Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

CHARACTERISTICS OF THE VOLCANIC-HYDROTHERMAL SYSTEM IN MT. LABO, PHILIPPINES: IMPLICATIONS TO DEVELOPMENT

Orlando Maturgo, Maribel Zaide-Delfin, Domingo Layugan and John Patrick Catane
PNOC Energy Development Corporation, Ft. Bonifacio, Metro Manila, Philippines 1201

Key Words: magnetotelluric surveys, acid fluids, outflows, gravity surveys, exploration drilling

ABSTRACT

Deep drilling results confirmed the presence of a high-temperature geothermal system beneath the southwestern slopes of Mt. Labo, an inactive andesitic stratovolcano in southeastern Luzon, Philippines. Numerous andesite and dacite domes exist around the central volcanic edifice. The most probable heat source of the present thermal activity is a cooling pluton related to the youngest deposits erupted by the central cone 27,000 years before present. Three of the seven completed wells produce low-pH, SO_4-rich brine with temperatures of 260°-280°C. The low pH is due to the dissociation of HSO_4^- upon flashing of the fluids during discharge.

In the reservoir, all wells encounter near neutral-pH fluids, although the acid wells have much higher dissolved sulfate (400-1300 ppm) compared to neutral bores (<20 ppm). The increase in pH, decrease of SO_4 concentrations, and decline in measured temperatures along the postulated major outflow direction signify fluid neutralization process through water-rock interaction and dilution by cooler fluids along the outflow paths and some permeable channels.

Vertical Electrical Sounding (VES) and Magnetotelluric (MT) survey data define a 5 ohm-meter resistivity anomaly within a larger 10 ohm-meter enclosure. This suggests a possible minor upflow zone west of the acidic sector. Measured temperatures and chemical geothermometry suggest reservoir temperatures between 230° and 240°C in this sector. The occurrence of acid fluids in the hottest region, the temperature decline west of the acid sector and the incompetent formation in the north restrain development of the Mt. Labo prospect.

1.0 INTRODUCTION

Mount Labo, an inactive volcano at the northern tip of the Bicol Peninsula in southeastern Luzon, Philippines (Fig. 1), has been the object of geothermal exploration since 1982. In 1987, the PNOC Energy Development Corporation (PNOC-EDC) completed an integrated geological, geochemical and geophysical exploration program covering an area of approximately 600 square kilometers. The area of immediate economic interest lies within a 10 ohm-meter resistivity anomaly delineated by D. C. Schlumberger Resistivity Traversing (SRT) and Vertical Electrical Sounding (VES) methods. A three-well exploratory drilling program was carried-out between 1990 and 1992 to assess its potential for electricity generation. However, two of the wells (LB-1D and LB-3D) produced acid fluids while the other one (LB-2D) was abandoned during drilling due to persistent stuck pipe problems. From 1993 to early 1997, five more wells were drilled to intersect hot neutral-pH brine and delineate the extent of the acid fluid reservoir. The fourth well (LB-4D) sustained flow of neutral-pH fluids under low wellhead pressure, while LB-5D discharged acid fluids with SO_4 concentrations exceeding 2000 mg/kg - the highest level in the field to date. Well LB-6D failed to discharge due to poor permeability and relatively low temperature (220ºC) at the bottom. The other wells (LB-7D and LB-8D) did not sustain flow of neutral-pH brine because of early massive pressure drawdown and damaged permeability.

2.0 GEOLOGIC SETTING

The Mt Labo geothermal field is characterized by the presence of numerous andesite and dacite domes around a large inactive andesitic strato-volcano (Fig. 1). Thermoluminescence dating reveals that most of the domes were extruded between 40,000 years and 200,000 years before present (Ramos et al., 2000). The most recent volcanic deposits are the pyroclastic materials erupted from the central cone 27,000 ybp. Pliocene-Pleistocene volcanic rocks rest on top of an Upper Miocene formation composed of andesitic lava flows, agglomerates, tuffs intercalated with fossiliferrous and carbonaceous, fine-grained sandstone, siltstone and claystone. Known collectively as the Susung Dalaga Formation (Sdf), it hosts the deep geothermal reservoir.

Drilling and well completion tests results indicate that the flow of geothermal fluids is controlled mainly by NE-SW trending faults. Most of the surface thermal features are localized along these structures. The stratigraphic boundary between the Labo volcanics and Sdf, and some intraformational lithologic contacts provide minor permeability (Delfin et al., 1995).

2.1 Surface Thermal Features

The hydrothermal activity in Mt. Labo is manifested by warm springs, hot springs and cold altered grounds located mostly on its southwestern slopes. Mud pools, hot altered grounds, solfatara and kaipohan have not been found in the field. The geographical distribution of the thermal springs depicts an andesite volcano-hosted geothermal system typically found in the Philippines. Acid SO_4 springs occur at relatively high elevations (540-780 mASL) along the Mabahong Labo and Wala Rivers. Dilute, neutral-pH brine emanates at much lower elevations (<100-200 mASL) in the Kilbay-Alawihaw thermal area. Springs located at intermediate elevations discharge neutral-pH waters with varying amount of SO_4 and HCO_3 (i.e. Hagdan, Baay, Natuldocan and Pagtigbungan).

The hot springs in Kilbay and Alawihaw rivers are neutral-pH NaCl waters with considerably high amount of SO_4 (97-240 mg/kg) and HCO_3 (460-831 mg/kg). These springs are probable manifestations of the outflow from beneath the drilled sector. On the other hand, the warm acid SO_4-Cl springs along the Mabahong Labo River suggest mixing of steam condensate and/or steam-heated meteoric waters with upwelling brine.

2.2 Hydrothermal Alteration

The wells encountered neutral-pH hydrothermal alteration mineral assemblages composed of smectite, illite-smectite, illite, chlorite, quartz, calcite, dolomite, epidote, anhydrite, pyrite, laumontite, wairakite, with rare garnet, actinolite and secondary biotite.

In the sector drilled by LB-3D, LB-7D and LB-8D, clays and epidote exhibit progradational occurrence with increasing depth and temperature (Delfin et al., 1995). They are generally in equilibrium with present borehole temperatures and are apparently produced by neutral-pH hydrothermal fluids. Euhedral epidote, together with rare actinolite, garnet and secondary biotite suggests circulation of hot (260º–280ºC) neutral-pH fluids below –1200 mRL.

In contrast, clays and epidote in the sector probed by wells LB-1D and LB-5D exhibit overprinting and show disagreement with present stable well temperatures. Thus, most of the neutral-pH alteration minerals in LB-1D and LB-5D are relict and/or detrital. In wells LB-4D and LB-6D, on the other hand, the lack of well-defined clay zonation and a lower rank of alteration reflect the poor permeability that impedes the circulation of deep geothermal fluids in the northeastern sector.

Recent acid alteration minerals occur mainly in LB-1D and LB-5D as thick layers of alunite and sulfur above sea level, and as thinner discrete zones of diaspore, pyrophyllite and dickite below -300 mRL often along fault intersections. Acid alterations in LB-3D and LB-4D are rare and confined to narrow zones near the surface. In LB-5D, the deep acid alteration minerals below -200 mRL are associated with pneumatolytic minerals such as topaz [Al_2 (F, $OH)_2SiO_4$] and lazulite [Al_2(Mg, Fe) $(OH)_2$ $(PO_4)_2$]. These minerals are formed by reaction of magmatic gases with the country rocks at temperatures above 370°C, and therefore can be considered relict of the past magmatism since the maximum temperature measured in LB-5D is only 262°C. Nevertheless, they indicate proximity of LB-5D to a deep-seated, degassing intrusive body associated with the youngest volcanic deposits in the field.

3.0 GEOPHYSICAL MEASUREMENTS

Early geophysical surveys in Mt. Labo consisted of Schlumberger resistivity traversings (SRT) and vertical electrical soundings (VES). These surveys delineated a large 10 ohm-meter anomaly beneath the west-southwestern flank of Mt. Labo, which provided a target for exploratory drilling. In mid-1995, gravity and magnetotelluric (MT) surveys were conducted to determine the overall subsurface geological structure and define the deeper (1 to 3 km) resistivity profile beyond the depths penetrated by the SRT and VES methods (Los Baños et al., 1996).

3.1 Magnetotelluric Survey

The low resistivity anomaly centered at the Mabahong Labo thermal springs probably outlines the size and extent of the upflow region (Fig. 2). This conductive zone coincides with the thick alteration halo that developed directly above the geothermal reservoir where hydrothermal activity is more intense and active. This alteration halo represents the hydrous low-temperature clays (primarily smectite) encountered in the boreholes. The resistive bottom layer located directly below the thick (1.5 to 2.0 km) conductive layer exhibits higher resistivity values of 30 to 40 ohm-m. It hosts the production zones of wells LB-1D, LB-3D and LB-4D. The rise in resistivity of the basement could be due to predominance of anhydrous high-temperature minerals such as illite and epidote. This resistivity structure modeled by the MT data departs from the previously thought signature of low resistivity horizons associated with the production zones mapped by SRT and VES methods.

Review of Vertical Electrical Sounding (VES) survey data defined a small 5 ohm-meter resistivity anomaly within the much larger 10 ohm-meter enclosure. This coincides with the steep resistivity boundary delineated by magnetotelluric surveys. Located near the Susung Maliit dome, it could represent a minor upflow zone west of the drilled sector.

3.2 Regional Gravity Survey

The residual gravity contours indicate a pronounced gravity low of -2 to < -6 mgals west of Mt. Labo (Fig. 3). Four zones of gravity highs with values ranging from +2 to > +7 mgals were located in the north, in the northeast, in the south (beneath wells LB-1D and LB-5D), and in the southwest within the Kilbay-Alawihaw area (Los Baños et al., 1996). The effect of free air, latitude, Bouger and terrain were corrected using GEOLINK software to produce the final Bouger anomaly map.

The low gravity zone correlates with the sedimentary rocks of the Susong Dalaga Formation. This formation thickens from east to west and is displaced by a major NNE-SSW fault inferred from the steep gradient separating the negative and the positive gravity values. The gravity high over the Mt. Labo edifice represents the intrusive body beneath LB-5D. The gravity highs observed in the north and northeast of Mt. Labo are attributed to metamorphic basement rocks at shallow depths. On the other hand, the gravity high in the Kilbay-Alawihaw area can be associated with silicified rocks that crop out. Alternatively, they can be signatures of the shallow intrusive body associated with the domes nearby.

4.0 WELL OUTPUT AND FLUID CHEMISTRY

The wells in Mt. Labo can be classified as non-commercial and commercial wells or as acid and neutral wells (Table 1). The neutral wells yield a non-commercial output due to poor permeability. Well LB-4D, for example, has an injectivity index of only 4.4 l/sec-MPa. The permeability of LB-7D and LB-8D, on the other hand, was affected adversely by the use of barite during drilling. The acidizing operation aimed to improve the permeability of LB-7D failed to deliver commercial output.

4.1 Chemical Trends

The area with the most mineralized fluids lies beneath well LB-7D where Cl_{res} ranges from 5400 to 5500 mg/kg, and the least in LB-5D (Table 2). However, if discharge of LB-5D and LB-1D had been prolonged, Clres from these wells would probably stabilize at about 4500 mg/kg, which is of the same magnitude as that in LB-3D (Maturgo, 1998). Well LB-4D and LB-8D have the lowest Clres ranging from 3600 to 3900 mg/kg.

The SO_{4res} content in LB-5D is high, ranging from 1300 to 1600 mg/kg. This is more than twice that of fluids in LB-1D, LB-3D and LB-8D. The values exhibit a decreasing trend from the sector drilled by LB-5D towards the southwest in LB-1D, LB-3D and LB-8D. However, although LB-8D produced neutral-pH brine, SO_{4res} in this well is of the same concentration level in LB-3D (Table 2). Comparatively, the SO_{4res} content in LB-4D and LB-7D are much lower, not exceeding 20 mg/kg. Thus, the brine produced by the wells can be categorized into low-sulfate and high-sulfate fluids.

The CO_2/H_2S ratio can be used to assess the proximity of a well to the upflow zone or heat source. Lower ratios or higher H_2S levels are characteristic of wells drilled close to the upflow zone. Otherwise, there is a direct communication with the heat source through a permeable structure. This implies that LB-1D lies closer to the upflow region. Otherwise, it has a good communication with the heat source through the Mabahong Labo fault. The comparatively high CO_2/H_2S ratios in LB-4D and LB-7D are consistent with their relative distance to LB-1D. The ratios in LB-3D and LB-8D suggest that there could be structural interconnection between LB-1D and these wells, most likely through the Mabahong Labo fault.

4.2 Origin of Fluids

With the high amount of SO_4 and absence of excess Cl, it is postulated that the deep fluids in Mt. Labo are in a transitional stage from a magmatic system to a mature hydrothermal system. This explains the presence of minor fraction of magmatic gases in LB-5D (Maturgo, 1998). Further, the enrichment in $\delta^{18}O$ of the fluids in LB-3D suggests 32 to 42% andesitic water components (Fig. 4). In areas like Alto Peak and Mt. Pinatubo where magmatic waters have been encountered, the brines exhibit 50% to 75% enrichment in $\delta^{18}O$. Moreover, in producing fields like Bacon-Manito, Mt. Apo and Palinpinon, stable isotope data indicate 27% to 30% andesitic water contributions in the brine.

The decline of fluid pH during the discharge testing of wells LB-1D, LB-3D and LB-5D was associated with an increase of SO_4 concentrations. A simulation of the changes in pH and concentrations of dissolved sulfur species due to flashing shows increase in SO_4 levels while HSO_4 declines. These trends indicate that the dissociation of HSO_4 to H^+ and SO_4^- upon flashing, which causes significant drop in temperature of the rising fluid, contributes to fluid acidity. However, the decline of HSO_4 in the acid wells is not as steep as that in the neutral wells. This and the concentrations of HSO_4 in the reservoir fluids, apparently, make the difference between the discharge pH of the acid and neutral wells.

4.3 Chemical geothermometry

An evaluation of the applicability of chemical geothermometers gives an insight in the state of fluid-rock equilibration in Mt. Labo. In the Na-K-Mg ternary diagram (Fig. 5), only the data points of LB-1D and LB-5D fluids plot outside the equilibration region. Nevertheless, they lie along a dilution line with most of the data points from other wells, indicating reservoir temperatures between 240° and 260°C. The acid and neutral Cl-SO_4 fluids in LB-3D, the neutral Cl-SO_4 brine of LB-8D and the Kilbay-Alawihaw hot springs plot within the partially equilibrated region. Only the brine from LB-4D and LB-7D represents fully equilibrated fluids. It is interesting to note that the neutral-pH, SO_4-rich fluids from LB-3D and LB-8D plot near the full equilibrium boundary. This implies that there is really a neutralization of the fluids through water-rock interaction as they flow towards the southwest.

5.0 PROCESSES AFFECTING FLUID CHEMISTRY

The deep geothermal fluids are equilibrating with the reservoir rocks as they flow from the upflow region to its periphery. This process, apparently, results in an increase of pH while SO_4 content declines from LB-5D towards the southwest in LB-3D. In fact, LB-7D produced fully equilibrated neutral-pH brine.

Based on the Cl-Enthalpy plot (Fig. 6), it is inferred that the parent fluid contains 4600 mg/kg of chloride with temperature of about 300°C. The fluids discharged by LB-7D appear to be residual fluids produced by boiling of the parent water (in the past) at 250°-270°C. The fluids from the other wells were produced by dilution of the parent fluid at 260°-290°C.

The Kilbay-Alawihaw spring waters, apparently, evolved from conductive cooling and dilution of the deep geothermal fluids as they migrate laterally towards the southwest. The neutral HCO_3-SO_4 springs in the northern region suggest a minor outflow to this direction. The scarcity of hydrothermal alteration in wells LB-4D and LB-6D implies that poor permeability impedes the circulation of neutral-pH brine waters in these areas.

6.0 IMPLICATIONS TO DEVELOPMENT

To be economically feasible, the exploitation of the Mt. Labo geothermal field requires a higher than 40 MWe-development. However, the occurrence of acid fluids in the hottest sector of the resource, the declining temperature towards Kilbay-Alawihaw and the poor permeability in the neutral-pH region need to be evaluated carefully before launching a development program.

6.1 Acid fluids

Aside from reducing the size of potentially exploitable resource substantially, the acid fluid has the potential of invading the neutral-pH sector in case of pressure decline due to continuous well discharge or mass extraction during exploitation. The possibility for this to occur is high considering that the proven neutral-pH region is located along the major outflow direction. A probable indication of this is the fact that LB-3D discharged neutral-pH fluids for about one month before it turned acidic.

6.2 Marginal temperatures

Another constraint is the probability of encountering marginal temperatures downstream of LB-7D or near the Susong Maliit dome. If there is a separate heat source for the minor upflow zone defined by the 5 ohm-meter resistivity anomaly in this sector, it is correlative with the dome-building episode that occurred 140,000 to 190,000 ybp. Its age therefore is significantly older than that of the system near LB-1D. Although it could mean a mature and evolved hydrothermal system in the southwest where fluids are of neutral-pH, reservoir temperatures may be lower.

If the Kilbay-Alawihaw springs were outflow features of this system, the temperatures in the area would range from 230° to 240°C based on the trend of measured temperatures and cation geothermometers.

6.3 Incompetent formation

In the sector probed by LB-2D and LB-4D, the incompetent sedimentary rock units restrains further drilling activity. Well LB-2D was abandoned during drilling without setting the production casing due to persistent cave-in and swelling of the claystone component of the Susong Dalaga formation. Because of similar problems, the last 500 meters of LB-4D was completed by slim hole with 5-inch slotted liner instead of the usual 7-5/8 diameter-liner.

The use of barite during drilling to mitigate such problem in LB-7D, however, has damaged its permeability. Although circulation losses occurred while drilling, completion tests results indicated an injectivity index of only 11.0 li/sec-MPag at wellhead pressures of 2.26 to 9.65 MPag.

Thus, unless there is a technique that will not affect permeability adversely, it is not encouraging to undertake delineation drilling in the area. Moreover, the economically feasible level of development in Mt. Labo cannot be realized without using the adequate materials that will eliminate the deleterious effects of acid fluids on the fluid collection and disposal system.

ACKNOWLEDGMENTS

The authors are indebted to the PNOC EDC geoscientific management staff for the permission to publish this report, and to their colleagues for the technical support and suggestions.

REFERENCES

Delfin, M. C. Z., Gerona, P. P., Layugan, D. B., Maturgo, O. O., Padua, D. O., Panem, C. C., Rosell, J. B. and Salonga, N. D. (1995). *Mt. Labo Resource Geothermal Project Assessment Update*. PNOC-EDC Internal Report, 152pp.

Giggenbach, W. F. (1991). *Chemical Techniques in Geothermal Exploration.* In: D'Amore, F. (coordinator), Application of geochemistry in geothermal reservoir development. Unitar/UNDP publication, Rome, pp. 119-142.

Los Banos, C. F., Layugan, D. B., Maneja, F. C., Apuada, N. A. and Delfin Jr., F. G. (1996). *Geophysical Model of Mt. Labo Geothermal Field, Southeastern Luzon, Philippines.* Proc. of the 1996 Annual Meeting of Geothermal Resources Council held in Portland, Oregon, U.S.A. on Sept. 29-Oct. 02, 1996, pp. 689-696.

Maturgo, O. O. (1998). *Geochemical evaluation of Mt. Labo Geothermal Project: Update and Review*. PNOC-EDC Internal Report, 37 pp.

Ramos, S. G., Zaide-Delfin, M. C., Takashima, I., Bayrante, L. F., Panem, C. C. and Pioquinto, W. C. (2000). *Thermoluminescence Dating in Mt. Labo and North Davao, Philippines: Implications on Geothermal Models.* A paper accepted in the World Geothermal Congress 2000.

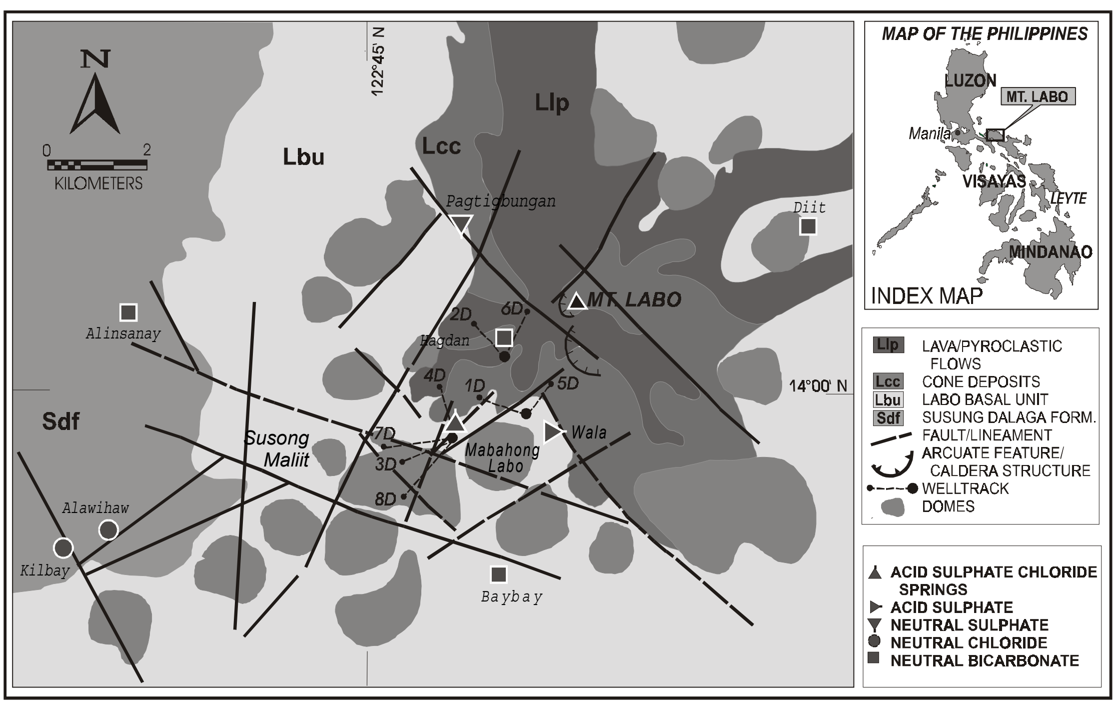

Figure 1. Geological map of Mt. Labo geothermal field showing location of wells and thermal features.

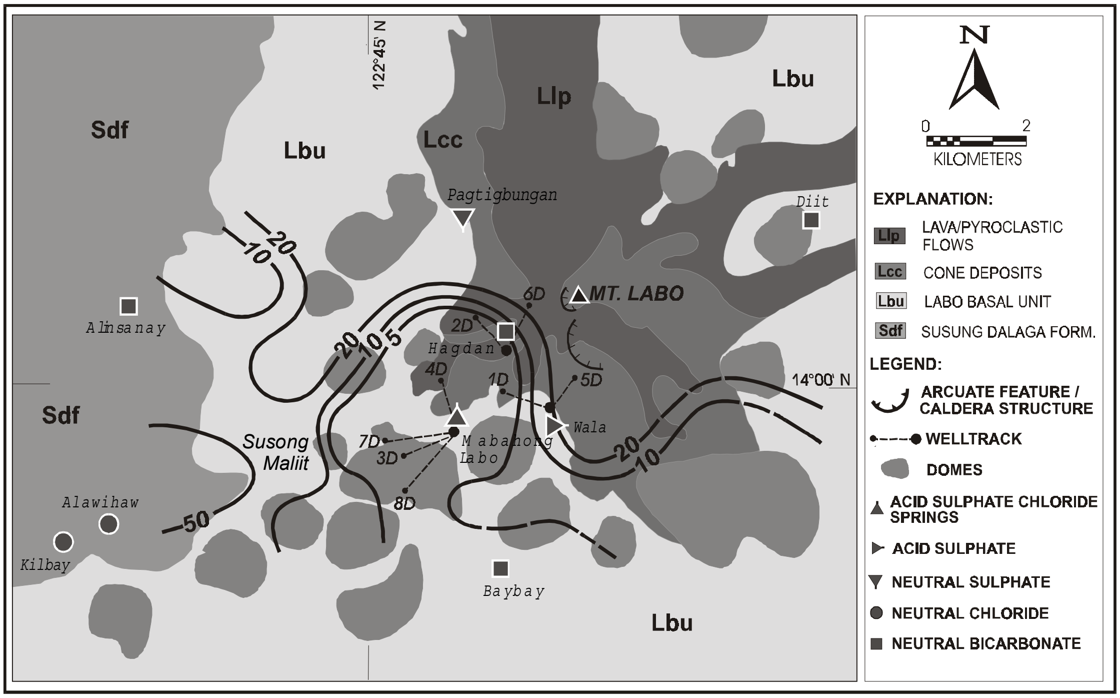

Figure 2. Isoresistivity map at 1000-meter depth based on magnetotelluric survey results.

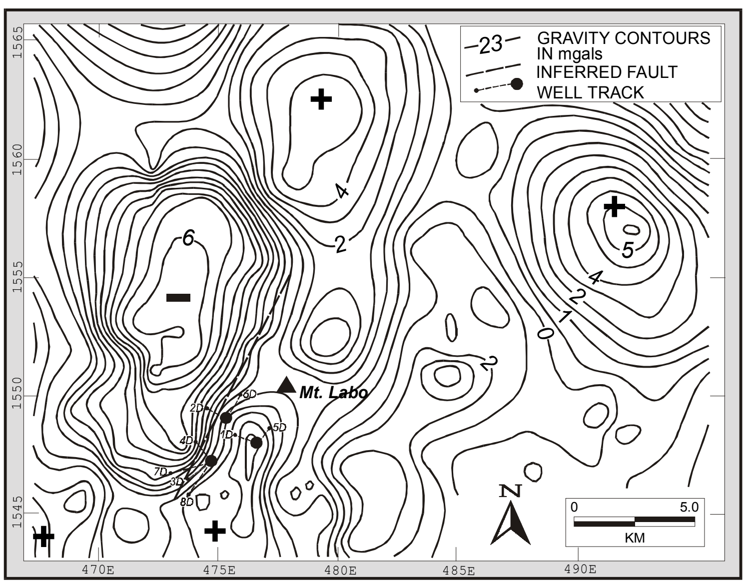

Figure 3. Residual Gravity Anomaly Map of Mt. Labo geothermal field (Los Baños et al., 1996).

Table 1. Summary of Well output Characteristics

Well Name	**WHP (MPaa)**	**Water Flow (kg/sec)**	**Total Mass Flow (kg/sec)**	**Enthalpy (kJ/kg)**	**Potential Output (MWe)**	**Fluid Type**
LB-1D	0.48	26	40	1240	4	Acid
LB-2D	Well not completed due to drilling problems. Plugged and abandoned.					
LB-3D	1.19	52	82	1224	8	Acid
LB-4D	0.07	4	9	1653	Non-commercial	Neutral-pH
LB-5D	0.24	16	23	1086	Non-commercial	Acid
LB-6D	Well did not discharge (poor permeability and relatively low temperature: 220°C)					
LB-7D	0.07	5	17	1932	Non-commercial	Neutral-pH
LB-8D	0.04	6	14	1745	Non-commercial	Neutral-pH

Table 2. Comparison of selected chemical parameters (concentrations are in mg/kg)

Well	Cl_{res}	SO_{4res}	Cl/SO_4	CO_{2td}	H_2S_{td}	CO_2/H_2S
LB-1D	4300-4500	500-650	18-22	18-19	274-695	37
LB-3D	4400-4500	500-600	18-22	25-28	800-900	34-36
LB-4D	3700-3900	18-23	412-525	250-735	90-100	<1
LB-5D	3500-3800	1300-1600	6-7	32-34	200-400	7-11
LB-7D	5400-5500	15-18	800-900	49-95	1000-1300	12-20
LB-8D	3600-3900	460-500	20-21	22-24	800-1400	33-62

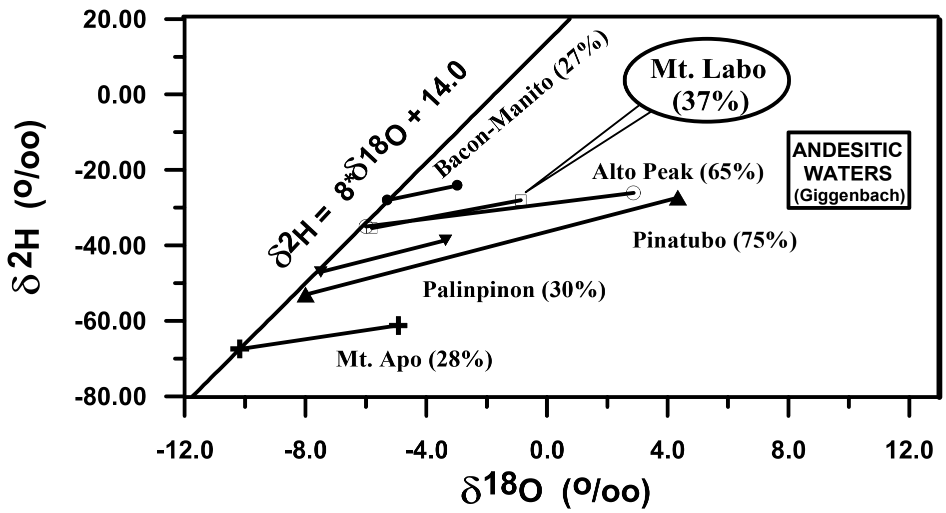

Figure 4. Stable isotope composition of acid fluids from various PNOC-EDC geothermal fields.

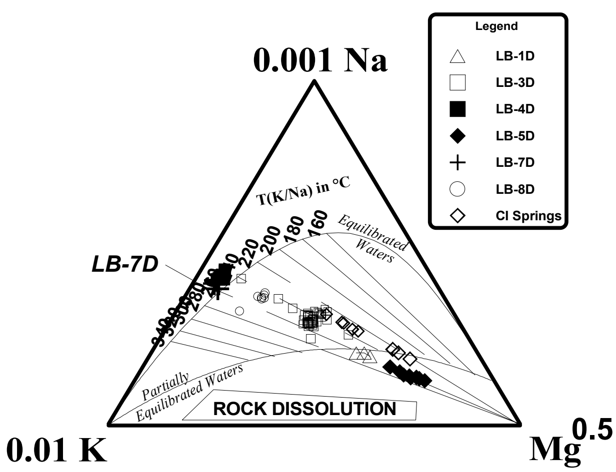

Figure 5. Estimated reservoir temperature from cation geothermometry (Maturgo, 1998).

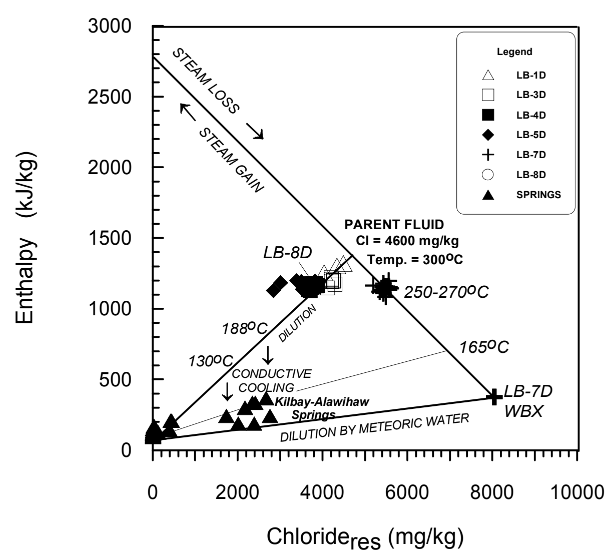

Figure 6. Processes affecting fluid composition in Mt. Labo geothermal field (Maturgo, 1998).