

GEOCHEMISTRY UPDATE OF THE SOUTHERN LEYTE GEOTHERMAL PROJECT, PHILIPPINES

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ABSTRACT

Exploration drilling in the Southern Leyte geothermal project began in 1997 with the completion of well SL-1D, based on geoscientific studies conducted between 1989 and 1996. After a three-year hiatus, the second well, SL-2D, was drilled in early 2003. Results of drilling and testing confirm the existence of an active geothermal system in SLGP possibly centered in the western flank of Mt. Cantoyocdoc. The upflow fluid is of neutral pH, with a temperature of ~260°C. Thermal springs to the west and east of the field are

produced by mixing of meteoric waters with the residual liquid of the upflow fluid boiled at a temperature of 190°C.

1.0 INTRODUCTION

The Southern Leyte geothermal project (SLGP) is located at the southeastern tip of Leyte island (Fig. 1). Exploration in Southern Leyte began with a reconnaissance survey in 1983, followed by more detailed surface geoscientific activities in 1989 and 1996. Prospect evaluation led to the drilling of the first exploratory well (SL-1D) in 1997. Disappointing drilling results induced the conduct of remote sensing (Camit, 1999) and magnetotelluric work (Rigor *et al.*, 2001). In 2003, a second exploratory well was drilled in Southern Leyte.

This paper incorporates recent drilling and testing data with existing geoscientific information in SLGP, and updates the fluid chemistry characterization of the geothermal reservoir as well as the current understanding of the hydrologic model of the hydrothermal system in Southern Leyte.

2.0 SUMMARY OF PREVIOUS WORKS

Based on the 1989 and 1996 exploration evaluation, Leynes, et al. (1997) proposed a pre-drilling hydrologic model of Southern Leyte (Fig. 2). The model invokes the presence of an active geothermal system centered in the vicinity of Mt. Cabalian. The system is perceived to host a $\geq 200^\circ\text{C}$, neutral-pH fluid with an estimated chloride content of ~2500 mg/kg. Preferential fluid migration is towards the northeast and west where thermal springs effuse. The model also suggests boiling of the reservoir fluid as it moves towards the outflow zones.

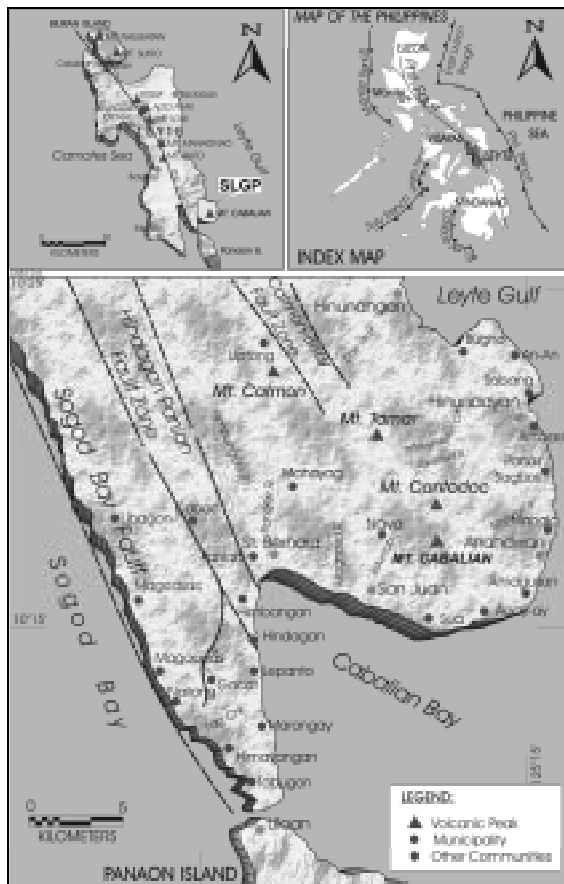


Figure 1. Location map of Southern Leyte geothermal project (SLGP).

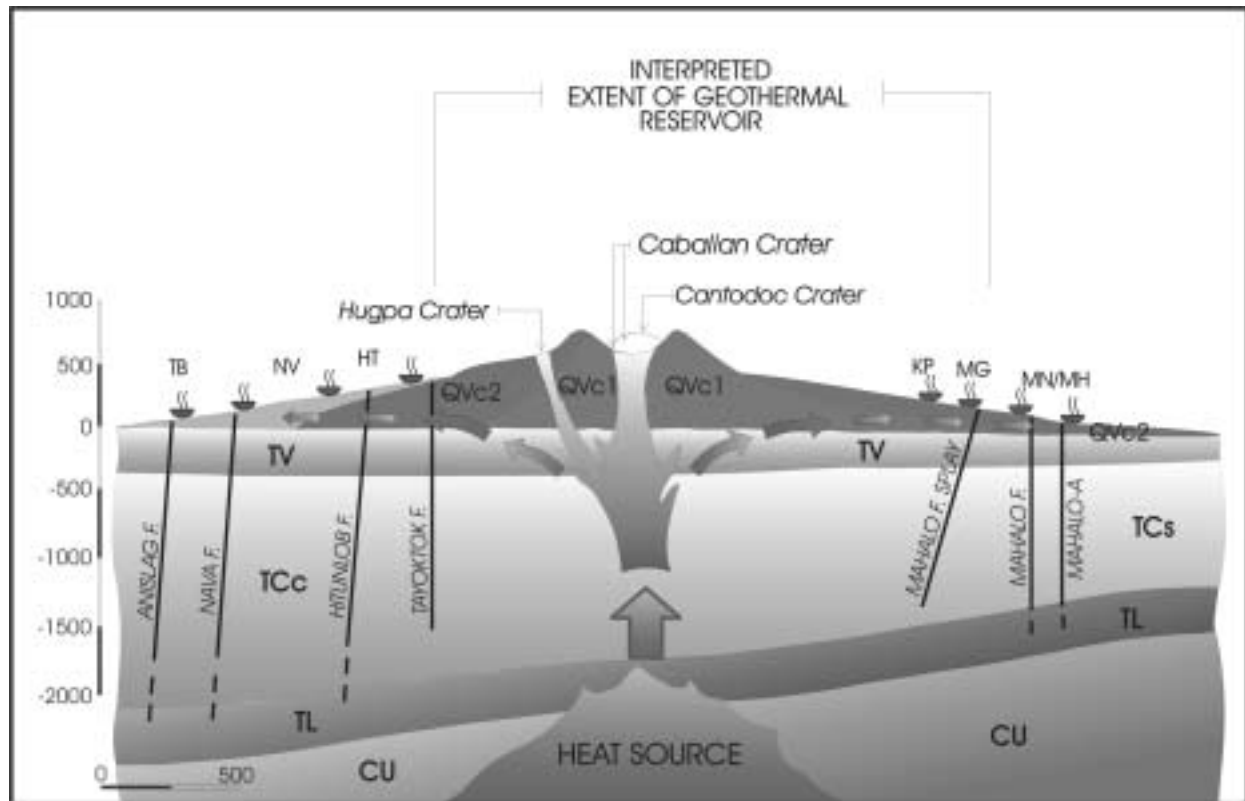


Figure 2. Pre-drilling exploration model

Thermoluminescence (TL) data (Ramos *et al.*, 1997) confirmed that Mt. Cabalian volcanic products are the youngest in the study area, with an estimated age of 17 ka. Mt. Cantoyocdoc and Mt. Tamar rock samples, on the other hand, yielded TL ages of 510 ka and 490-670 ka, respectively. TL ages of Mt. Cabalian and Mt. Cantoyocdoc volcanics are comparable to previously determined ^{14}C and K-Ar ages. Furthermore, TL data tagged the age of at least one hydrothermal event at 5-6 ka.

One-dimensional and Occam inversion modeling of magnetotelluric (MT) data (Los Banos, 1997) yielded a general three-layer model for the prospect, consisting of a high-resistivity surface layer, low resistivity second layer at 1000-2000 m depth, and another high-resistivity bottom layer. Two low-resistivity anomalies were detected – west and northeast of the Cabalian volcanic edifice. These low-resistivity anomalies mirror those detected in the 1989 DC Schlumberger resistivity sounding survey. Present between Mts. Cabalian and Cantoyocdoc is a high-resistivity mass coincident with a modeled gravity high,

interpreted to represent a shallow intrusive body. The 1997 MT survey did not refine the 1996 hydrologic flow model of the prospect.

In 2000, additional MT stations were occupied, and new data were combined with the 1997 survey data to generate a geophysical model of SLGP (Rigor *et al.*, 2001). This geophysical model similarly invokes a single hydrothermal system in Mt. Cabalian, but the system is thought to be centered west of Mt. Cantoyocdoc coincident with the high-resistivity body (Fig. 3). Preferential fluid flow is towards the east (Mainit-Mahalo thermal area) through a narrow zone bounded by Tunga and Mahalo faults. The western outflow direction (Nava-Magcasa thermal areas) is minor, thermal springs here fed by NW and EW trending faults. Although the SLGP MT signature of a 3-layer resistivity model is similar to those in producing geothermal fields such as Bacman and Northern Negros, the conductive second layer in SLGP is less coherent than in the above production fields. This implies that the hydrothermal system in SLGP is probably smaller than Bacman and Northern Negros.

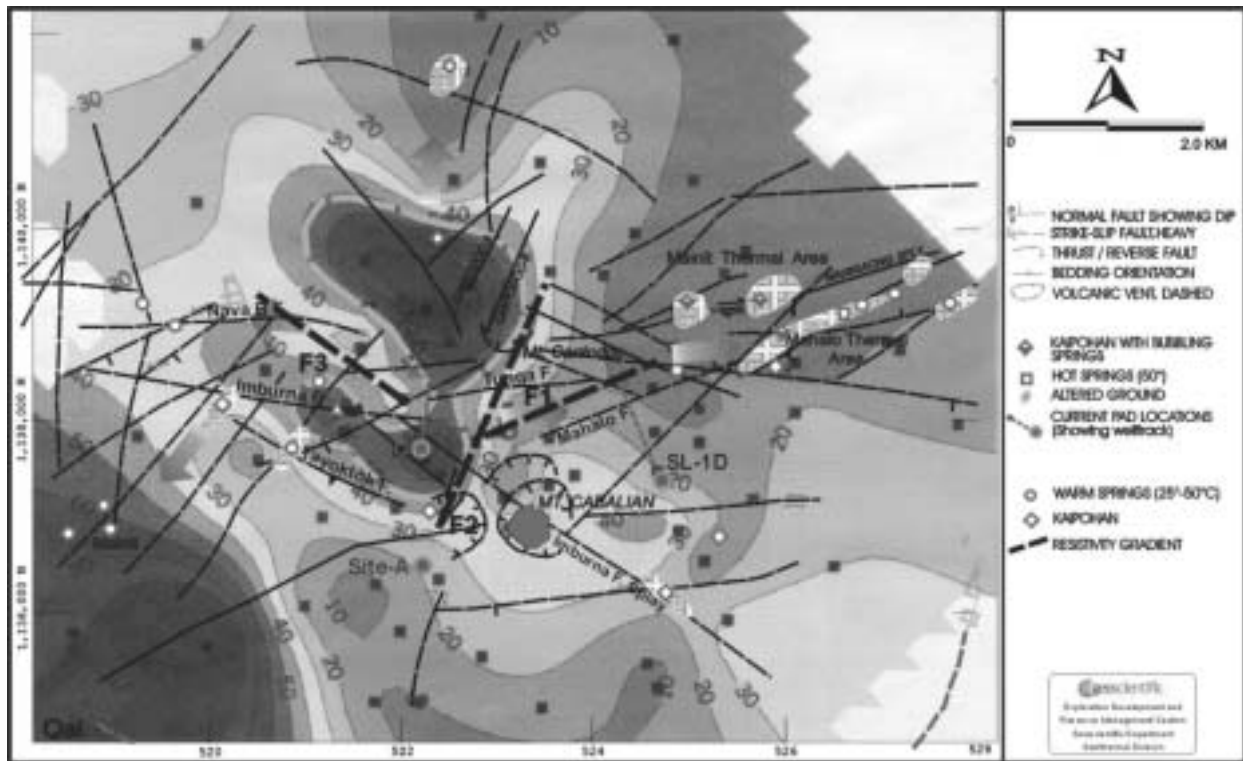


Figure 3. SLGP geophysical model

Camit (1999) proposed a 2-system model for SLGP – one centered in Huga and another close to Mts. Tamar and Cantoyocdoc. This model is based primarily on spatial distribution of thermal springs and acid-altered grounds, structural analysis from remote sensing data, and presence of a deep and thick low-resistivity anomaly northeast of Mt. Cantoyocdoc and southwest of Mt. Tamar. The Cantoyocdoc-Tamar system supplies fluid to the acid-altered grounds found in the north, while the Huga system is associated with the east and west thermal areas described earlier.

3.0 DRILLING RESULTS

3.1 Well SL-1D

This well was drilled in 1997 to a depth of 2710 mMD/2398 mVD (Leynes and Bien, 1998). It was spudded on a pad east of Mt. Cabalian (Fig. 4), and deviated to the northwest to intersect the structural controls of the eastern (Mainit-Mahalo) thermal area. The well intersected fresh andesitic to dacitic Upper Quaternary volcanics from surface down to 260 m, altered andesitic and dacitic Lower

Quaternary volcanics down to 660 m, and Tertiary clastics composed of breccias, fine clastics and limestone lenses down to total depth (Rosell and Zaide-Delfin, 1997). Hydrothermal alteration is of neutral-pH type throughout the well, with no acid alteration minerals identified. Alteration mineralogy and fluid inclusion data show a progradational trend from 120 m down to 1450 mMD. Further down the well, however, an isothermal temperature profile was observed, with highest temperature estimated at 230°C at bottomhole. Subsequent heat-up surveys predicted the same stable well temperature.

Although the well intersected about five geologic structures, none of these faults exhibited good permeability. The most permeable zone is within the cased-off section at 700-1000 m, correlative with Mahalo Fault Splay. Below the casing shoe, no massive circulation losses were experienced, and petrologic evidence of good permeability was likewise absent. The low injectivity index of 2.8 li/s-MPa is further proof of the poor permeability of the well. As a result, the well was never flow-tested.

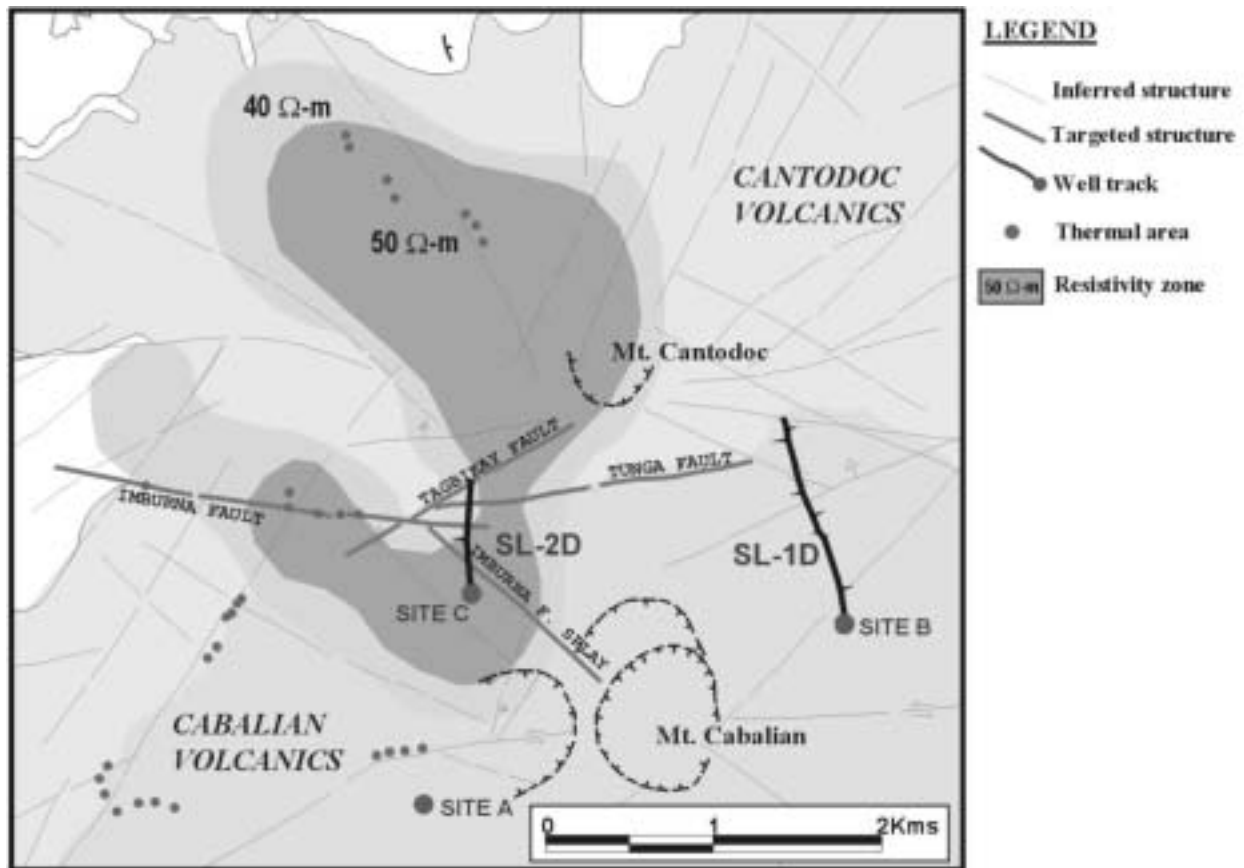


Figure 4. SL-1D/SL-2D welltrack map

3.2 Well SL-2D

The second exploratory well was drilled in early 2003, spudded from a pad WNW of Mt. Cabalian and deviated north-northeast towards the western flank of Mt. Cantoyocdoc. It reached a total depth of 2494 mMD/2362 mVD with a throw of 624 m (Zaide-Delfin *et al.*, 2003). It was principally designed to confirm the existence of an upflow region between Mts. Cabalian and Cantoyocdoc.

Well SL-2D intersected the same stratigraphic units as the first well - Quaternary volcanics (QV) and Tertiary (TC) clastics. The Upper QV was encountered from surface to 550 m, while the Lower QV was intersected down to 1085 mMD. Tertiary clastics were identified from 1085 m to total depth. Based on alteration mineralogy and mineral temperature indicators, temperatures in SL-2D progressively increase with depth. Epidote developed from incipient (suggesting a fluid temperature of 180°C) at shallow depths to crystalline veins (>260°C) near bottomhole. Similarly, low-temperature

(~120°C) clay minerals like vermiculite and smectite exist at shallower depths while high-temperature clays illite-smectite (~180°C) and illite (>220°C) occur at deeper levels. Vein fluid inclusions in calcite, anhydrite, and quartz showed a wide range of homogenization temperatures, although the minimum or average values are often close to temperatures predicted by mineralogy. Higher values (~320°C) are interpreted to be likely related to dike intrusions rather than with the current hydrothermal system.

Post-drilling completion test (Saw *et al.*, 2003) showed only one permeable zone below the casing shoe, at 1800-2000 mMD coinciding with the well's intersection of Imburna Splay Fault. A suspected second zone near well bottom was not detected by the survey. The permeable zone was characterized by massive circulation loss during drilling, although circulation was partially recovered by injecting drilling mud. The relatively low injectivity index of 9.8 li/s-MPa is attributed to the high mud volume pumped into the well to recover circulation, rather than to

poor permeability of the well. Acidizing operation is being programmed in the near future to displace the mud inside the well and improve its permeability significantly. Permeable zone temperature at 3-days and 13-days shut was constant at 190°C.

SL-2D was subsequently flow-tested from 01 June to 31 July 2003.

4.0 FLUID CHEMISTRY UPDATE

4.1 SL-2D Discharge History

The well was discharged by air-lifting on 01 June 2003. Its initial wellhead pressure (WHP) was 0.30 MPaa at full-bore opening. The well discharged at this condition for a week with zero lip pressure, thus no massflow and enthalpy measurements were taken. After a week at a stable WHP of 0.34 MPaa, manual throttling of the side-valve (SV) was performed regularly to determine the maximum discharge pressure limit. The recorded highest sustainable WHP attained was 0.45 MPaa. Unfortunately, lip pressure remained zero, rendering James' lip pressure method useless in measuring enthalpy and massflow.

Beginning 11 July, a steady decline in WHP was observed. At full-bore discharge (FBD), WHP declined from the original value of 0.34 to 0.25 MPaa. When the well was shut on 31 July, WHP had dropped to 0.20 MPaa.

4.2 SL-2D Reduced Fluid Chemistry

Given in Table 1 is the summary of the well's fluid chemistry. These stable values were consistent at all bore openings, indicating that only the Imburna Splay Fault feedzone was contributing to the well discharge. Since no enthalpy measurement was taken, fluid enthalpy was assumed to be correspondent to liquid-saturated enthalpy at silica geothermometer temperature. Total discharge values for liquid chemical species were thus assumed to be the same as reservoir concentrations.

A few "peculiarities" are observed in the chemical signature of the well. Firstly, reservoir Mg is unusually high at 3.80 ± 0.60 mg/kg. In comparison, Mg_{res} is commonly <1 in Leyte, Bacman, and other geothermal areas. Secondly, the Na-K-Ca and Na-K

Table 1. Summary of SL-2D fluid chemistry

WHP	0.45 MPaa (Maximum)
Laboratory pH	7.50
Enthalpy	1080 ± 10 J/g (based on Tqtz, assuming liquid saturation)
Water Chemistry	
Cl res	$5,000 \pm 200$ mg/kg
Ca res	100 ± 10 mg/kg
Mg res	3.80 ± 0.60 mg/kg
SiO ₂ res	455 ± 10 mg/kg
SO ₄ res	50 ± 5 mg/kg
Cl/Ca	55 ± 5
Cl/B	30 ± 3
Gas Chemistry	
CO ₂ TD	750 ± 90 mmoles/100 moles-steam
H ₂ S TD	6.25 ± 1.25 mmoles/100 moles-steam
% NCG w/w at TD	0.30 ± 0.01
➤ @ 1.00 MPaa SP	1.90%
➤ @ 0.90 MPaa SP	1.82%
➤ @ 0.80 MPaa SP	1.70%
➤ @ 0.70 MPaa SP	1.62%
➤ @ 0.60 MPaa SP	1.53%
CO ₂ /H ₂ S	120 ± 5
Geothermometers	
Tqtz	$250 \pm 2^\circ\text{C}$
TNaK	$230 \pm 2^\circ\text{C}$
TNaKCa	$230 \pm 2^\circ\text{C}$
TH ₂ S-CO ₂	255 ± 5
TCO ₂ -CH ₄ -H ₂	255 ± 5
TCO ₂	255 ± 5

geothermometers give much lower temperatures compared to the quartz geothermometer. Thirdly, gas geothermometers are consistent in fluid temperature estimates, and these tally with the quartz temperature.

The high Mg content of the well fluid is consistent with earlier observation that Ca and Mg in SLGP thermal springs are rather high (Bayon, 1996). High amounts of Ca and Mg have been attributed to the occurrence of thick carbonate beds in the regional stratigraphic sequence, although these have not been encountered in the wells drilled. According to Fournier (1991), Mg and Ca interfere with the crystal structure of participating minerals governing the Na-K and Na-K-Ca equilibria (such as albite and K-feldspars for TNaK), which may explain the lower temperature estimates given by the two geothermometers in SL-2D. The true reservoir fluid temperature in SL-2D is probably 250-260°C as reflected by the quartz

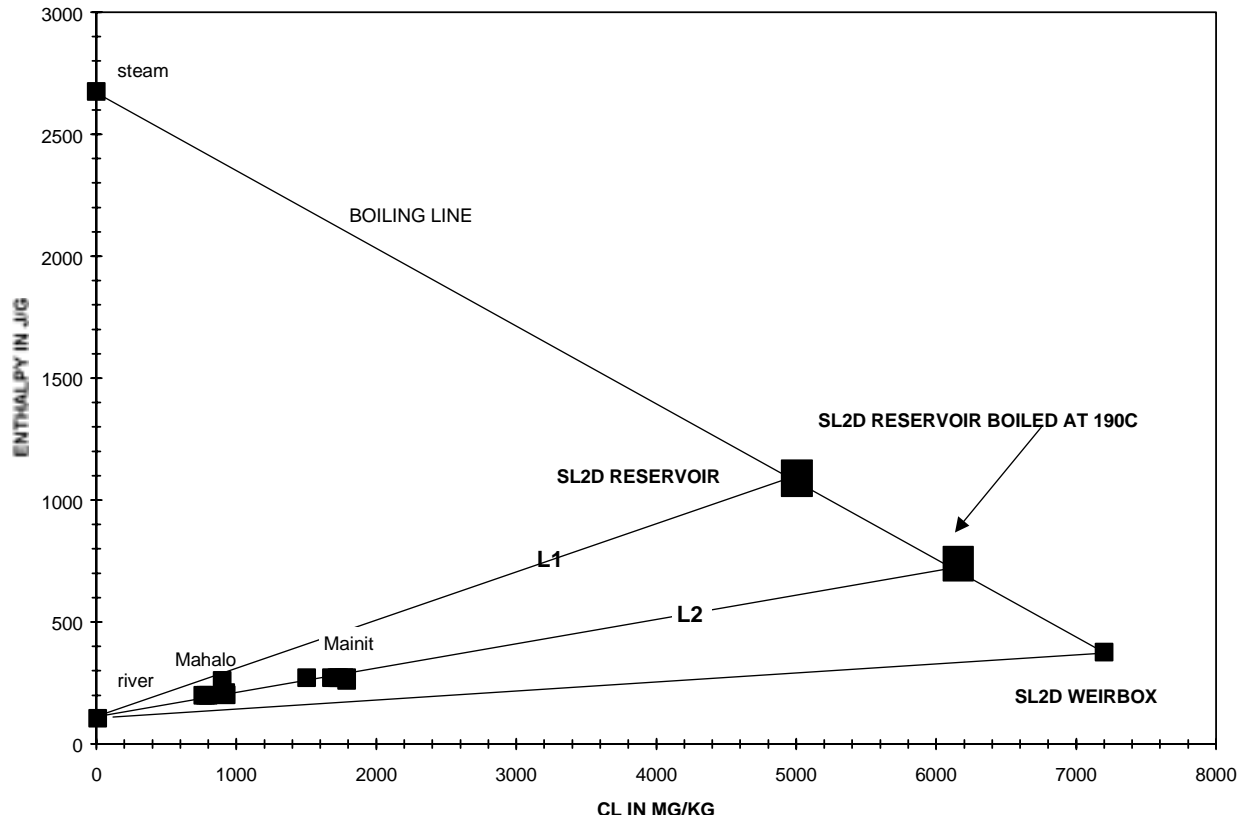


Figure 5. Cl-H cross plot of SLGP waters

and gas geothermometers. The consistent temperatures given by quartz, mineral and gas geothermometry further implies that this is probably the reservoir fluid temperature of the hydrothermal system. Given the Mg interference, Na-K and Na-K-Ca temperatures are most probably unreliable.

A chloride-enthalpy plot (Fig. 5) integrates well and spring fluid chemistry. The thermal springs do not connect with SL-2D reservoir fluid by simple dilution, and need an intermediate process to establish a relationship. If the well reservoir fluid is boiled to 190°C, the residual brine (with ~6000 mg/kg Cl), connects to the surface springs through simple dilution and cooling. This diagram agrees with the previously estimated reservoir fluid temperature of 200°C based on spring data, with strong evidence of subsurface boiling (Leynes *et al.*, 1996).

4.3 Calciting Potential

The lowering of WHP of SL2D was suspected to be due to calcite deposition; possible inflow of

colder fluids (<200°C) was eliminated because of the high Tqtz (250°C). To evaluate the possibility of calcite deposition, calcite saturation indices (CSI) at different boiling temperatures were simulated using Weber gas and water chemistry of 18 July 2003 as the representative fluid chemistry. Figure 6 shows the computed CSI at various boiling temperatures (from reservoir to 120°C assuming adiabatic cooling). The figure shows that the fluid is calcite-supersaturated at the temperature range of 140-230°C, and maximum supersaturation is at 200°C. Thus, potential for calcite deposition in SL-2D is present. Calcite scaling in the well may be prevented by either boiling the fluid above 230°C, possibly at 240°C, or installing a calcite inhibition system.

5.0 HYDROLOGIC MODEL

Results of exploratory drilling and testing confirm the presence of an active geothermal system in SLGP, the center of which is possibly located at the western flank of Mt. Cantoyocdoc. The existence of hot (~260°C), neutral-pH fluid has

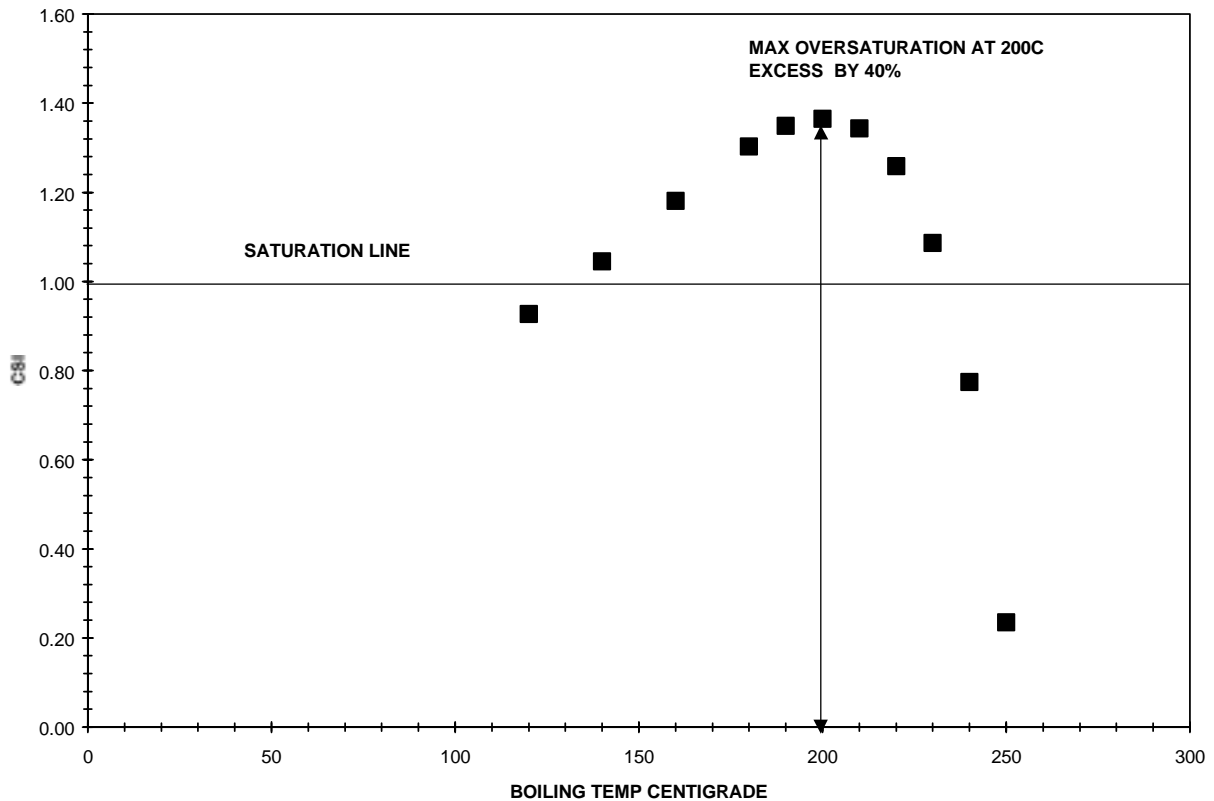


Figure 6. Simulated CSI curve for SL-2D

been established by the discharge test of well SL-2D, as well as the relationship between the thermal features in the area and well fluid. Apparent shallow permeability in well SL-1D also corroborates the westerly outflow of the reservoir fluid towards the Mahalo-Mainit thermal area. Results of SL-1D, however, imply that aside from the shallow outflow zone, not much can be expected away from the center of the geothermal resource. In addition, the reservoir fluid is prone to calcite deposition.

The relationship between the acid-altered grounds in the north and the SLGP geothermal system is not yet fully established. The northern thermal area may either be part of the SLGP system or part of a separate system in Mt. Tamar as postulated by earlier workers.

Immediate activities that need to be done in SLGP include 1) acidizing and repeat flow testing of SL-2D, and 2) drilling of the 3rd exploratory well north of SL-2D to further define the upflow zone. Drilling of the third well is especially critical since, as inferred from SL-1D,

the possible exploitable resource is confined to the upflow region and its immediate vicinity.

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