HAZARD ASSESSMENT OF THE PINATUBO VOLCANIC-GEOTHERMAL SYSTEM: CLUES PRIOR TO THE JUNE 15, 1991 ERUPTION

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ABSTRACT

Geothermal exploration, including the drilling of three deep wells, was conducted at the Mt. Pinatubo prospect until 13 months before the phreatomagmatic eruptions of April 2, 1991 and subsequent cataclysmic caldera-forming eruption of June 15, 1991. Data from pre-eruption thermal features and deep wells showed that the Pinatubo hydrothermal system had a significant magmatic fluid component. Produced fluids were too corrosive to develop with existing technology and materials. Lacking obvious precursor activity, it was not possible to predict the initial phreatomagmatic activity of April 2, 1991, nor the ensuing volcanic eruption. A model for the phreatomagmatic activity is proposed based on the thermal and chemical state of the system in 1990.

INTRODUCTION

Geothermal explorationists must contend with both surface hazards (e.g., landslides, hydrothermal eruptions, and earthquakes) and subsurface dangers (e.g., corrosive brines and gases, and collapsing formation). These hazards are considered from the standpoint that most geothermal fields operate only 20-40 years. Volcanoes which erupt with this frequency can usually be avoided during the exploration phase; only a few of the 65 operating geothermal fields around the world are located on or near historically active volcanoes. Volcanic hazard assessments are expensive and time-consuming, and it is very difficult to accurately predict volcanic/hydrothermal eruptions. In the absence of obvious precursor activity or reliable historical data, few geothermal developers have conducted detailed hazard assessments prior to field exploitation.

Most geothermal systems contain meteoric waters (Craig, 1963) which have interacted with reservoir rocks to varying degrees (Ellis and Mahon, 1977). However, many geothermal systems are close to young or active volcanoes, and the intrusion of magmatic fluids into a hydrothermal system is a practical concern to geothermal developers. Magmatic components in hot springs and fumaroles have been inferred from chemical and isotopic data (Giggenbach et al., 1990; Sturchio and Williams, 1990; Hedenquist and Aoki, 1991). Reyes and Giggenbach (in press) identified at least seven "magmatic-hydrothermal" systems in the Philippines based on similar data from deep wells.

Pinatubo volcano came abruptly to life on April 2, 1991 with a series of phreatomagmatic explosions (early reports called them phreatic, e.g., Punongbayan et al., 1991a). On June 12-15, the volcano erupted violently, discharging 7-11 km^3 of dacitic airfall and pyroclastic flows (Scott et al., 1991). In the 10 years prior to the eruption, PNOC-EDC collected surface and subsurface data at the Mt. Pinatubo geothermal prospect as part of an exploration program to find new electric power sources for Luzon island. Geologic mapping, and geophysical and geochemical surveys were done between 1982 and 1985, and three deep wells were drilled around the volcano in 1988-89. All three wells encountered high temperature fluids, but the wells were sub-commercial due to low permeability and the presence of corrosive reservoir brines. All three wells were plugged and abandoned by 1990.

In this paper we review the 1982-1990 exploration data to propose a model for the April 2, 1991 phreatomagmatic eruptions, and show that the pre-eruption data did not indicate an imminent eruption.

GEOLOGY

Mt. Pinatubo is located on Luzon island (Figure 1, inset) within the West Luzon volcanic arc. Basement rocks near Pinatubo consist of obducted oceanic rocks of the Zamboanga Ophiolite Complex overlain by marine, non-marine, and volcaniclastic sediments. Geologic mapping (Delfin, 1984) showed that the 2-km-diameter summit of Pinatubo, a composite andesite dome, occurred within a 5x4 km diameter caldera (Figure 1). The dome complex was surrounded by extensive fans of pyroclastic flow and

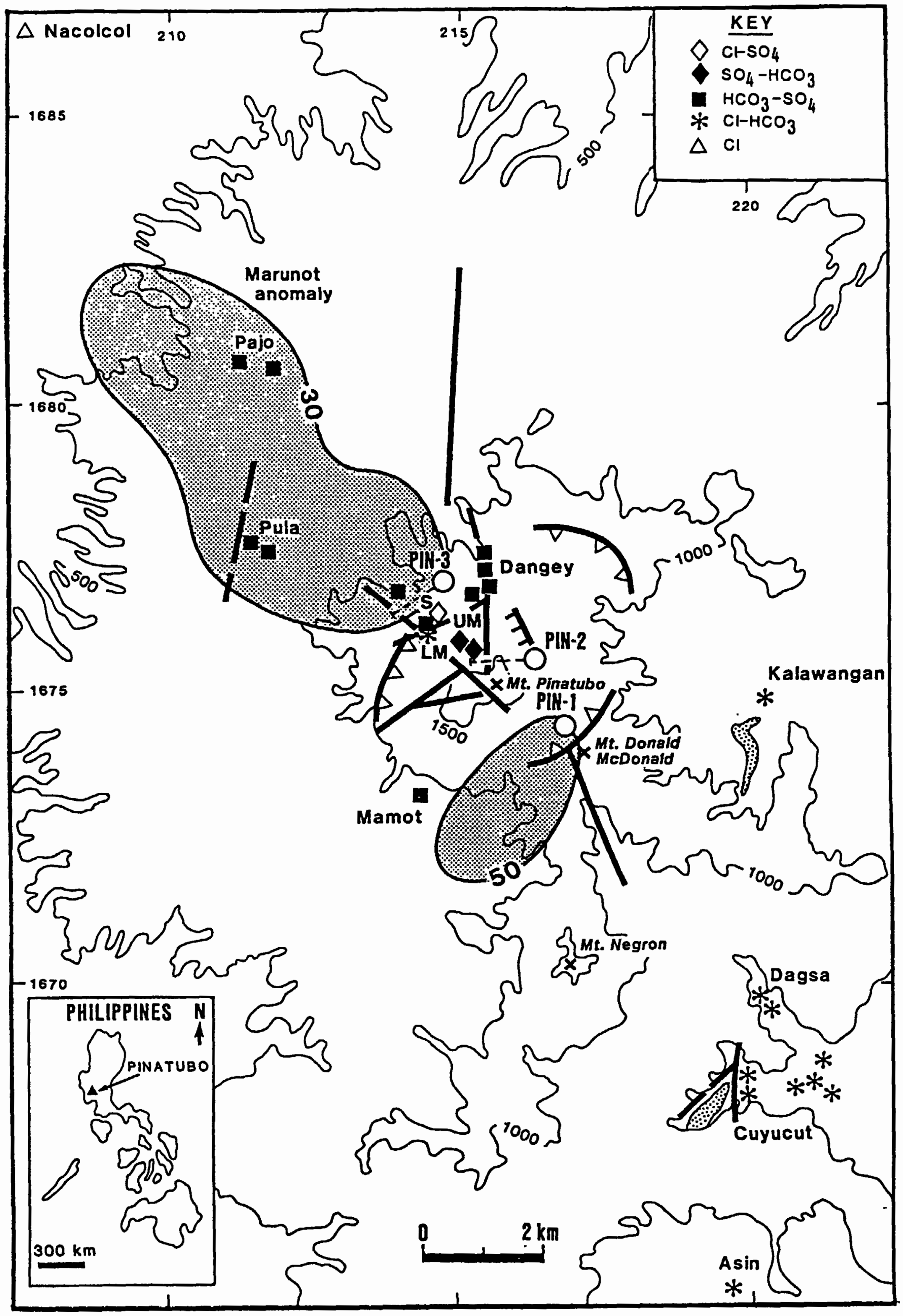

Figure 1. Map of pre-1991 thermal features at Mt. Pinatubo, Philippines showing ancestral caldera (sawteeth), major structures (heavy straight lines), resistivity anomalies (dense stippling), and altered ground (light stippling). LM = Lower Marunot, UM = Upper Marunot, S = Pinatubo solfatara pool. Elevations in meters.

lahar deposits, partially filling the older caldera and extending up to 20 km beyond its margins. The age of caldera collapse is unknown, and Newhall et al. (1991a) suggest that the dome complex was 10,000 years old. Radiocarbon dating done in the 1970s indicated that the youngest ashflow was 635 years old. After the April 2 eruptions, further ^{14}C dating of charcoal in the exposed pyroclastic deposits showed that large explosive eruptions have taken place every 500-2000 years during the Holocene (Newhall et al., 1991a). The most recent pre-1991 Pinatubo products are 460 +/- 30 ybp (Newhall et al., 1991b).

Northwest- and N-trending normal faults are the dominant structures at Pinatubo; shorter E and ENE-trending faults crosscut the main structures (Figure 1). Pre-April 2, 1991 thermal features were mainly located along N- and NW-trending faults, while the April 2 explosion craters and fumaroles were aligned along an ENE-trending fault.

GEOPHYSICS

PNOC-EDC conducted Schlumberger resistivity traversing (SRT) and vertical electrical soundings (VES) around Mt. Pinatubo between 1982 and 1985 (PNOC-EDC, 1990). The SRT electrode half-spacings (AB/2) were 250m and 500m. The location of two low-resistivity anomalies are shown in Figure 1. The Marunot anomaly (30 ohm-m) was interpreted to represent northwesterly outflow from a geothermal system underlying the Pinatubo dome complex. The smaller Mt. Donald McDonald anomaly (50 ohm-m) was thought to represent either minor eastward outflow from the Marunot area, or the main upflow zone of a much larger hydrothermal system, with outflows to the northwest (toward Marunot), north and southeast (PNOC-EDC, 1990). The surveys did not penetrate deep enough to detect low-resistivity hydrothermally altered rocks or a higher resistivity magma body below about 500 m depth under the mountain.

CHEMISTRY OF HOT SPRING AND RESERVOIR FLUIDS

Prior to the catastrophic 1991 eruption, thermal springs, minor solfatara and gas seeps occurred in a 27-km-long, northwesterly belt that extended from Asin in the southeast to Nacolcol in the northwest (Figure 1).

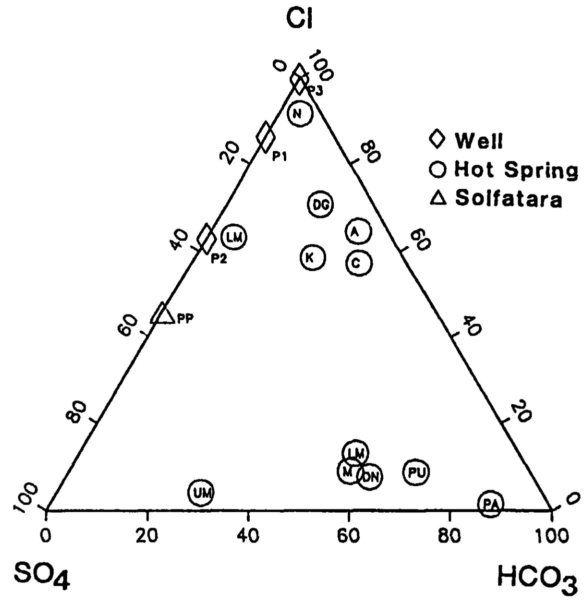

Figure 2. Classification of water samples from Mt. Pinatubo in terms of Cl, HCO_3 and SO_4. See Table 1 for symbols.

Four main types of thermal waters were identified at Pinatubo (Table 1 and Figure 2). The spring chemistry varied systematically with elevation, as shown in Figure 1. High on Mt. Pinatubo's flanks, the "solfatara pool" was a concentrated acid-Cl-SO_4 water, and the Upper Marunot springs were SO_4-HCO_3 waters; farther down the flanks, the Lower Marunot, Dangey, Mamot, Pajo and Pula springs were HCO_3-SO_4 waters; and the lowest elevation springs Dagsa, Cuyucut, and Asin were Cl-HCO_3 waters. A single chloride spring, Nacolcol, occurred about 16 km NNW of Mt. Pinatubo. The solfatara fumaroles and Upper Marunot springs reached 95°C, otherwise spring temperatures were <55°C. Except for the solfatara pool, most springs were neutral pH waters (Table 1). The low pH Cl-SO_4 fluids at higher elevations are typical of waters modified by magmatic steam (Ruaya et al., in press; Sturchio and Williams, 1990), in which the SO_4 and Cl are derived from magmatic SO_2 and HCl, respectively. The mid-elevation SO_4-HCO_3 and HCO_3-SO_4 springs indicate condensation of steam rich in CO_2 and H_2S. The lowest elevation Cl-HCO_3 springs and the Nacolcol chloride spring may represent distal outflow from an inferred Cl reservoir located closer to the volcano (Ruaya et al., in press). The hotspring waters are characteristic of shallow groundwaters (Figure 3) out of equilibrium with reservoir rocks. Conventional

Spring/Well Name	KEY	DATE yymmdd	T°C	pH	Na	K	Ca	Mg	Li	Cl	SO_4	HCO_3	B	SiO_2	TDS	Del-^{18}O	Del-D
Lower Marunot	LM	821012	47	7.6	369	28	82	155.0	0.5	787	391	64	23.3	158	2058		
Lower Marunot	LM	900403	50	7.9	157	15	62	62.7	0.4	265	260	165	16.2	157	1160	-8.2	-51.3
Upper Marunot	UM	821012	76	7.8	58	14	186	55.1	0.1	37	613	259	5.4	200	1427		
Dangey		830514	41	8.0	113	8	139	88.1	0.4	77	322	603	2.4	149	1502		
Dangey	DN	900326	39	8.0	68	6	133	64.3	0.3	44	198	562	3.5	111	1190	-9.4	-58.7
Pin. Solfatara	PP	830515	58	1.0	10134	2276	69	1056.0	10.5	34053	40600	0	423.0	605	89227		
Nacolcol	N	821006	35	7.1	203	3	117	1.5	0.0	493	23	22	1.6	65	929		
Nacolcol	N	900404	49	7.2	232	3	138	1.6	0.0	576	31	28	3.2	60	1073	-8.3	-55.4
Mamot		821007	40	7.8	74	7	163	45.2	0.2	72	282	445	2.0	132	1223		
Mamot	M	900324	43	8.0	158	11	86	68.5	0.4	127	373	382	6.4	120	1332		
Kalawangan	K	830511	38	7.9	785	64	303	47.4	1.3	1347	417	537	5.4	104	3611		
Kalawangan	K	900323	40	7.6	570	49	114	47.2	1.1	950	247	456	11.0	112	2557	-8.4	-53.5
Dagsa	D	830314	39	7.9	2240	154	182	33.5	3.6	3159	468	832	37.5	145	7255		
Dagsa	D	900327	44	7.8	19	3	241	33.1	0.1	10	681	66	3.1	58	1114	-8.8	-56.9
Cuyucut	C	830313	44	8.0	1687	123	197	43.5	2.7	2304	388	1334	27.7	152	6259		
Cuyucut	C	900329	47	8.3	1720	184	26	60.8	3.2	2387	413	481	33.5	142	5450	-6.9	-50.2
Asin	A	830513	51	7.8	2169	158	123	48.9	3.0	3123	291	1416	16.4	126	7474		
Asin	A	900328	54	8.0	2180	229	287	48.3	4.0	3167	483	1549	8.7	127	8083	-5.8	-47.8
Pajo	PA	821028	27	7.7	21	5	45	27.7	0	5	37	288	0.2	146	575		
Pula	PU	821014	22	7.3	8	4	13	9.2	0	9	23	71	0.4	94	231		
PIN-1	P1	890924		3.9	3391	379	58	48	5.6	5729	364	0	84	271	10329		
PIN-1	P1	891026		4.2	1094	114	20	39	1.7	1853	296	0.83	33	103	3555		
PIN-2D, 1650 m	P2	890206		3.1	1274	253	52	36	-	2574	295	-	86	795	4091	4.7	-27.3
PIN-2D	P2	890213		2.3	1153	208	18	96	2.4	1914	1129	0	67	454	5042		
PIN-2D, 1300 m	P2	890217		2.2	1680	317	17	93	-	3552	694	-	78	834	7265	4.3	-26.7
PIN-3D	P3	900125		3.8	2252	417	239	134	3.1	4598	21	-	73	121	7858		
PIN-3D		900126		3.5	7071	1506	669	60	6.6	14965	41	0	82	266	24667		
PIN-3D, steam	P3	9001--														8.7	-41.4

Note : Well data represent reservoir compositions; pH is measured.

Table 1. Chemical and isotopic data from Mt. Pinatubo thermal features and wells.

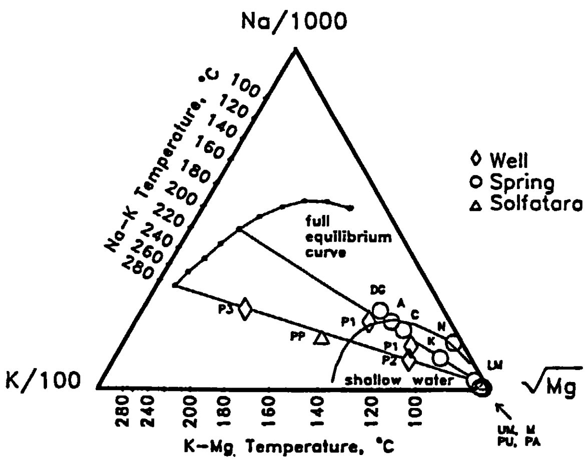

Figure 3. Giggenbach ternary diagram. See Table 1 for symbols.

fluid geothermometers are not applicable to the acid fluids. Estimated subsurface temperatures for the more benign distal springs are <200°C. This may be too low due to extensive mixing with cooler meteoric waters.

The wells generally had higher TDS than the thermal springs (3,500-25,000 mg/l vs. 230-8000 mg/l, respectively; Table 1). Weirbox and downhole fluids were acidic Na-Cl waters (Pin-2 samples were contaminated by drilling fluids). Anomalous concentrations of Fe, Mg, and B found in Pin-3 have been attributed to magmatic input (Michels et al., 1992). Fluids from Pin-3 are partially equilibrated with reservoir rocks, and fall on a tie-line with Pin-2 and the solfatara pool (Figure 3; Ruaya et al., in press). Pin-2 and Pin-3 had Na/K temperatures of 280-300°C. Pin-1 fluids resemble shallow waters, and fall on a tie-line with most of the hot springs (Figure 3); its Na/K temperature is 200°C, much lower than measured temperatures.

ISOTOPES

A plot of $\delta^{18}O$ versus δD for thermal springs and wells Pin-2 and Pin-3 is shown in Figure 4. Most of the hot and warm spring waters fall on the local meteoric water line. The 13 per mil oxygen isotope shift for Pin-2 may be partly due to water-rock interaction. However, the 25 per mil hydrogen

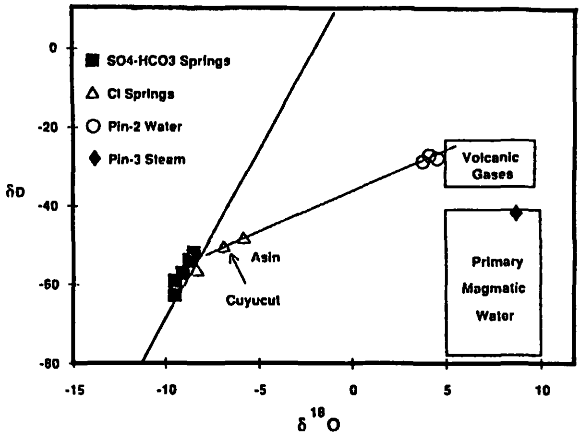

Figure 4. Isotopic composition of Mt. Pinatubo springs and well waters.

isotope shift provides strong evidence for the presence of "andesitic" water (Reyes and Giggenbach, in press), and they calculated that the Pinatubo well fluids contain 70% andesitic water. The isotopic values for Pin-2 are close to the average values for high temperature fumarolic steam from volcanic areas in Japan (Matsuo et al., 1974). Fluids from Pin-3 show a smaller δD shift than Pin-2, and plot in the "magmatic" water region (Craig, 1963). The Cl-bearing springs Asin and Cuyucut show small positive $\delta^{18}O$ and δD shifts and fall along a possible mixing line connecting Pin-2 and other thermal springs on the meteoric water line (Figure 4). However, the Asin and Cuyucut springs may be related to local meteoric waters by simple evaporation (Ruaya et al., in press).

GAS CHEMISTRY

The presence of a magmatic component in thermal springs and wells is also demonstrated by the gas chemistry, the high total gas content (20 wt% in total discharge), and the presence of up to 550 mg/l Cl in sampled steam. Well and solfatara gases plot near White Island volcanic gas in Figure 5. Because of the high magmatic input, the gases are not controlled by typical hydrothermal mineralogy (H. Crecraft, pers. comm.), so the gas geothermometers yield inconsistent results. The gas chemistry from the Pinatubo solfatara did not change significantly between 1984 and 1990 (PNOC-EDC, 1990).

WELL DATA

Basic well data for the three Pinatubo wells are presented in Table 2, and temperature-depth profiles

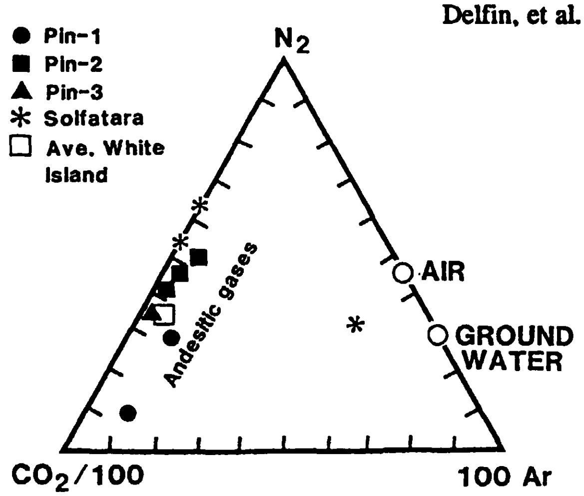

Figure 5. Relative CO_2, Ar, and N_2 contents of Mt. Pinatubo magmatic-hydrothermal gases. White Island data from Giggenbach, in Ruaya et al. (in press).

are shown in Figure 6. Pin-1 was drilled east of Mt. Pinatubo and reached a maximum temperature of 261°C at the well bottom (TD). This well had the longest flow test, and sampled brines were free of drilling fluids. With a nearly isothermal section >240°C below 1800 m, Pin-1 had a typical convective temperature profile. Pin-2 was drilled on the NE flank of the volcano. It reached 338°C at TD, the highest measured in the three wells. The temperature profile was steep and largely conductive, indicating low permeability. This was confirmed by a rapid increase in enthalpy and percent flash during the flowtests. The two flowtests were cut short due to the corrosive brine, so stable flow rates were not reached. Well Pin-3 was drilled near the solfatara and reached 330°C at TD. The static temperature profile was dominantly conductive from 500 to 1400 m depth, followed by a steep (but not isothermal) section to TD. Pin-3 also showed low permeability, and never reached a stable output (Michels et al., 1992). Ruaya et al. (in press) modeled the Pinatubo geothermal system as a two-phase reservoir essentially sealed off from the overlying aquifer of heated meteoric waters.

Well cuttings and core mainly contained neutral-pH hydrothermal minerals; minor zones of acid mineral assemblages (e.g., alunite + diaspore) were restricted to permeable zones. Calcite persisted to elevations of -490 m, further suggesting that acid fluids followed limited structural pathways in the reservoir. Overlapping alteration patterns indicate that several regimes of hydrothermal activity have come and gone at Mt. Pinatubo.

Well	Date Drilled	Elevation masl	Depth, m MD/VD	BHT C	Mass flow @ kg/s	WHP MPag	Enthalpy kJ/kg	Remarks
Pin-1	1988	1150	2771/2733	261	13-23 cycling	<0.4	1050-1070	Required stimulation; discharged 138 days; NCG=8-16% wt.; pH=4.2
Pin-2	1988	1230	2216/1697	338	27.2	0.6	2145	Rapidly increasing enthalpy indicated dry-out; 7 MW steam; Brine pH=2.3, fluids corrosive; NCG=4% wt.
Pin-3	1989	1098	2553/2190	330	10.1 (initial)	0.12	1950	Brine pH=3.4-4.3; NCG=20% wt. well not stable after 40-day test;
					0.3 (final)	0.2	?	low permeability, non-commercial

Notes: MD/VD = measured/vertical depth; BHT = bottom hole temperature; WHP = wellhead pressure (1MPag = 145 psig)

Table 2. Summary of well data from Mt. Pinatubo exploration wells.

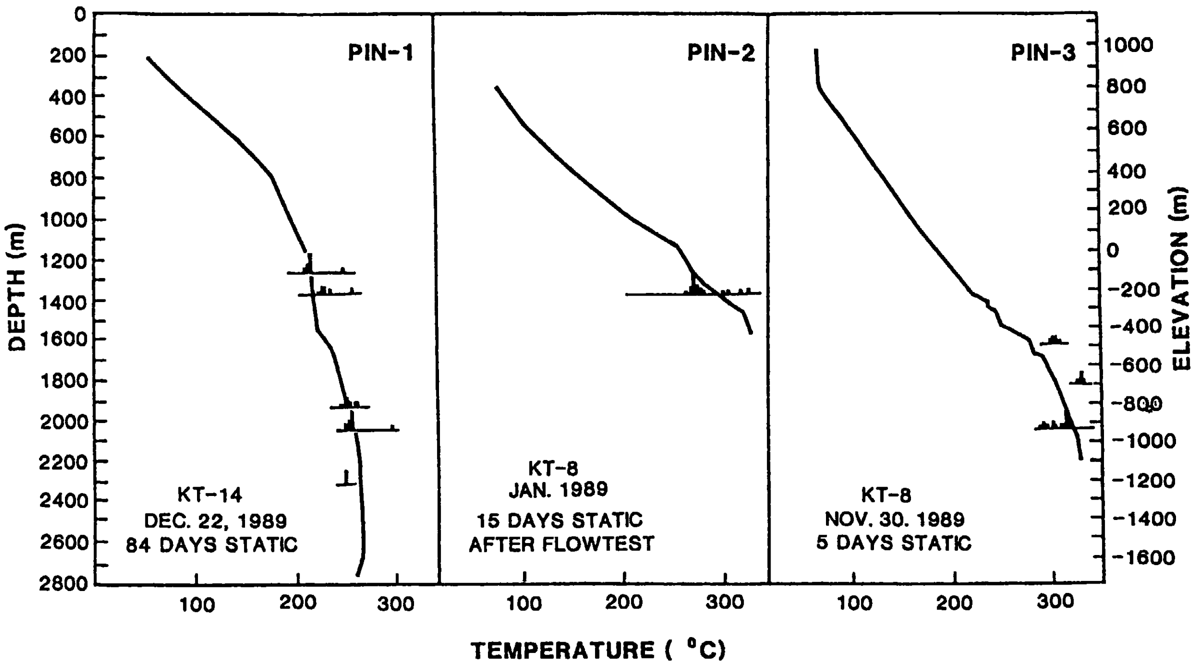

Figure 6. Temperature-depth plots for Pinatubo exploration wells, with fluid inclusion data superimposed.

FLUID INCLUSIONS

Fluid inclusions (mostly in anhydrite) were collected from identified permeable horizons in all three wells. Homogenization temperatures are plotted on the well temperature-depth curves in Figure 6. There is a good correlation between homogenization and measured temperatures in wells Pin-1 and Pin-2, suggesting thermal equilibrium in the pre-1991 hydrothermal system. However, homogenization temperatures were 25°C hotter than measured temperatures in Pin-3 between -450 and -650 m elevation. This could represent a hotter relict hydrothermal system. However, some low-temperature alteration minerals, e.g., illite-smectite persist to depths with higher measured temperatures, suggesting a cooler overprint and a more recent local heating event. Most of the fluid inclusions yielded salinities of 10,000-40,000 ppm, although values of 40,000-109,000 ppm were obtained at discrete depths in Pin-2 and Pin-3 (PNOC-EDC, 1990). The highest values appear to be associated with young faults encountered by the wells.

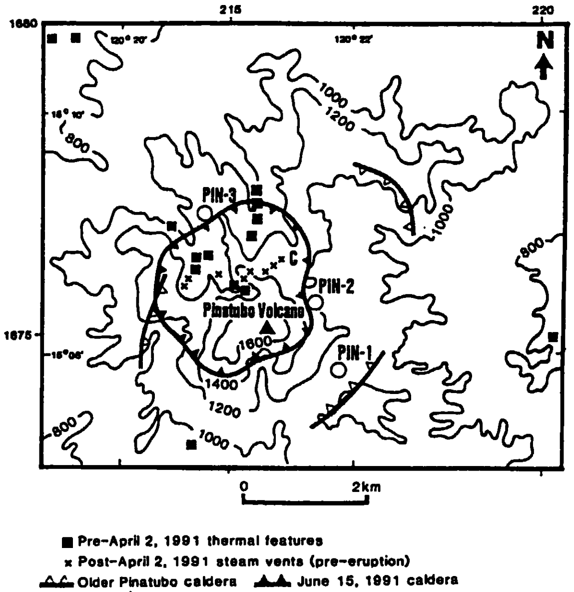

Figure 7. Location map of April 2, 1991 phreatic craters (C) and fumaroles, and pre-1991 thermal features. A NNE-trending fault connects the fumaroles and bisects the June 15 caldera. Elevations in meters. The June 15 caldera boundary provided by R. S. Punongbayan, PHIVOLCS.

APRIL 2 PHREATOMAGMATIC AND SUBSEQUENT FUMAROLIC ACTIVITY

On April 2, 1991 several explosions formed three closely-spaced craters on the NE flank of Mt. Pinatubo ("C", Figure 7). Fine-grained, fresh glassy dacite shards (<5%) mixed with fragments of hydrothermally altered rock were found around the vents. The juvenile material indicates that the eruptions had a magmatic component, so they can be called phreatomagmatic (phreatic eruptions have no juvenile component). At least six high-discharge fumaroles (steam plumes rose 200-500 m above the vents) formed during or soon after these eruptions along an ENE-trending fault extending 1.5 km west of the craters (Figures 7 and 8)(Punongbayan et al., 1991b). The largest fumaroles were near the Upper and Lower Marunot springs and solfatara pool, the hottest and chemically most "volcanic" of the thermal features. Measured SO_2 fluxes of 500 to 5000 t/day (Daag et al., 1991) indicated a large volcanic gas component was present in the fumaroles soon after the explosions. This flux is much greater than the 0-40 t/day emitted during the phreatic phase at Mt. St. Helens 0-1.5 months before the May 18, 1980 volcanic eruption (Casadevall et al., 1981).

DISCUSSION

Prior to April 2, 1991 there was little evidence of instability in the Pinatubo geothermal system. No historic phreatic explosion craters were observed, and no unusual seismic activity was reported (a local net was installed after April 2). There were no significant changes in hot spring or gas chemistry in the 10 preceding years. The April 2 eruptions and intense seismic swarm that followed were the first clues of a sudden magma intrusion event below the high temperature geothermal system.

We propose the following model for the April 2 phreatomagmatic eruptions: the pre-1991 geothermal system was heated by the partially cooled >460 year old magma chamber beneath the pre-1991 dome. Magmatic gases rising through the brittle carapace of the magma body entered the deep hydrothermal system, causing the low pH and chemical disequilibrium of the reservoir fluids. The deep reservoir leaked to the surface only at the Marunot springs and Pinatubo solfatara along NE- and NW-trending faults. Just before April 2, magma was rapidly injected into the hydrothermal reservoir. The resulting pressure increase created a new NE-SW trending fault along the northeastern base of the dome, and broke the alteration seal over the reservoir. The new fault bisects the June 15 caldera (Figure 7). Reservoir fluids rose quickly along this fault, flashed to steam, violently ripping debris from the fault walls and ejecting it to the surface along with a small amount of magma. The contribution of magmatic heat to generate the explosions need not have been large, since the heat necessary for flashing was contained in the rising >300°C fluids (cf. Kawerau, NZ; Nairn and Wiradiradja, 1980). Magma intrusion continued, lengthening the fault to 2 km and allowing magmatic gases and steam to vent to the surface.

Evidence from exploration at Mt. Pinatubo suggests that benign fluids existed at some distance from the corrosive reservoir penetrated by Pin-2 and Pin-3. Other geothermal reservoirs with highly acidic and corrosive brines have been drilled, occasionally with discouraging results, e.g., Tatun, Taiwan (Ellis and Mahon, 1977), and Sulphur Springs, St. Lucia (D'Amore et al., 1990). However, benign chloride reservoirs located adjacent to "magmatic-hydrothermal" systems have been successfully developed. These include Onikobe, Japan; Tiwi, Philippines; and Palinpinon, Philippines.

Figure 8. High discharge fumaroles on the north flank of Mt. Pinatubo taken on April 27, 1991. View is to the south from a distance of two kilometers.

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