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HAZARD ASSESSMENT IN GEOTHERMAL EXPLORATION: THE CASE OF MT. PARKER, SOUTHERN PHILIPPINES

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ABSTRACT

Hazard assessment of the Mt. Parker geothermal prospect, conducted in parallel with the surface exploration from 1992 to 1994, was undertaken to determine the long-term suitability of the prospect for development. By comparison with other acidic magmatic-hydrothermal systems in the Philippines, the geochemical data indicated minimal input of acidic magmatic fluids into Mt. Parker's hydrothermal system. This system was regarded to be a neutral-pH and high-enthalpy chloride reservoir with temperature of at least 200-250°C. These favorable geochemical indications contrasted sharply with the C-14 and volcanological data indicating a shallow magmatic body with a potential for future eruption. This hazard led PNOC EDC to discontinue the survey and abandon the prospect by late 1994. On September 6, 1995, a flashflood of non-volcanic origin from the caldera lake killed nearly 100 people on the volcano's northwestern flank.

INTRODUCTION

Mt. Parker is a Quaternary andesitic-dacitic volcano located in the southcentral region of Mindanao island (Fig. 1). In 1992, PNOC EDC began a surface exploration program in Mt. Parker in order to asses its geothermal potential (Bayon and Salonga, 1992; Salonga, 1992). Although Mt. Parker has no recorded historic eruptions (Commission on Volcanology, 1981), several geologic similarities with Mt. Pinatubo prompted us to examine the volcanic hazard of Mt. Parker in parallel with the geothermal resource evaluation. Such hazard assessment is essential in judging the long-term suitability of geothermal systems residing in possibly extinct volcanoes (Casadevall, 1992; Delfin et al., 1996). An added impetus for this study comes from the fact that Mt. Parker is near General Santos City, a major population center about 30 aerial km east of the volcano.

We examined the hazard potential of the area from the following perspectives: 1) the geology of the volcano, particulary the geochronology of the most recent pyroclastic deposits, 2) the chemistry of hydrothermal discharges and 3) the results of geophysical surveys.

GEOLOGY AND VOLCANIC HISTORY

The subvolcanic structure of Mt. Parker has been established by geologic mapping (Bayon and Salonga, 1992; Delfin, 1994) and regional Bouguer gravity survey (Apuada and Hallinan, 1995). Pre-Tertiary to Oligocene metamorphics and metasediments that crop out west of the volcano constitute the local basement (Fig. 1). This basement is downfaulted beneath the western flanks of Mt. Parker where it is filled with nearly 2 km of Quaternary volcanics and Tertiary sediments. The latter, consisting of Miocene-Pliocene clastic sediments, is widely exposed north of Mt. Parker where it is folded along NW-SE-trending fold axes. Related sediments outcrop southeast of Mt. Parker suggesting that the Tertiary sedimentary sequence extend below the lower eastern flank of the volcano. A large late Miocene dioritic body and associated volcanics, exposed north of Mt. Parker, intrude into the base of the sedimentary sequence. This intrusion is believed to extend south directly beneath the immediate eastern flank of Mt. Parker where it replaces both the Pre-Tertiary metamorphics and the Tertiary sediments as the basement of the volcanic pile.

Three major episodes of volcanism built the Parker volcanic complex. The earliest phase is seen in the sequence of variably altered andesitic lavas, coarse breccias, and tuffs (QPo in Fig. 1) that make up the topographically elevated terrain south and east of Mt. Parker. Overlying this sequence are the deposits that constitute the present Mt. Parker stratocone (QPl). This edifice is made up largely of fresh hornblende andesite lavas and subordinate pyroclastics. The

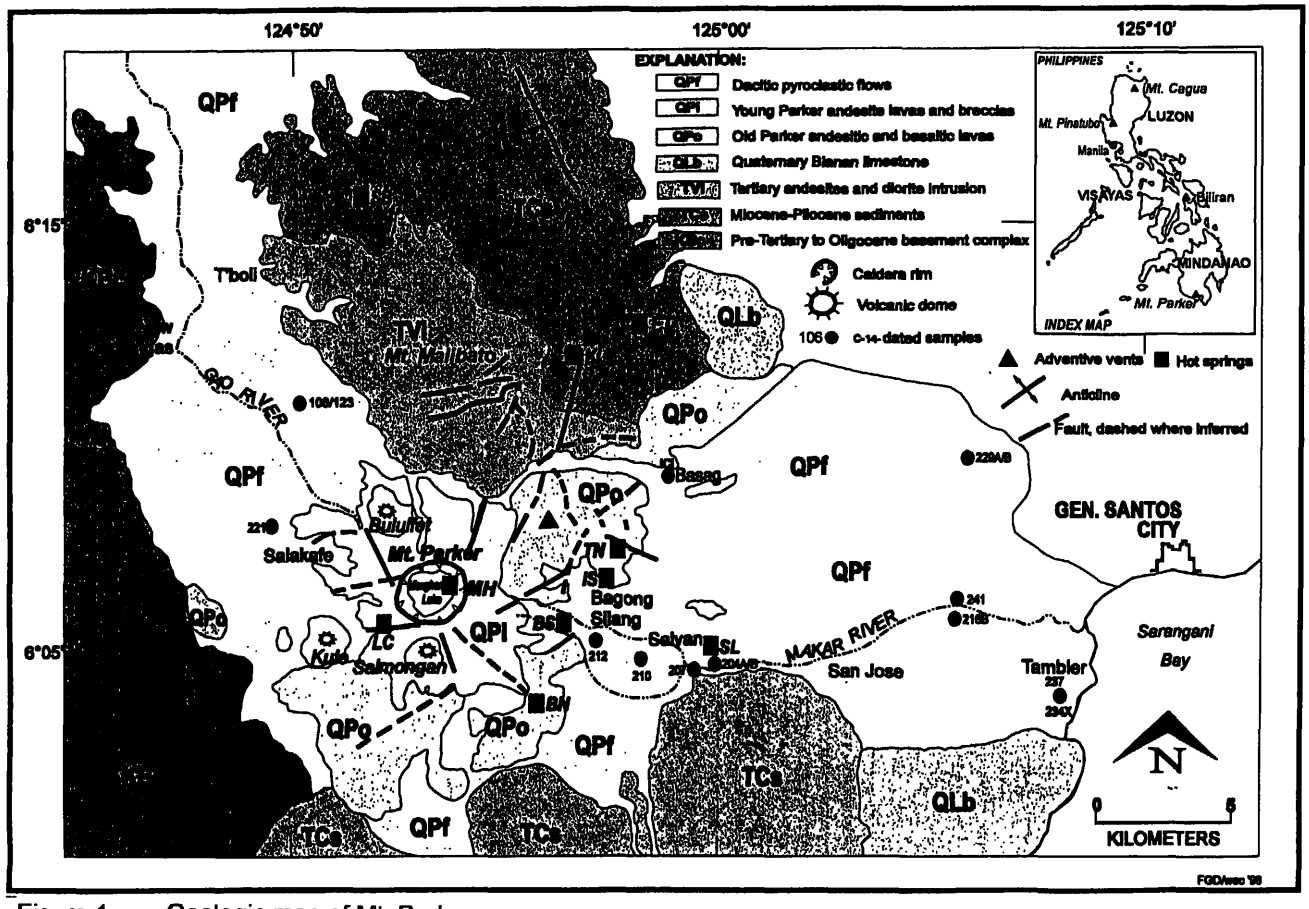


Figure 1. Geologic map of Mt. Parker.

youngest Parker deposits (QPf) are pumiceous dacitic pyroclastic flows and related laharic breccias that surround and form an apron extending more than 20 km around the volcano. These depositional features make Mt. Parker's terrain similar to Mt. Pinatubo. The eruption of these deposits led to the formation of the volcano's 3 km-wide summit caldera now occupied by Lake Maughan (Fig. 1).

From a geothermal perspective, therefore, the presence of a shallow silicic intrusion that could fuel the hydrothermal system is indicated on the surface by Mt. Parker's caldera and its related pyroclastic flows. From a hazard viewpoint, it is critical that the age of the caldera formation and the repose periods between successive explosive eruptions be established.

Results of C-14 dating of 15 charred wood samples in the pumiceous pyroclastic flows revealed four major explosive eruptions: 23-27ka, 3.8 ka, ~600 yBP and ~300 yBP. These dates indicated: 1) a general decrease in repose period between succeeding eruptions, 2) a 300 y repose interval between the last 2 eruptions, and 3) the latest Parker eruption must have occurred in historic times. A search for historical records revealed a giant eruption on January 4, 1641 (Magisa, 1641) from a volcano in the Sarangani (southcentral) region of Mindanao (Le Gentil, 1779-1781) where Parker is located. Subsequent second- and third-hand accounts of this event obscured the date and site of the eruption. That this event coincides with the ~300 yBP caldera-forming eruption of Parker is suggested by: 1) the calibration of the radiocarbon ages to calendar ages yielding equivalent dates, at $\pm 1\sigma$ standard deviation, of 1473-1645 AD, 2) the consistency of the historical descriptions of the eruption with the geology of Mt. Parker, and 3) oral traditions among Mt. Parker's indigenous tribes of an "explosion many generations ago".

C-14 dating and historical records thus showed that Mt. Parker should be properly classified as an "active volcano". More importantly, the 300 y repose interval between the last two eruptions and the recency of its last eruption clearly demonstrated that a previously unrecognized and significant volcanic hazard exists in Mt. Parker. Furthermore, such young magmatic event may be expected to leave a geochemical imprint in the volcano's hydrothermal system.

Table 1. Selected chemical analysis of Mt. Parker thermal springs.

Source	Elev (m)	T°C	pH[1]	Li	Na	K	Ca	Mg	Cl	SO4	HCO_3	B	SiO_2	$\delta^{18}O$	δ^2H
Maughan (MH)	1300	55	5.50	0.12	301	23.5	338	61.6	150	1434	206	8.74	90	-6.28	-45.1
Lake Maughan[2]	1300	25	8.43	0.10	130	12.3	148	43.5	78	447	234	1.47	47	-5.36	-39.5
Laconon (LC)	1280	37	5.50	nd[3]	38	4.6	197	26	30.8	583	57.6	0.86	75.2	[4]na	na
Bagong Silang (BS)	950	56	8.06	0.74	322	29.7	9	1.8	480	16	150	9.34	118	-7.73	-50.0
Islakit (IS)	910	74	8.00	1.52	892	58.3	77	5.4	1496	77	127	34.9	138	-7.16	-49.8
Tinulang (TN)	870	95	8.47	2.13	1028	97.3	74	32.6	1720	47	270	27.8	160	-6.81	-49.0
Bungo (BN)	675	77	8.40	3.05	849	62.5	77	17.7	1269	198	814	66.3	160	-6.95	-41.8
Salvan (SL)	605	45	8.17	0.89	41	34.8	45	9.1	680	52	180	13	161	na	na
Kule (KL)	530	35	8.30	0.11	689	11.9	7	4.3	216	925	474	6.05	102	na	na
Siman Bong (SM)	445	47	8.15	0.74	1025	27.5	143	32.6	1140	337	1195	20.8	60	-6.42	-42.9
Estaw (ET)	380	29	7.00	nd	129	5.8	20	3.1	84	31	221	1.21	41	-7.70	-47.7
Mambukal (MB)[5]	290	50	7.85	1.33	2210	79.2	286	102	3550	81	1192	49.9	76	-4.54	-37.7

[1]pH is measured at 25°C; [2]non-thermal water; [3]not detected; [4]not analyzed; [5]thermal spring located 35 km north of Mt. Parker and not shown in Figure 1.

GEOCHEMISTRY OF THE THERMAL SPRINGS

Ten groups of hydrothermal springs exist around Mt. Parker (Fig. 1). One group is found in the summit caldera while another occurs about 15 km north of the volcano; majority, however, is found at distances of 6-11 km on the volcano's eastern flank. Selected chemical analyses of waters from these features are given in Table 1.

The waters discharged by the Bagong Silang (BS), Islakit (IS), and Tinulang (TN) springs are typical alkali-chloride brine (Cl=1,000-1,500 ppm, Na=300-1000 ppm, SiO2=130-180 ppm). Their chemical features indicate that these waters represent the most direct leakage of the geothermal reservoir.

In contrast, the Maughan (MH) and Laconon (LC) springs on the volcano's summit discharge neutral-pH sulphate waters characterized by elevated SO_4, HCO_3 and Mg values and low Cl contents. These waters are regarded to have evolved by steam-heating of the ground and lakewater by ascending gases boiled off from an upwelling chloride brine.

Although the Cl/B ratios of the thermal springs are fairly uniform implying a homogenous source (Salonga, 1992), two dilution lines can be discerned on a Na-K-Mg ternary diagram (Fig. 2). One line is defined by the springs on Mt. Parker's east flank which yields a source temperature of about 230°C. The other line is defined by the springs 15-30 km north of Mt. Parker which yields a source temperature of only 160°C. Two separate circulation systems are thus suggested. Furthermore, the Islakit spring is indicated in Figure 2 to be the only feature discharging "partially equilibrated waters" suitable for geothermometric calculations. Na-K and silica mixing model geothermometers for the Tinulang springs suggest a source temperature of 200-250°C, comparable to the reservoir temperature estimate from the Na-K-Mg ternary diagram.

Drilling and investigations of magmatic-hydrothermal systems associated with young volcanic complexes in the Philippines and elsewhere have revealed several geochemical features of these acidic systems. These include: 1) fumarole or solfatara gases containing excess chloride 2) gas ratios (e.g. N_2/Ar, He/Ar) typical of volcanic exhalations, 3) acid chloride-sulphate springs at high elevations, 4) large isotopic ($\delta^{18}O$ and δ^2H) shifts towards the magmatic composition.

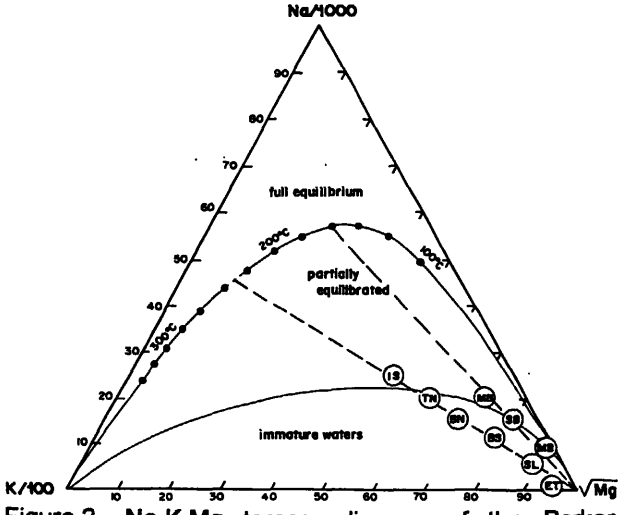


Figure 2. Na-K-Mg ternary diagram of the Parker thermal Springs. Symbols are keyed to Table 1.

On a N_2-CO_2-Ar ternary diagram (Figure 3), the composition of gases from confirmed magmatic-hydrothermal systems in the Philippines such as Pinatubo and Biliran (Ramos-Candelaria et al., 1995; Delfin et al., 1996) and those from White Island volcano in New Zealand and several active Japanese volcanoes (Ruaya et al., 1992) fall near the N_2-CO_2 line with N_2/Ar ratios of 800-4,000. In contrast, the gases from Mt. Parker have N_2/Ar ratios of less than 100 and lie closer to the air and groundwater fields indicating minimal magmatic contribution to these features. This trend agrees with those of the He-N_2-Ar systematics and the low absolute H_2S content of the springs (Salonga, 1992) implying either a crustal or meteoric source rather than a magmatic origin for the Mt. Parker gases.

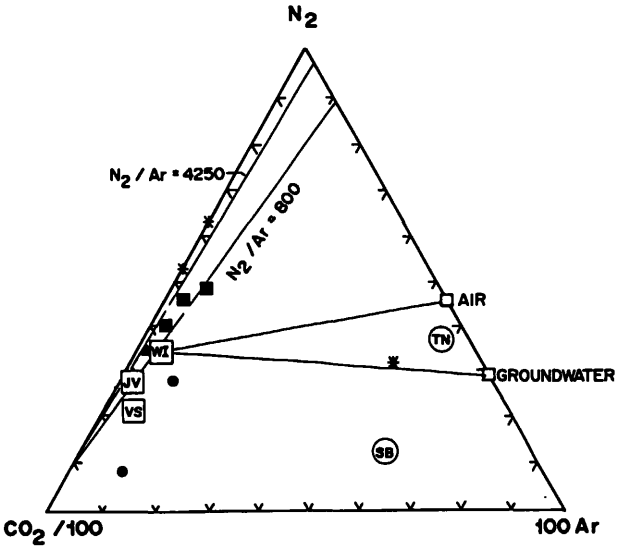


Figure 3. N_2-CO_2-Ar ternary diagram of the Tinulang (TN) and Siman Bong (SM) Springs. Composition of gases from Japanese volcanoes (JV), White Island (WI), Biliran Solfatara (VS), Pinatubo Solfatara (*) and steam from wells PIN-1 (●), PIN-2D (▲) and PIN-3D (■) are also plotted

The minimal involvement of magmatic fluids to the Parker hydrothermal system is further supported by the stable isotope data. Figure 4 shows that most of the chloride springs in the area have distinct but small enrichments in $\delta^{18}O$. Fluids from acidic magmatic-hydrothermal systems such as Cagua, Biliran, and Pinatubo are characterized by strong enrichments in $\delta^{18}O$ and $\delta^{2}H$ that approximate the isotopic composition of high-temperature volcanic gases (Matsuo et al., 1975; Sakai and Matsubaya, 1977) and primary magmatic water (Taylor, 1979).

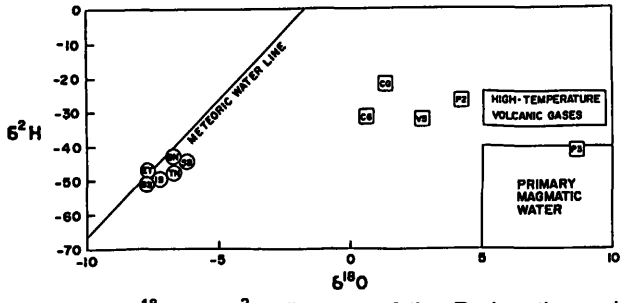


Figure 4. $\delta^{18}O$ vs. $\delta^{2}H$ diagram of the Parker thermal spings, Bilirans solfatara gases (VS), wells Cagua-1D (GC) and Pinatubo-2D (P2) waters and Pinatubo-3D (P3) steam.

In summary, the geochemical data indicated minimal, if any, active input of acidic magmatic fluids to the hydrothermal system. A neutral-pH chloride reservoir with minimum subsurface temperature of 200-250°C, typical of most mature high-enthalpy Philippine geothermal systems, is suggested to exist in Mt. Parker.

RESISTIVITY AND GRAVITY SURVEYS

From 1992 to 1993, D.C. resistivity surveys were conducted in 63 vertical electrical sounding (VES) sites using the Schlumberger array with maximum half-current electrode (AB/2) spacing of 1000m (Maneja and Los Banos, 1993). Three low-resistivity (<25 ohm-m) zones were delineated, the Kule, Bagong Silang, and Laconon anomalies (Fig. 5). These conductive zones surround a broad resistive region corresponding to the summit area of the volcanic complex. The Bagong Silang anomaly's resistivity layer configuration and its close association with the hot chloride springs on Mt. Parker's east flank made it the most geothermally significant. This anomaly was interpreted to represent altered volcanics and hydrothermal fluids of the system's outflow Due to the possible presence of conductive mudstones and siltstones beneath this region, however, a non-geothermal cause of the anomaly was equally plausible. To help resolve this ambiguity and further constrain the setting of the geothermal resource, a regional Bouguer gravity survey was run in late 1994.

A total of 458 stations spread over the entire volcanic complex and outlying region was surveyed (Apuada and Hallinan, 1995). North of Mt. Parker, the Bouguer gravity contours showed a pronounced northwest-trending gravity low centered on the Gao river valley flanked on both sides by similar-trending gravity highs over the Daguma range foothills on the west and over the TVi intrusion on the east.

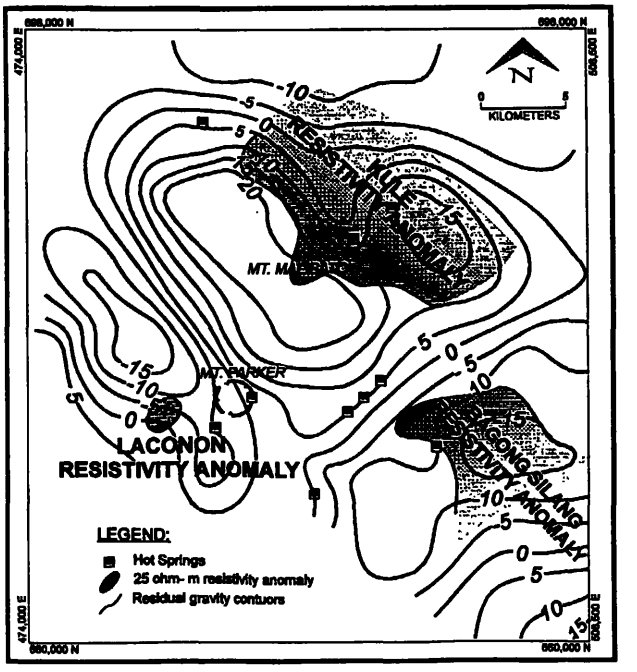


Figure 5. Residual Bouger gravity map (contours in mgal) of Mt. Parker including zones of low-resistivity anomaly.

Mt. Parker itself is not associated with any strong gravity anomaly (Apuada and Hallinan, 1995) but is situated on the southwestern edge of the positive anomaly associated with the TVi body. Immediately southwest of Mt. Parker's summit, a residual gravity high is modeled as dioritic intrusives associated with the Quaternary volcanism.

The Bagong Silang resistivity anomaly covers residual gravity highs on the west and steep gradient and low gravity anomaly on the east. Thus, the gravity and resistivity results do not reflect a single geological feature. Gravity modelling suggests that about 1000 m thick Parker volcanics underlie the upper region of the Bagong Silang anomaly but decreases to less than 300 m thick farther to the east. These imply that, near Mt. Parker, the low resistivity anomaly is probably due to alteration of the volcanics but farther east, the low-resistivity values are due to conductive Tertiary sediments.

The geophysical surveys predict that the geothermal reservoir in Mt. Parker will likely be hosted by Tertiary sediments instead of volcanics which have maximum thickness of only 1000m. Beneath the summit region of Mt. Parker, where reservoir temperatures are also likely to be high, the geothermal fluids will be contained in fractured but low-porosity intrusives (Apuada and Hallinan, 1995).

DISCUSSION

Geologic hazards common in geothermal resource development include landslides, hydrothermal eruptions, earthquakes, corrosive brines, and collapsing subsurface formations. Arguably the most serious threat is the hazard posed by volcanic eruptions. Active or frequently-erupting volcanoes may easily be written-off during the exploration stage as worthy geothermal prospects. Hydrothermal systems in dormant or in young volcanoes with no record of historic eruptions are less easy to dismiss.

Perhaps, the principal lesson from Pinatubo, El Chichon, Nevado del Ruiz and other similar systems is that during the surface exploration stage, the chemical composition of the surface discharges provide the best clue in determining the degree of direct magmatic involvement into these systems, and hence the quality of the resource. When applied to Mt. Parker, however, these criteria suggest little, if any, magmatic input. High-temperature summit fumaroles with excess chloride or acid chloride-sulfate springs at high elevation, indicative of magmatic HCl or SO_2 input, are not present in the prospect. Moreover, the chemistry and isotopic composition of the thermal water and vapor discharges strongly suggest that a "mature" geothermal system exists beneath the volcano.

The geochemical arguments for an apparently suitable geothermal system with minimal magmatic input are in direct contrast to the geological data suggestive of a very young, presumably degassing, magma at shallow levels. The C-14 dating and stratigraphic evidence for recurring explosive eruptions in Mt. Parker with repose periods generally decreasing with time and a 300 y interval between the last two eruptions argued strongly for a major development risk. These two factors were the principal considerations in PNOC EDC's decision to discontinue the exploratory studies and abadon the prospect by late 1994 despite the encouraging geochemical indications.

An additional factor in the hazard assessment was the risk to the potential development site posed by future pyroclastic flows or debris flows. The evaluation of the surface exploratory data indicated that the east flank of Mt. Parker, partly coincident with and upstream of the Bagong Silang resistivity anomaly, is the most likely site of the resource. This region, however, lies along the axis of the Makar river valley which has been the site of several past pyroclastic flows and related laharic breccias. Along with the Gao river valley in the northwest, this sector was rated to have a high probability of being inundated by future pyroclastic flows and related debris deposits.

The decision to abandon the geothermal prospect proved correct and fortuitous because on September 6, 1995, a flashflood from the caldera lake killed nearly a hundred people on the volcano's northwestern flank. Although the exact nature of the flashflood remains controversial, the official government investigation (PHIVOLCS, 1995) attributed it to breaching of the dam on the lake's northwestern outlet. The dam failure released about 30 million cubic meters of lake water into the Gao (Alah) river system and its tributaries causing a 9-10 m drop in the lake level. Apparently, the water level in the lake had been slowly rising over the decades possibly due to a constrictions on its northwestern outlet. The triggering mechanism for the sudden breaching of the lake's northwestern dam is not known for certain. However, absence of volcanic seismicity, low lake water temperature, absence of fish kill, and absence of fresh tephra suggest that 1) eruption of juvenile magma into the lake bottom, 2) hydrothermal explosion, and 3) release of stratified gas from the lake bottom can be ruled out as triggering mechanisms (PHIVOLCS, 1995).

The flashflood confirmed our initial assessment that the Gao river valley, along with the Makar valley, faced serious risk from debris flows. Admittedly, our study emphasized the potential hazard from explosive eruptions over those of flashfloods or debris flows. Despite this, the hazard assessment proved instrumental in saving PNOC-EDC from financial and political losses. Had the potential geothermal

development site in Parker's east flank drilled, PNOC EDC might have been criticized, blamed, and, perhaps even, penalized for the disaster notwithstanding the nature of the flashflood.

CONCLUDING REMARKS

The case at Mt. Parker demonstrated the value of conducting even a semi-quantitative volcanic hazard assessment of geothermal systems in young volcanoes. The experience at other magmatic-hydrothermal systems in the Philippines, where chemistry of surface discharges provide some indications of magmatic involvement and hence the hazard, did not apply to Mt. Parker. In this case, C-14 dating and volcanological considerations proved more applicable in quantifying the hazard to resource development.

Many young volcanoes without historic record of eruptions exist along the Pacific Rim, possessing geothermal resources that will undoubtedly become exploration targets in the future. Our recent experience at Mt. Parker shows that meaningful hazard assessments in these young systems can be made without any great increases in the exploration budget, manpower or survey duration.

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