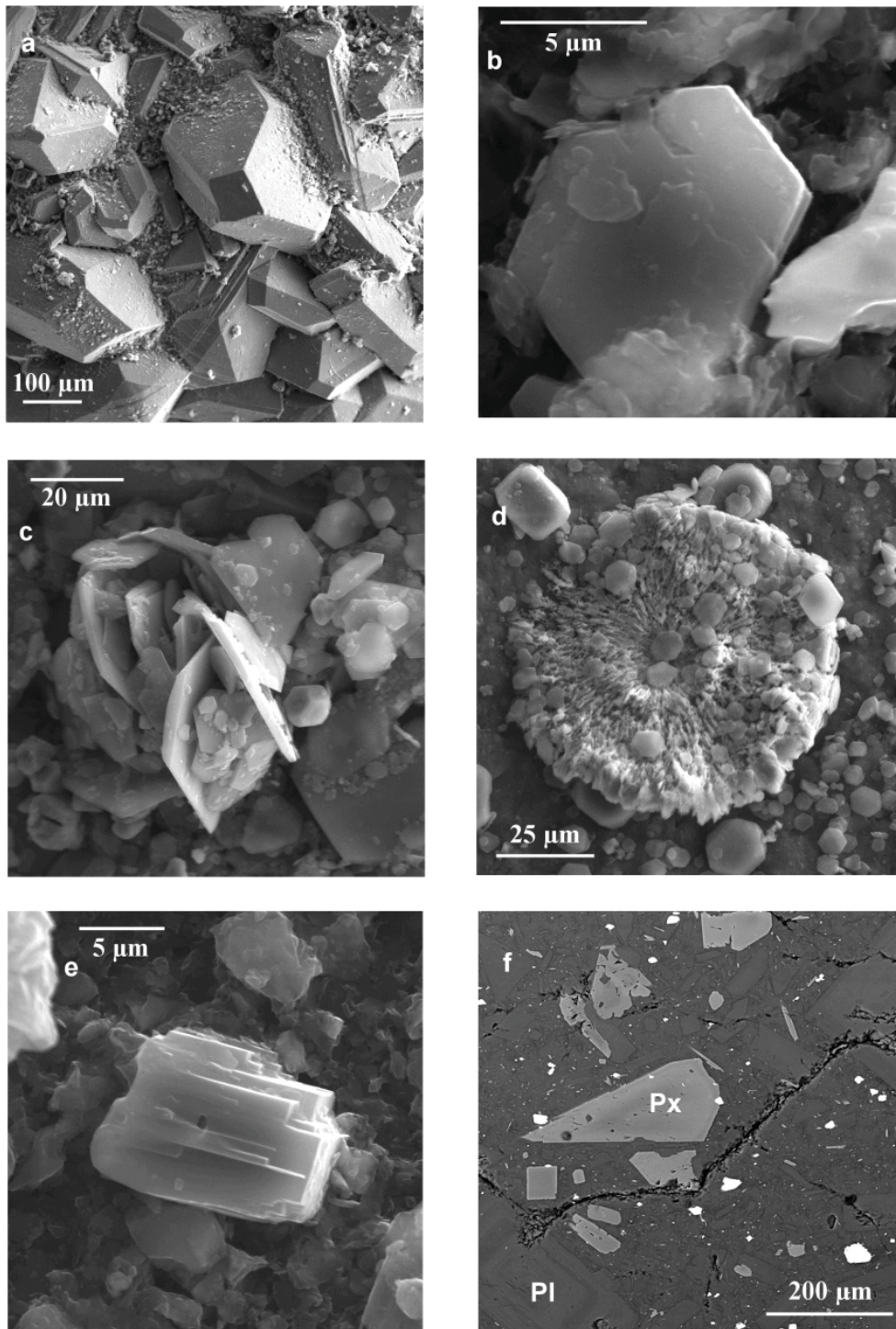


Figure 2. Secondary electron image (SEI) photomicrographs (a, b, c, and d) and back scattered electron image (BEI) photomicrograph (f) of altered minerals. (a) Octahedral pyrite in ejecta, (b) Crystal of clay (pyrophyllite or kaolinite) in ash, (c) Rhombohedral alunite in ejecta, (d) Radiating pyrite or marcasite covered by crystals of alunite in ejecta, (e) Crystal of anhydrite in ash, (f) Section in bread crust bomb: phenocrysts of plagioclase (Pl) and pyroxenes (Px) in glass with microlites of plagioclase.

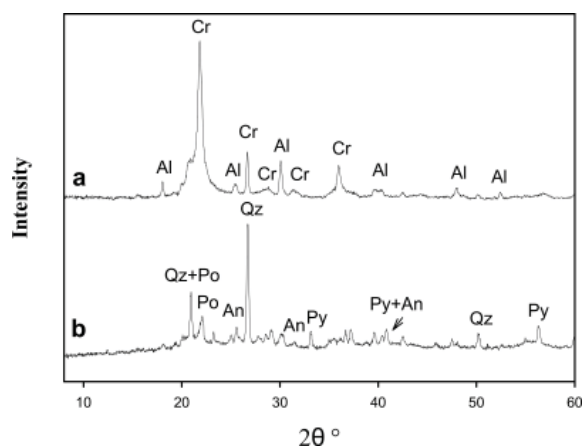


Figure 3. X-ray microdiffraction of (a) PAP-06 (assemblage 3) and (b) ash-1. Mineral abbreviation: Al= Natroalunite; An= Anhydrite; Cr= Cristobalite; Po= Pyrophyllite; Py= Pyrite; Qz= Quartz.

to 91°C and TDS concentrations between 1350 to 5660 mg/l. Mud-pools differing greatly from the two groups of springs, have low pH (0.3 and 1.1), temperatures close to boiling (87 to 95°C) and high TDS concentration (2860 to 41610 mg/l). These types of water are highly enriched in Boron due to the strong evaporation of the pools.

DISCUSSIONS

Chemical Composition of Gases

Relative concentrations of HCl, St and CO₂ are

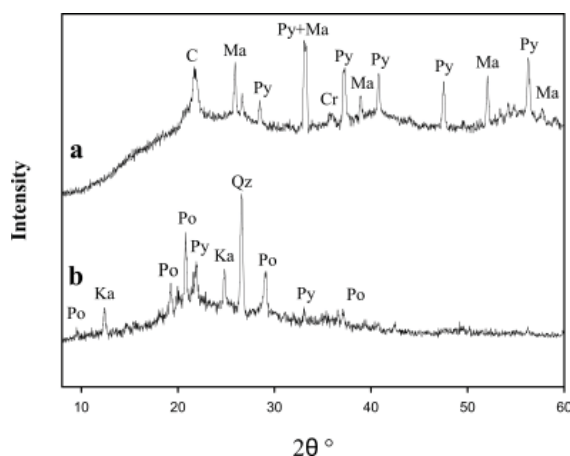


Figure 4. X-ray microdiffraction of (a) PAP-03 (assemblage 4) and (b) ash-2. Mineral abbreviations: C= Opal; Ka= Kaolinite; Ma= Marcasite.

shown on Figure 5. The St/HCl ratio of the gases vary, while the CO₂/St ratios remain constant. These variations are probably caused by a selective absorption of more soluble water species, H₂S, SO₂ and HCl, by the hydrothermal water and re-equilibration of magmatic gases at a low temperature (<400°C). To confirm the origin of the volcanic gases, the hydrogen (D/H) and oxygen (¹⁸O/¹⁶O) isotopic ratios for the Papandayan gases and hot springs (Tables 3 and 4) are compared (Figure 6) with the compositions of local meteoric water and high temperature gases from volcanic arc magmas (Taran *et al.*, 1989; Giggenbach, 1992). The local meteoric water line

Table 2. Chemical Composition (μ.mol.mol⁻¹) and Isotopic (‰) of Volcanic Gases and Temperature (C). (From (a) Giggenbach (1996), (b) Giggenbach *et al.* (2001), and (c) Fisher (pers.com))

Sample	date	Temp.	H ₂ O	CO ₂	H ₂ S	SO ₂	St	HCl	H ₂	HF	N ₂	O ₂	CH ₄	CO	δ ¹⁸ O	δD	réf.
gaz1	-	400	960000	29400	2900	6750	9650	1250	140	33	550	<20	0.6	0.3	-	-	(a)
gaz2	23/07/1994	282	965000	24900	7010	1490	9030	-	-	-	-	-	-	-	-	-	(b)
gs1	12/07/1995	360	949530	36042	7935	2563	10498	1846	268	99	1687	28	0.9	<0.04	4.6	-31	(c)
gs2	14/07/1995	148	971570	20560	5354	1029	6383	1073	72	13	324	<7	0.4	<0.02	2.8	-35	(c)
gs3	14/07/1995	170	969730	25398	4052	319	4371	15	17	14	440	<9	2.3	<0.003	-3.5	-54	(c)
gs4	14/07/1995	99	989770	14406	2266	<100	2070	317	22	0.7	415	<5	0.7	<0.001	0.1	-41	(c)
gs5	14/07/1995	150	971150	20734	4419	805	5224	<2400	70	7.6	389	<7	0.7	<0.002	3.5	-32	(c)
gs6	16/07/1995	280	977170	16142	3931	1169	5100	1109	53	26	377	<7	0.4	<0.002	4.5	-32	(c)
gs7	16/07/1995	100	962400	29785	5570	1387	6957	<280	17	2.8	543	12	0.4	<0.004	1.3	-41	(c)
gs8	18/07/1996	300	967880	23469	5819	1198	7017	918	310	25	368	<12	1.2	0.004	4	-36	(c)
gs9	18/07/1996	128	973900	18418	4647	1133	5780	1639	8.7	22	229	<6	0.6	0.002	3.1	-34	(c)
gs10	18/07/1996	103	971620	23550	4034	401	4435	17	14	0.4	353	<9	0.2	<0.003	-3.3	-53	(c)
gs11	22/07/1996	138	963230	28315	6058	1578	7636	<370	76	5.1	357	<10	3.0	<0.004	2.5	-35	(c)
gs12	22/07/1996	160	964050	25666	6146	2032	8178	1466	270	4.9	361	<13	1.1	0.004	3.2	-39	(c)
gs13	22/07/1996	96	969160	25041	4931	399	5330	<16	9.2	0.9	432	<10	1.0	0.003	-0.7	-49	(c)

Table 3. Chemical (mg.kg-1) and Isotopic Compositions of Waters from the Papandayan Volcano

Sample	Date	Temp (°C)	pH meas	Na	K	Ca	Mg	Si	B	Mn	Al	Fe _{Tot}	Fe ²⁺	F	Cl	SO ₄	H ₂ S	TDS	SO ₄ /Cl	Mg/Cl	δ ³⁴ S _{SO4} (‰)	Δ ¹⁸ O of Water (‰)	δD of Water (‰)	
Acid sulphate-chloride waters																								
Pap1	Jul.94	63	2.5	24	11	33	13	73	2.2	0.6	31	0.4	-	4	216	222	-	631	1.0	0.06	-	-	-	
Pap2	Jul.94	55	2.5	21	10	35	12	108	1.2	0.5	49	2.8	-	4	183	404	-	830	2.2	0.07	-	-	-	
Pap3	Jul.94	80	1.9	20	17	28	11	111	4.1	0.4	91	4.5	-	11	747	481	-	1526	0.6	0.01	-	-	-	
Pap5	23/08/1998	75	2.3	21	10	28	11	80	1.7	0.4	17	0.4	-	3	163	215	-	551	1.3	0.07	-	-	-	
Pap6	23/08/1998	93	1.6	28	21	32	11	145	4.0	0.4	141	8.7	-	13	1186	509	-	2099	0.4	0.01	-	-	-	
Pap7	23/08/1998	70	2.2	28	22	26	12	93	1.6	0.3	33	4.1	-	4	198	364	-	787	1.8	0.06	-	-	-	
Pap8	23/08/1998	71	2.5	16	9	23	9	76	1.5	0.3	16	0.8	-	4	159	191	-	506	1.2	0.06	-	-	-	
Pap9	05/02/2000	88	1.7	48	20	73	27	245	7.3	1.4	146	21	18	17	981	867	-	2453	0.9	0.03	9.5	-7.3	-56	
Pap10	05/02/2000	92	1.9	28	15	45	14	166	4.1	0.8	80	8.0	8	11	566	518	-	1457	0.9	0.03	10.3	-7.1	-53	
Pap11	05/02/2000	86	1.9	37	24	52	18	220	4.2	1.0	107	13	13	11	606	605	-	1698	1.0	0.03	8.7	-7.2	-54	
Pap12	05/02/2000	93	2.0	29	18	38	14	151	3.1	0.7	57	7.0	-	8	380	427	-	1122	1.1	0.04	9	-	-	
Pap9	31/07/2001	64	1.7	26	22	37	13	169	4.7	0.6	114	6.5	8	11	919	417	-	1741	0.5	0.01	14.5	-6.7	-56.5	
Pap13	31/07/2001	66	2.4	14	11	25	10	70	1.7	0.3	21	0.2	-	3.4	190	200	-	547	1.1	0.05	-	-	-	
Pap12	31/07/2001	69	2.1	26	18	31	12	136	2.1	0.4	45	3.3	-	5	364	291	-	935	0.8	0.03	9.5	-7.6	-55.5	
Pap14	14/09/2002	91	1.5	22	19	33	14	112	7.2	0.5	86	10	9	8	1420	531	-	2263	0.4	0.01	-	-	-	
Pap13	14/09/2002	64	2.4	14	8	25	9	115	1.9	0.3	25	0.3	0.3	3.9	213	174	-	590	0.8	0.04	-	-	-	
Pap12	14/09/2002	66	2.2	22	21	26	11	105	2.4	0.3	53	2.8	-	6	384	295	-	928	0.8	0.03	-	-	-	
Pap13	14/09/2002	90	1.7	24	25	33	10	154	5.3	0.4	160	7.3	8	<10	1422	790	-	2630	0.6	0.01	17	-	-	
Pap15	29/01/2003	45	2.6	74	17	550	134	99	3.8	21.8	396	854	-	8	679	5544	-	8380	8	0.2	-	-	-	
Pap16	29/01/2003	17	3.1	42	16	498	44	180	1.2	11.0	7.2	22	6	<8	198	1449	-	2469	7	0.2	-	-	-	
Pap17	31/01/2003	40	3.8	30	7	99	20	51	1.1	2.3	6.5	1.0	-	<4	46	359	-	623	8	0.4	-	-	-	
Pap18	29/06/2003	75	3.3	56	20	97	38	77	7.4	1.6	10	28	-	<10	185	393	-	835	2	0.2	-	-	-	
Pap19	30/06/2003	88	1.9	84	26	209	92	162	17.1	6.3	172	561	-	4.5	1192	2769	-	5134	2	0.1	1.4	-	-	
Pap20	23/07/2004	48	2.6	86	19	338	112	104	-	1.5	211	473	-	<20	298	2962	0	4513	10	0.4	-	-	-	
Pap18	23/07/2004	82	3.2	56	22	101	41	86	-	2	4	44	-	<5	149	433	3	852	3	0.3	7.3	-	-	
Pap19	23/07/2004	85	1.9	120	20	234	122	147	-	9	79	798	-	<10	639	3090	0	5111	5	0.2	0.4	-	-	
Pap21	24/07/2004	49	2.4	80	22	437	123	97	-	2.2	131	427	-	6.9	308	3042	0.2	4599	10	0.4	-	-	-	
Pap22	24/07/2004	92	2.6	47	10	336	122	75	-	6.1	153	668	-	<10	539	3123	-	5058	6	0.2	2.0	-	-	
Pap17	16/08/2004	36	4.6	17	6	84	22	41	-	3	0.22	0.32	-	<5	25	286	-	443	11	0.9	-	-	-	
Pap23	30/07/2005	86	2.3	113	15	134	48	178	-	16	62	-	9	93	1187	-	1676	13	0.5	3.5	-	-	-	
Pap18	30/07/2005	86	3.2	55	20	111	46	97	-	-	4	60	-	4	142	513	-	954	4	0.3	6.4	-	-	-
Pap19	30/07/2005	84	1.9	140	23	284	170	155	-	-	106	1010	-	20	631	4386	-	6750	7	0.3	-0.3	-	-	-
Crater lake																								
Pap24	27/06/2003	50	3.2	98	35	645	125	116	7.4	19.4	44	44	49	<10	580	2241	-	3839	4	0.2	6.0	-	-	-
Pap24	23/07/2004	42	2.7	26	8	481	60	40	-	9	67	176	-	<10	108	2142	16	3078	20	0.6	4.8	-	-	-
Pap24	30/07/2005	37	2.7	13	4	367	38	30	-	-	85	219	-	<10	60	2086	-	2873	35	0.6	2.9	-	-	-
Acid sulphate waters																								
Pap25	05/02/2000	23	1.2	34	23	70	31	75	0.3	1.7	313	248	-	5.3	27	4905	-	5658	182	1.2	-0.99	-	-	-
Pap26	27/06/2003	92	2.5	41	8	177	77	161	1.6	4.0	81	556	-	<10	14	2886	-	3845	206	5.5	1.8	-	-	-
Pap27	27/06/2003	45	2.4	47	22	550	84	193	0.6	2.9	249	220	-	<16	15	4012	-	5202	269	5.6	4.5	-	-	-
Pap26	23/07/2004	91	1.7	28	7	79	52	154	-	2	241	204	-	<10	24	3839	45	4575	161	2.2	1.8	-	-	-
Pap27	23/07/2004	52	1.8	18	8	85	29	138	-	0.89	160	69	-	0	<5	2201	18	2570	-	-	3.4	-	-	-
Pap26	30/07/2005	82	2.1	19	6	76	42	152	-	-	234	250	-	3	10	2656	-	3296	263	4.2	-	-	-	-
Pap27	30/07/2005	79	1.9	14	5	62	16	150	-	-	93	19	-	2	4	1579	-	1794	367	3.7	-	-	-	-
Pap28	30/07/2005	94	2.6	43	9	96	28	153	-	-	23	130	-	<5	8	1011	-	1347	135	3.7	-	-	-	-
Sulfur-mud pools																								
Pap29	05/02/2000	88	0.4	35	22	77	32	177	500	2.3	250	110	-	212	26797	1107	-	29145	0.04	0.001	-	-	-	-
Pap30	05/02/2000	87	1.1	3	3	7	4	169	3.6	0.2	63	33	-	6.5	1520	1215	-	2857	0.08	0.003	-	-	-	-
Pap31	31/07/2001	95	0.3	26	16	54	24	140	100	1.1	99	36	-	45	26771	1256	-	28428	0.05	0.001	-	-	-	-
Pap30	31/07/2001	89	0.8	4	8	7	5	165	8.4	0.2	80	37	-	9.4	2858	1644	-	4661	0.58	0.002	-	-	-	-
Pap30	14/09/2002	-	0.9	6	6	12	6	150	11.4	0.3	89	36	-	1.2	4443	2272	-	6883	0.51	0.001	-	-	-	-
Pap32	24/07/2004	90	0.6	362	141	1432	643	214	-	26	5020	1871	-	21	26963	5134	12	41613	0.19	0.024	-	-	-	-

(LMWL) was constructed from the GNIP data covering the period 1962-1997 for Indonesia (Jakarta station). The isotopic compositions of the Papandayan fumaroles lie on a mixing line between “magmatic end member” and local meteoric water. The water discharges are dominated by meteoric waters with a minor magmatic contribution. The $\delta^{18}\text{O}$ values of gases close to the local meteoric waterline are shifted by ~ 4 ‰ from the hot springs $\delta^{18}\text{O}$ values. A similar shift has been observed in fumaroles from Kudryavy volcano (Taran *et al.*, 1995) and Galeras (Fischer *et al.*, 1997). These authors attributed this shift to an interaction between meteoric water and magmatic gases leading to enrichment in $\delta^{18}\text{O}$ of the vapor phase. The same process may be present at the Papandayan Volcano.

Changes in the Chemistry of Thermal Water after the Eruption

Different processes which can occur between the cooling magma at depth and the hot springs at the surface are as follows: injection of magmatic gases into the hydrothermal system, dissolution of rock by the acid fluids and dilution of acid fluids by meteoric water. On Figure 7, a positive correlation between Cl and hydrogen ion activity ($10^{-\text{pH}}$) is shown. The increase in Cl⁻ is concomitant with the more H⁺ value. The correlation indicates that the Cl in the springs was supplied in the form of HCl solution or vapor. Furthermore, the concentrations in F, Cl and SO₄ in the acid chloride-sulphate water reflect an injection of magmatic gases (SO₂, H₂S, HCl, HF) in to the hydrothermal system.

Table 4. Average Chemical Composition of Andesite

SiO ₂ (wt%)	Al ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na ₂ O (wt%)	K ₂ O (wt%)
57.27	18.52	7.49	0.13	3.03	7.10	2.80	1.38

The chemistry of samples collected two months before the November 2002 eruption show no detectable changes, suggesting that no significant modification occurred in the pre-eruptive degassing. The chemistry of samples collected after the eruption reveals however notable changes. The most significant changes are an increase in SO₄/Cl and Mg/Cl ratios (Figure 8, Table 3). This could be due to the intrusion of a fresh magma at shallow depth (Giggenbach, 1974; Pasternack and Varekamp, 1994). The acid sulphate water that are likely to have been generated at subsurface show the same increase in Mg/Cl ratio than the acid chloride-sulphate water. A more likely explanation for the changes observed in the 2003 data is the opening of new fractures where unaltered or less altered volcanic rocks were brought in contact with the ascending acid water. To confirm this hypothesis, we evaluated the degree of water-rock interaction was evaluated by calculating the percentage of residual acidity (PRA) recently introduced by Varekamp and Kreulen (2000) for crater lake studies. The PRA is defined as the residual acidity left after the neutralization of a fluid

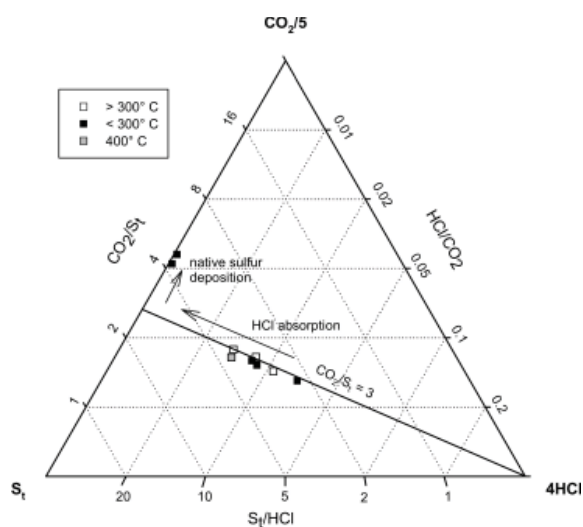
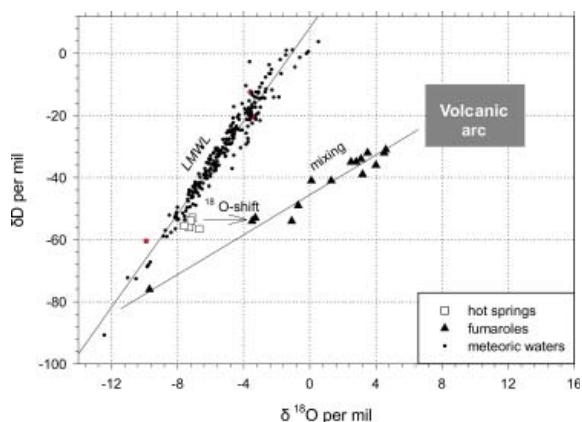
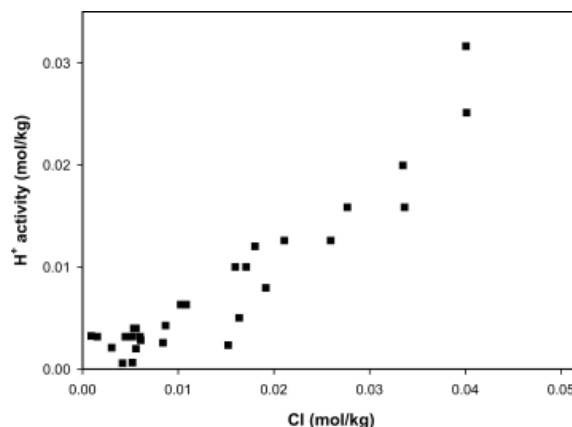
Figure 5. HCl-CO₂-St concentrations in fumarolic gases of the Papandayan Volcano.

Figure 6. Oxygen and hydrogen isotopic compositions of the Papandayan gases, hot springs and meteoric water. LMWL is local meteoric line.

Figure 7. Cl versus H⁺ activity of the Papandayan hot springs.

by water-rock (WR) interaction. Since acidity is consumed by hydrolysis reaction during WR interaction, PRA is independent of dilution or boiling. The pure acid or initial acidity was computed for each sample from their Cl and SO₄ concentrations with PHREEQC. The graph 100 × Mg / (Σ RFE) versus residual acidity is shown on Figure 9, corresponds to the easily leached element Mg on a molar basis relative to the sum of major rock forming elements (RFE = Na + K + Mg + Ca + Al). The data show a net decrease in the residual acidity for the sampled collected in 2003-2005 accompanied by an increase in the relative Mg concentration. This trend reflects an increase in the neutralization of the acid springs and show that the WR interactions were more significant after the eruption.

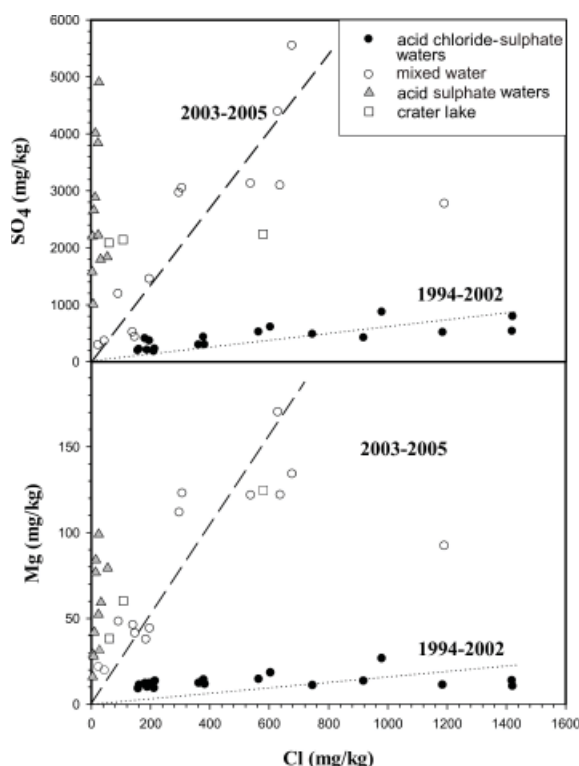


Figure 8. Cl concentration versus SO_4 and Mg concentrations of water sampled before (1994-2002) and after the eruption (2003-2005).

Sulphur Isotopic Composition

Figure 10 shows $\delta^{34}\text{S}$ of sulphates versus the SO_4 weight fraction $100 \times c\text{SO}_4 / (c\text{SO}_4 + c\text{Cl})$. The high $\delta^{34}\text{S}$ values (9-17‰) observed in acid sulphate-chloride water before the November 2002 eruption strongly indicates that dissolve sulphates are mainly formed from the disproportionation of magmatic SO_2 (Ohmoto and Goldhaber, 1997; Kusakabe *et al.*, 2000) according to the reaction of: $4\text{SO}_2 + 4\text{H}_2\text{O} \rightarrow 3\text{HSO}_4 + \text{H}_2\text{S} + 3\text{H}$ or $3\text{SO}_2 + 3\text{H}_2\text{O} \rightarrow 2\text{HSO}_4 + \text{S} + 2\text{H}$. Kusakabe *et al.* (1992) show that the disproportionation of SO_2 leads to a large isotopic fractionation between dissolved sulphates and H_2S or elemental sulphur. The low $\delta^{34}\text{S}$ of sulphates in the chloride-depleted water collected before the eruption indicates that the origin of sulphates for this water is the surficial oxydation of hydrogen sulphide (Kiyosu and Kurahashi, 1983). This Cl-depleted water has been formed from the condensation of steam rising from the boiling hydrothermal system

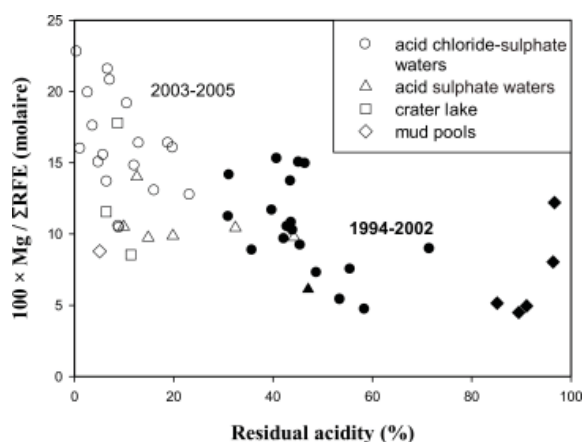


Figure 9. Plot of the percentage of residual acidity versus $100 \times \text{Mg}/\text{ERFE}$ (Sum of major rock-forming elements) = $\text{Na} + \text{Ca} + \text{Mg} + \text{K} + \text{Al} + \text{Fe}$.

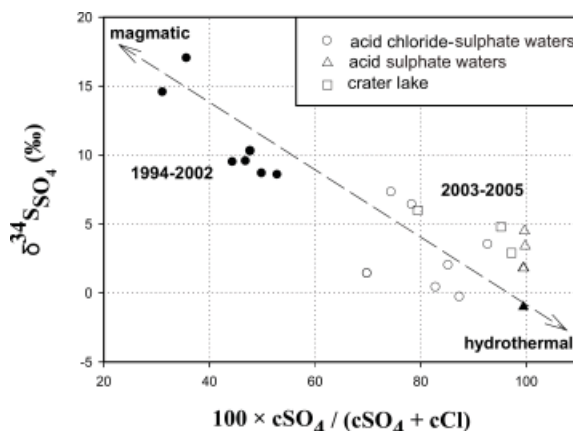


Figure 10. Plot of $\delta^{34}\text{S}$ SO_4 versus $100xc\text{SO}_4 / (c\text{SO}_4 + c\text{Cl})$ of hotsprings from the Papandayan Volcano. Ci= Concentration of element I in mg/kg.

to the subsurface above the water table (Reed and Spycher, 1985). The water samples collected after the eruption show low values of $\delta^{34}\text{S}$ of dissolved sulphates (7 to -0.3‰). This indicates that there was no increase in the contribution of magmatic fluids in the upper part of the hydrothermal system.

Crater Lake

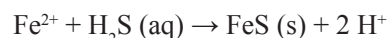
Water from the new crater lake have been collected since 2003. An evolution in the SO_4/Cl ratio is observed during 2003-2005 showing a decrease in Cl content, whereas SO_4 value remains stable (Table

4). The low values of $\delta^{34}\text{S}$ (3-6 ‰) for sulphates of the lake water indicates that the origin of these sulphates may be the result of H_2S surficial oxidation and not the disproportionation of SO_2 . The lake water reflects the hydrothermal fluids present at depth with a magmatic contribution less important with time. Cation concentrations have decreased since 2003, but the residual acidity increased slightly (Figure 9). This indicates a decrease in water-rock interaction or a contact between acid waters and wall rock has already completely leached.

Water-rock Interaction

A relationship between rock forming elements (RFE) concentrations and their abundance in volcanic rocks from sample data collected before the November 2002 eruption is presented in Figure 11. An average composition of 4 samples of andesite reported is used for the comparison (Table 4). A congruent dissolution is observed with thermal water and corresponds to 1g of andesite per kg of acid waters. This water is depleted in Si, Al, and Fe compared to their rock abundance. The solubility of Si decreases with a decrease in temperature (Nicholson, 1993). Aluminium is strongly negatively correlated with the pH, where solubility of Al decrease with an increase in pH and can co-precipitates

with Si. The iron is highly depleted compared to its rock abundance. Fe solubility is pH dependent but this can not explain the very low concentrations in water. However, abundant pyrites have been found in the ashes and altered rocks. Therefore, Fe could be consumed in the reaction that formed pyrite. In experimental studies (Schoonen and Barnes, 1991) two steps of formation of pyrite and marcasite has been described. The first step is the precipitation of iron monosulphide (FeS) by the reaction:



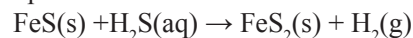
In the second step, iron monosulphide is converted to an iron disulphide either

(1) Fe loss:

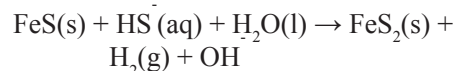


or

(2) sulphidation:



or



Iron disulphides are formed most readily if the solutions contain an excess of thiosulphates, poly-

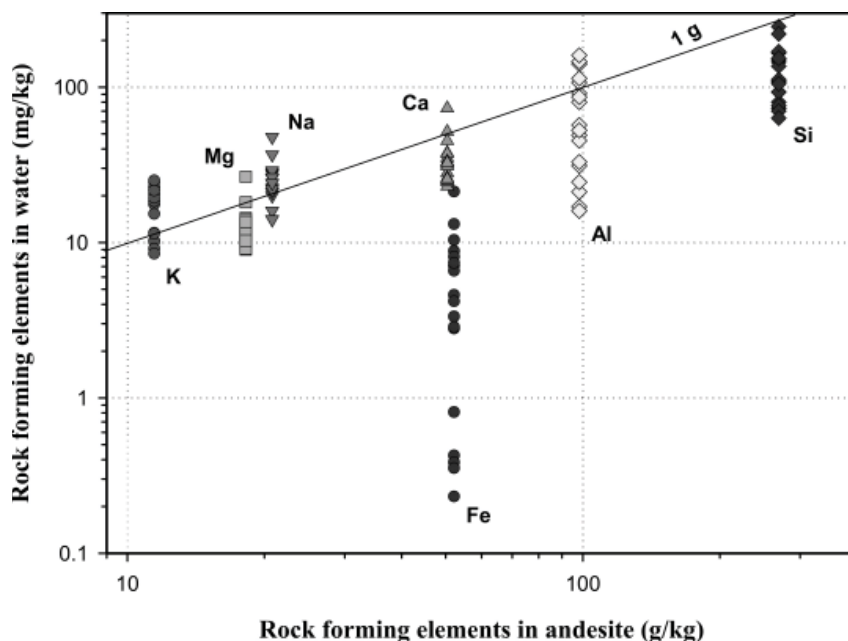


Figure 11. Concentration of rock forming elements (RFE) in lake water compared to the Papandayan andesite.

thionates and/or polysulphides.

Congruent dissolution of rock has been reported by Bernard *et al.* (2004) for Santa-Ana Crater Lake and by Ohba (1994) for Yugama Crater Lake as the main source of RFE in water. However, other processes can affect the concentration of RFE in crater lakes. The dissolution of lava rock by magmatic volatiles leads to leaching different rates for the RFE (Christenson and Wood, 1993; Varekamp and Kreulen, 2000). The incongruent dissolution can be explained also by the precipitation or dissolution of minerals in lake water or in the hydrothermal system depending on the temperature and chemical fluctuations of acid fluids injected in to the system (Delmelle and Bernard, 1994; Christenson and Wood, 1993). The congruent dissolution of RFE at the Papandayan Volcano may be explained by a large circulation of thermal water in the subsurface

system. However, the assemblages of alteration minerals found in the ejectas show that an interaction between acid fluids and non-altered lava rocks (or less altered) occurs. So, a precipitation of minerals and neutralization of fluids took place in the hydrothermal system (Giggenbach, 1992; Hedenquist *et al.*, 1994; Reyes, 1990).

To improve our knowledge about the water-rock interaction in the system, a model is used on the basis of the stability of pyrophyllite, kaolinite and alunite as a function of $\log a_{\text{SiO}_2, \text{aq}}$ and pH (figure 12). The code SUPCRT92 (Johnson *et al.*, 1992) was used to compute the thermodynamic constant needed to build the stability field diagram. Quartz is assumed to be oversaturated in the model, because this phase is largely present in the altered rocks. The limits of stability reported on Figures 12a, b, c, and d correspond to the fluids Pap-2 (higher pH = 2.5)

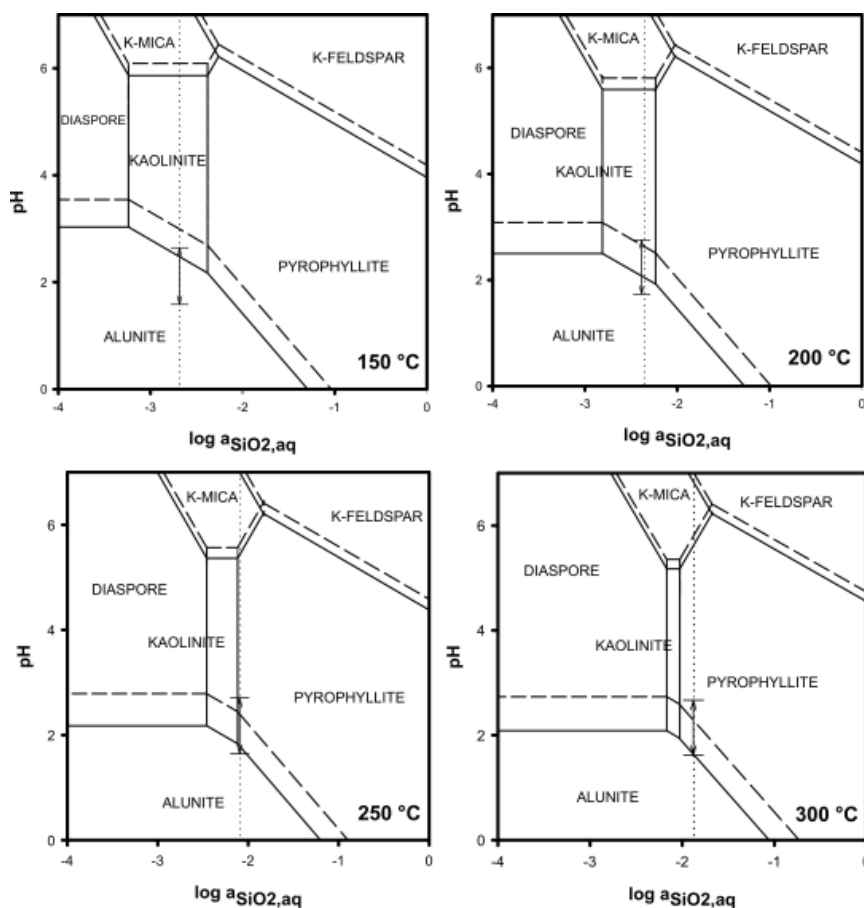


Figure 12. Stability diagram of pH versus $\log a_{\text{SiO}_2, \text{aq}}$ of the acid sulphate-chloride alteration phases from 150°C to 300°C. The dotted line corresponds to the saturation of silica.

and Pap-14 (lower pH=1.5) at different temperature and computed with PHREEQC (Parkhurst and Appelo, 1999) by using the thermodynamic database Wateq4f (Ball and Nordstrom, 1991). In Figure 12, the range in pH measured in the fluids and calculated at different temperatures is also indicated by arrows on the diagram. In the stability diagrams (Figures 12c and d), pyrophyllite and kaolinite coexist at 250°C. Experimental studies by Hemley *et al.* (1980) show that kaolinite and pyrophyllite can coexist at temperature about 270°C at quartz saturation. The presence of kaolinite is pH dependent and for water with pH below 2 and temperature of 250°C, kaolinite is no more stable. Pyrophyllite is a mineral that may form at high temperature in geothermal systems (Reyes, 1990; Nogami *et al.*, 2000; Hedenquist *et al.*, 1998), in many ore deposits districts (Marumo,

1989; Hedenquist *et al.*, 1994; Yilmaz, 2003) and on active volcanic sites (Christenson and Wood, 1993; Nogami *et al.*, 2000). Alunite can also coexist with kaolinite and pyrophyllite between 250-300°C (Hedenquist *et al.*, 1998). For the fluids studied, alunite is a stable phase between 200 and 150°C.

To specify the temperature of formation of alunite, another stability diagram was used (Stoffregen *et al.*, 2000; Figure 13). In this diagram, stabilities of alunite, kaolinite/pyrophyllite and muscovite were plotted versus $H^+ \cdot SO_4^{2-}$ activities and $K^+ \cdot SO_4^{2-}$ activities. Silica is fixed by the quartz saturation. On Figure 13, equilibrium compositions of fluids calculated at different temperatures are also plotted. Alunite appears at temperatures below 300°C and this is the Al-bearing phase stable at temperatures below 150 °C (Figure 13).

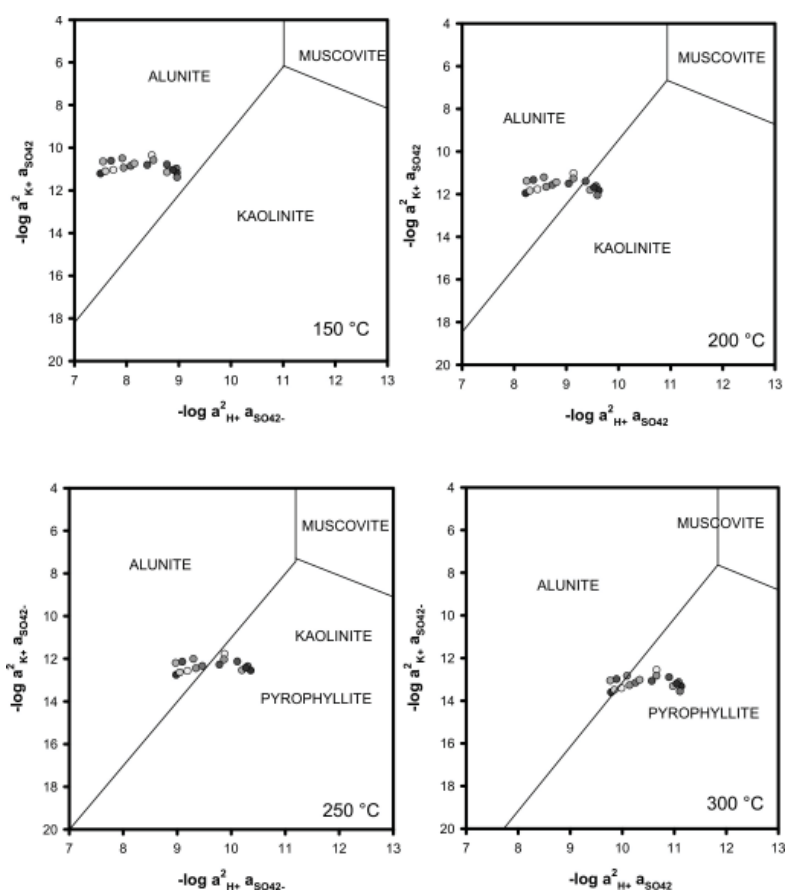


Figure 13. Stability diagram of $\log(a^2H^+ \times a_{SO_4^{2-}})$ versus $-\log(a^2K^+ \times a_{SO_4^{2-}})$ of the muscovite, pyrophyllite, and alunite phases from 150°C to 300°C. Data from the Papandayan water is also reported on the diagram.

CONCLUSIONS

The chemical and isotopic compositions of acid hot springs from the crater of THE Papandayan Volcano sampled since 1994 indicate that a contribution of magmatic volatiles (HCl , SO_2 , H_2S , HF) to the hydrothermal system is likely present and that interaction between acid fluids and rocks took place. The altered mineral assemblages identified in the rocks ejected during the November 2002 eruption and coming from the hydrothermal system is a typical of an advanced argillic alteration.

The eruption produced notable changes in the chemistry of the hot springs. Most of these chemical changes can be related to a modification in the dynamic circulation of these fluids to the surface by the opening of new fractures. Furthermore, no evidence of intrusion of fresh magma in the upper part of the hydrothermal system has been found. The hydrothermal zones are likely restrained to faults or permeability structure (Reyes, 1990; Stoffregen, 1987). The acid fluids could ascend to the surface and lead to the formation of hot springs or descend along the structures to deep level and react with the host rock. This interpretation may explain why closely different fluids can cause different type of advanced argillic alterations.

The chemical monitoring at the Papandayan Volcano is a useful tool for understanding the processes in the hydrothermal system and to survey the level of activity, especially after the phreatic eruption like that in November 2002 which was able to be followed by a magmatic eruption.

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