The Geology and Geochemistry of the Southern Leyte Geothermal Project

R.D. Leynes, F.E.B. Bayon and G.R.A. Camit

PNOC Energy Development Corporation, Merritt Road, Fort Bonifacio, Makati City, Philippines

Abstract

Semi-detailed geologic mapping and sanipling of thermal waters and gases were conducted in Mt. Cabalian and its vicinity to determine the geothermal potential of the Southern Leyte Geothermal Project (SLGP).

The rock sequences at SLGP include Late Cretaceous (?) serpentinites, Earl?, to Mid Tertian, limestones, Mid to Late Tertiary clastics capped bv coralline limestones, and Late Tertiary to Quaternary andesitic to dacitic volcanics and minor intrusives of dacitic. andesitic and microdiorite composition. Two niajor splays of the Philippine Fault - the Catmon-Bisay Fault and the Hindagan Panian Fault - and several other minor faults traverse the area, some of which are potential permeable drilling targets. The geochemistry of spring waters and gases indicate a near-neutral to neutral-pH reservoirfluid having a chloride content of 2500 mg/kg and a minimum temperature of 200°C. Sub-surface boiling of the deep fluids is suggested by the elevated Cl concentration, high SO_4 content of the springs and by the presence of several kaipohans around Mt. Cabalian.

Geological and geochemical data indicate a viable geothermal resource probably centered and upflowing beneath Mt. Cabalian. Preferential outflows are postulated to the northeast along Mahalo, Mahalo-A and Mahalo Splavfaults and to the west along Nava, Hitunlob and Anislag faults.

1.0 INTRODUCTION

The Southern Leyte Geothermal Project (SLGP), previously referred to as the Mt. Cabalian prospect is situated at the southeastern tip of the island of Leyte (Fig.1).

Several geothermal studies have been conducted in the area starting with an inventory of surface discharges by the Bureau of Energy Development and Electroconsult of Italy (BED/ELC, 1979). PNOC-EDC's initial involvement in the project was marked by the reconnaissance survey of Anahawan conducted by Bayrante and Apuada (1983). Based on the favorable geological setting and significant thermal manifestations along Mahalo River, the reconnaissance team recommended that a more detailed geoscientific investigation be done. Thus, in 1989 an integrated geoscientifk exploration was undertaken by PNOC-EDC. This included semi-detailed, 1:50,000 scale geologic mapping, Schlumberger Resistivity Traversing (SRT) and Vertical Electrical Sounding (VES) surveys, and geochemical sampling and analyses of thermal waters and gases (PNOC-EDC, 1989).

In preparation for exploration drilling in SLGP, semidetailed 1:20,000 scale geologic mapping, detailed fault set analysis, and repeat geochemical sampling surveys were conducted. Preliminary geologic and structural intersections were done based on aerial photographs, and results were then ground-truthed. About 70 rock samples were collected for petrologic, paleontologic, XRD analysis and density determination. Selected rock and charred wood samples were collected for K-Ar and ^{14}C dating.

These surveys were aimed at determining the geological and geochemical characteristics of the geothermal reservoir.

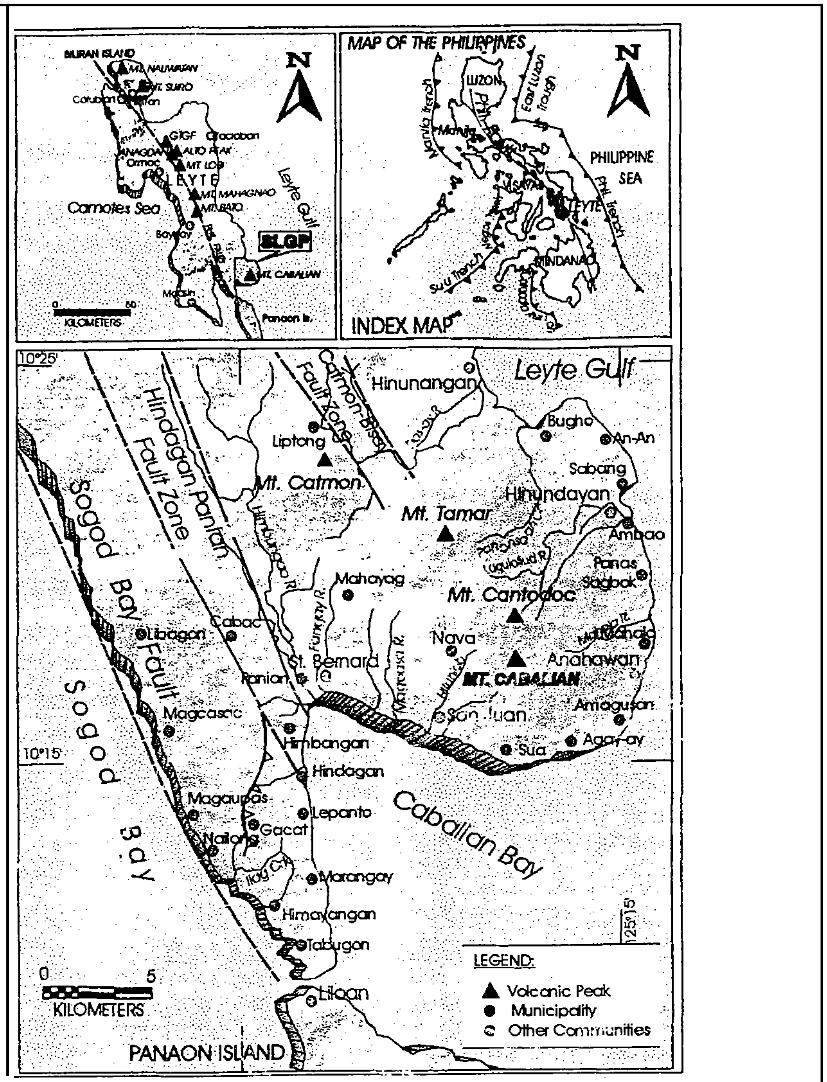

Figure I: Location map of Southern Leyte GeothermalProject; inserts show the volcanic centers on Leyte island and the major tectonicfeutures of the Philippines

2.0 GEOLOGY OF THE AREA

The SLGP in Southeastern Leyte is located west of the Philippine Trench where the Philippine Sea plate is subducting in a northwestward direction (Fig. **1).** Mt. Cabalian, along with Biliran, Janagdan, **Bato** and Lobi volcanoes in Leyte, form **part of** the eastern Philippine volcanic front (Datuin, 1982) running from Camarines Norte in the **north** to Davao del Norte in the south.

2.1 Stratigraphy

The lithologies mapped in **SLGP** are generalized into five major stratigraphic entities, namely: Cretaceous Ultramafics (CU), Tertiary Limestones (TL), Tertiary Clastics (TC), Tertiary Volcanics (TV) and Quaternary Volcanics (QV) **(Fig.** 2).

The oldest rock unit in SLGP is the Cretaceous Ultramafics (CU), considered to be the basement rocks in the area. The CU outcrops southwest of Mt. Cabalian, and is composed of dark green to green, highly fractured serpentinites possibly derived from a peridotite parent rock.

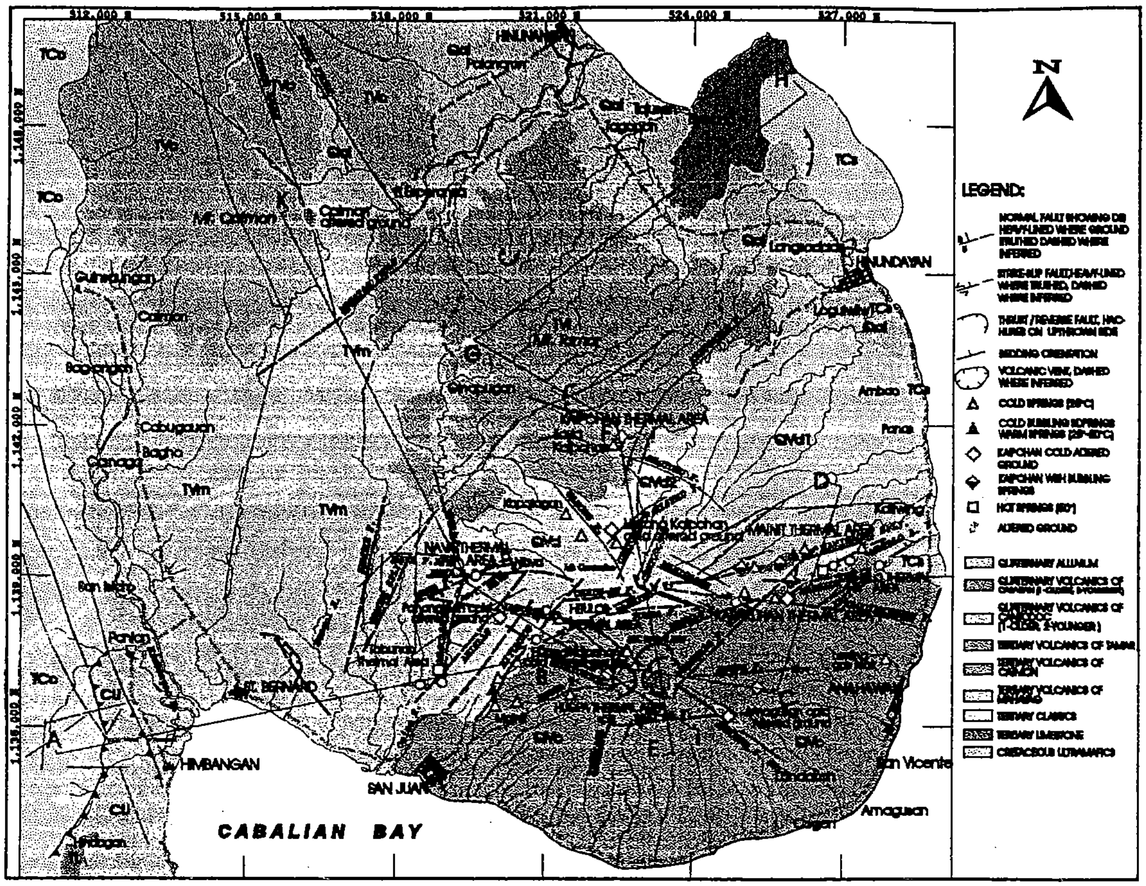

Figure 2. Surface Geologic Map of Southern Leyte Geothermal Project

Tertiary Limestones (TL) are exposed both northeast and southwest of Mt. Cabalian. It is believed to unconformably overlie the CU in the southwest. The limestones are buff-to cream-colored, bedded, fossiliferous and dense but with small vesicles. Microfossil assemblage indicates that the TL was deposited in a marine shelf environment during the Early to Middle Miocene (Lubas, et al; 1996). Exposed southwest and northeast of Mt. Cabalian are sequences of mid-to late-Tertiary clastic sedimentary units capped by thin but massive coralline limestone deposits collectively referred to as the Tertiary Clastics (TC). The sedimentary sequence consists of conglomerates, turbidites, calcareous sandstones and calcisiltites. Microfossil assemblage in the coralline limestone give a probable age of Middle Miocene to Late Pliocene, and a middle to outer neritic paleoenvironment of deposition (Lubas, et al., 1996).

Late Tertiary volcanic rocks (TV) found north and west of Mt. Cabalian are composed of moderately to highly altered basaltic andesite to andesite lava flows, tuffs and tuff breccias intruded by microdiorite dikes and a dacitic dome. These volcanic rocks, individually named after their probable volcanic sources (i.e., Tamar Volcanics), have a probable age of Late Pliocene based on its stratigraphic position.

Mt. Cantodoc and Mt. Cabalian comprise the Quaternary volcanoes in Soulhcm Lcyte. Both volcanoes arc small stratocones consisting of alternating sequcnccs **of** pyroclastics and lava flows. Dcposits extruded from these volcnnocs are termed Quaternary Volcanics of Cantodoc (QVd) and Cabalian (QVc).

Two volcanic episodes are prominently represcnted in Mt. Cantodoc. The oldcr deposits overlying the modemtely to highly altered TV tuff breccias. consist mainly of highly to intensely osidized monolithologic tuff breccias, hornblende-pyrosene basaltic andesite to two-pyroxene hornblende andesite porphyry lava flows and pyroclastic deposits. The younger eruptive products. on the other hand, are dominantly tuff deposits blanketing on the northern slopes of the volcano.

Mt. Cabalian deposits are believed to have formed during at **least** three eruption episodes. These deposits. from oldest to youngest, are basaltic andesite to pyroxene hornblende andesite lava flows in the western and southern slopes. sub-rounded to angular. consolidated monolithologic tuff breccias exposed at Hugpa crater to the west of the main edifice. and pyroclastic flows exposed in the southeast and northeast. The pyroclastic flows occupy an area of about **8** km^2 **and** have an average thickness 10 m. K-Ar dating of a few rock samples of Mt. Cantodoc give an age of 0.45 ± 0.03 Ma (from a lava flow at the western *flank)*and 0.12 ± 0.04 Ma (for a flow sample near the peak). Mt. Cabalian. on the other hand. has and age ranging from 0.19 ± 0.01 Ma to 0.18 ± 0.04 Ma. Furthermore. carbon-14 dating of charred wood samples taken from a pyroclastic flow deposit east of Cabalian edifice yielded an age range of 25.000-36.00 yBP. The ages suggest an overlap of volcanic activity behveen Mt. Cantodoc and Mt. Cabalian. with a much younger episode in Cabalian producing the eastern pyroclastic **flow** deposit. Magma for both Cabalian and Cantodoc volcanism may havc been **fed from** a single chamber, at **leas!** during the overlap period.

2.2. Structural Geology

Two major splays of the Philippine Fault. the Hindagan-Panian Fault and Catmon-Bisay Fault. were delineated west and north-northwest of the study area. In addition. several smalier-scale faults were also mapped in the area. These faults trend in three general directions: northeast/east-northeast. northwest and east-west (Fig.3).

The northeast/east-northeast-trending faults predominate over the other smaller faults in the area. These faults have long strike lengths and cut across the young volcanics of Mt. Cabalian and the Mt. Cabalian crater itself. Several thermal **springs** and altered grounds appear to be controlled by these structures. Fault measurements along the trace of these structures indicate that most are left-lateral strike-slip faults with - predominant northwest-southeast maximum principal *stress* (σ_1) direction. However. a younger normal faulting event appears **to** overprint older strike-slip and thrust faults. This observation is particularly evident along Maaslom Fault. Dip slip movements also characterize Mahalo Fault and Nava Faults. In contrast, the northwest-trending structures are fewer than the dominant fault set. and possess shorter strike-lengths. These structures are mainly seen as cutting ridges and offsetting streams. Cold altered grounds such as the Amagusan and Panangkilon are also observed along the trace of these faults. The fault readings along these structures indicate both normal and strike-slip movements. although the chronology of the faulting events cannot be established with certainty.

East-west-trending faults in the area are few in number and far apart. These faults, exhibiting both strike-slip and dip-slip movement, cut across ridges and follow stream tributaries. No thermal manifestation is associated with these faults.

3.0 GEOCHEMISTRY OF SURFACE THERMAL FEATURES

Majority of the thermal features such as hot and **warm springs** in SLGP are found on the eastern and western flanks of the volcano. Also present in the area are ***"kuipohan"*** features - patches of ground with intense acid alteration and high concentration **of** gases such **as** CO_2 and H_2S **(Fig. 2)**.

The Tabunan. Nava and Hitunlob springs discharge at the western **flank** of the volcano, 'and form what is termed here as the western spring cluster. Mainit and Mahalo springs, on the other hand, are located on the eastern **flank** of Cabalian, principally along Mahalo river. Surface waters are represented by the Hugpa cold springs along Mainit river (which is on the western side and not the drainage where Mainit spring discharges into) **and Lake** Danao. Gas samples were collected from Ilaya "kaipohan" in the north, Maaslom and Manigaong "kaipohans" on the eastern slopes along Mahalo River, and Mainit HS. The Hugpa "kaipohan" to the west was not sampled as there was no clear spring discharge point or gas vent when the feature was visited.

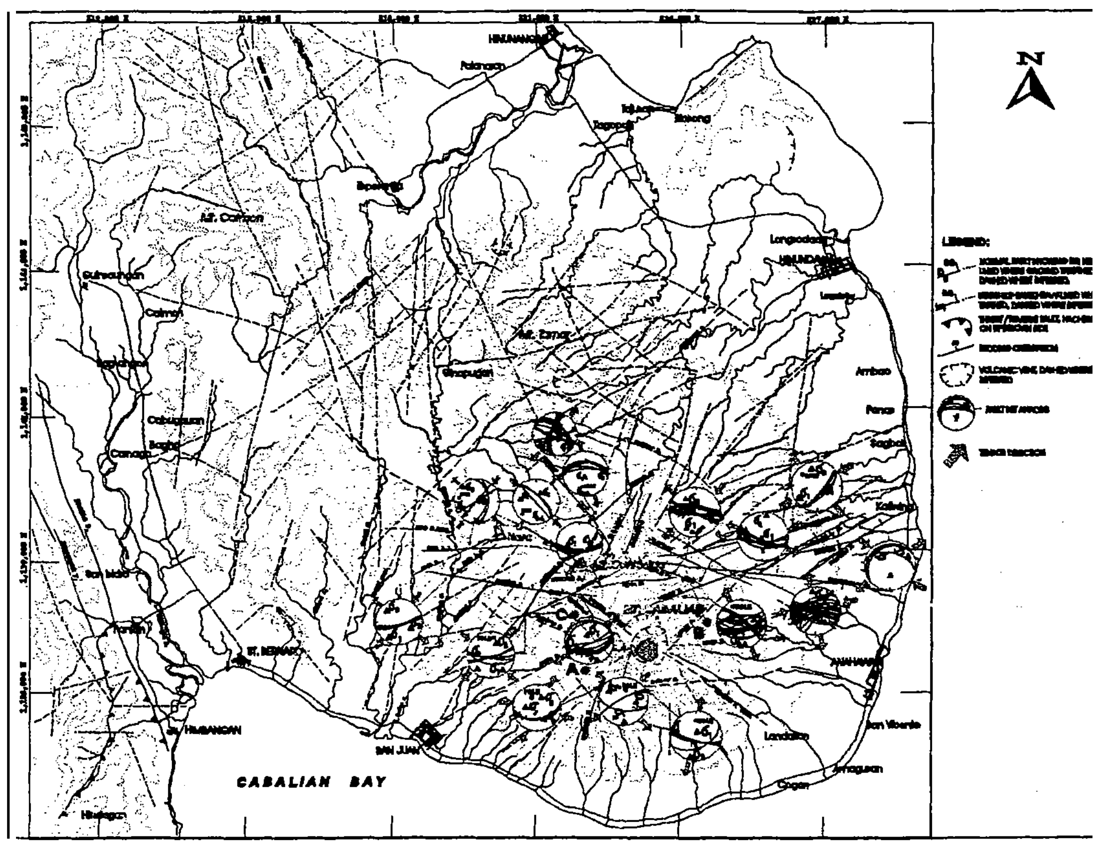

Figure 3. Stress Map of Southern Leyte Geothermal Project

Except for the Ilaya 'kaipohan" sample. all other thermal features have near neutral to neutral pH values (6.2-7.6 against 2.3-2.7 at Ilnya). A $Cl-SO_4-HCO_3$ ternary plot of SLGP spring waters (Fig. 4), shows 3 general groups of waters: acid condensate (Ilaya). mixed $Cl-HCO_3-SO_4$ (Mainit. Mahalo and Tabunan) and dominantly HCO_3 fluids (Nava. Hitunlob, Hugpa). The diagram indicates that Nava and Hitunlob waters are compositionally similar to typical groundwaters and contain only a minor hydrothermal component. The Ilaya sample was taken from a vigorously-bubbling pool within the kaipohan. and its position in the figure is probably because the discharge fluid is composed mostly of dissolved gases. primarily H_2S. The high Cl waters of Mainit, Mahalo and Tabunan, although mixed to varying degrees, indicate significant deep hydrothermal components. Mainit HS water discharge may be the most representative of the deep fluid although this spring is still discharging mised fluid and Cannot really be considered primary Cl water.

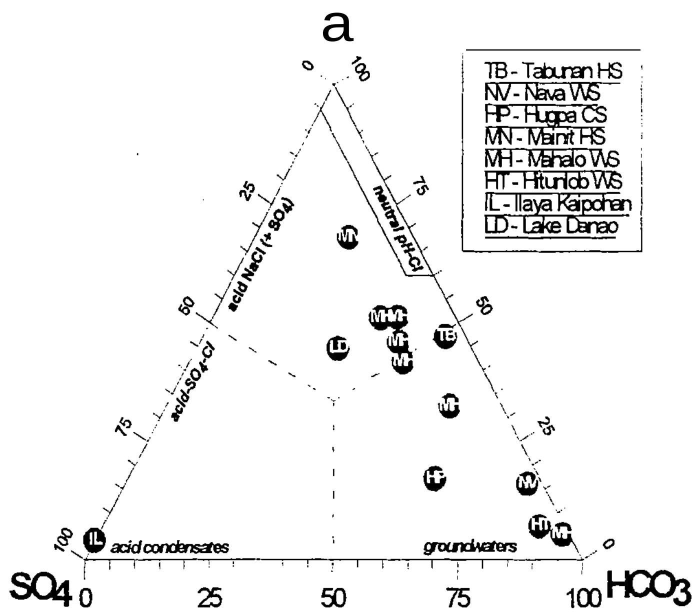

Figure 4. Classification of SLGP waters

Concentrations of Ca and Mg are relatively high in SLGP compared to other areas. These may be attributed to the presence of Ca-Mg carbonate deposits underlying the Cabalian volcanics. Ca and Mg levels in SLGP are comparable to those in Northern Negros, where limestone/dolomite beds are extensive (Maturgo and Sanchez, 1996)

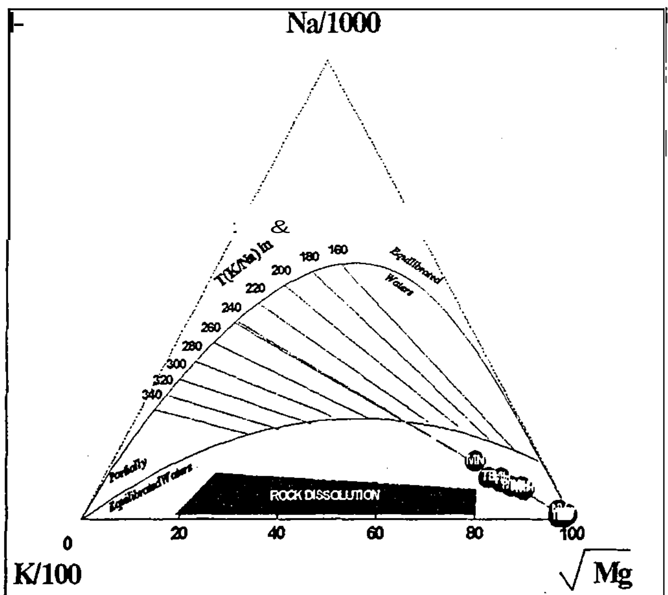

Figure 5. Na-K-Mg ternary plot of SLGP waters

The Na-K-Mg ternary plot (Fig. 5) shows that all water samples cluster near the immature water region of the diagram (typical of surface features). Only the Mainit, Tabunan and Mahalo thermal springs deviate from the Mg comer, with Mainit HS being the farthest from the Mg corner. The Cabalian thermal features form a single dilution line which yields a source fluid temperature of 240°C. The single dilution line suggests that the thermal springs come from just one hydrothermal system. despite diversity in Cl/B molecular ratios. Non-uniformity of Cl/B ratios may sometimes indicate diverse sources for spring waters, but this may not be true in SLGP, Even for the same cluster of springs (i.e., Tabunan) where the same source may be expected, Cl/B ratios still do not approximate each other. The diversity in Cl/B ratios in SLGP may be taken as a function of differences in flowpath lithology of spring waters and not of different parent fluids or separate convection systems.

The alignment of springs in the above figure suggests that indeed there is only one source fluid for the thermal discharges.

The elevated SO, concentrations in thermal waters may be caused by: i) the presence of dissolved H_2S in neutral-pH parent brine. which is oxidized near surface to produce SO, in water; ii) an acidic SO,-rich parent fluid being neutralized on its way to the surface; and iii) seawater contribution. Of these three possibilities, the first is most likely. The occurrence of kaipohans around the volcano suggests the presence of rather abundant geothermal gases, in particular CO_2 and H_2S, which can be dissolved and oxidized. An acidic source fluid is not manifested in the overall spring chemistry (i.e., neutral waters with high Cl being discharged). Similarly, seawater sulfate contribution is probably not significant. If based on sulfate levels alone, it would appear that the SLGP fluid contains a maximum of 13% seawater. The much lower concentration of other ions (i.e., Cl, Na, Mg) in spring waters compared with seawater, however. indicate that the dominant component is meteoric water.

Gas analyses of samples from Ilaya "kaipohan," Mainit HS, Manigaong and Maaslom "kaipohans", and Hitunlob spring reveal that in terms of volume percent, SLGP gases are typical of geothermal fluids anywhere. CO_2 is the dominant non-condensable gas (97%). followed by H_2S (1.7-2%). Residual gases make up less than 2% of the discharge.

Gas chemistry supports a single parent reservoir in SLGP as implied from water chemistry. Gas composition of the Ilaya "kaipohan" to the north and the two "kaipohans" in the east are very similar. Figure 6 shows a N_2-He-Ar ternary plot of Mt. Cabalian gases: and most of the samples generally lie dong a single dilution line connecting the He comer and an end-point close to air. Since all points plot away from the magmatic corner, it is likely that Mt. Cabalian gases are not derived directly from a magmatic source. which is also additional indication that the parent fluid may not be acidic.

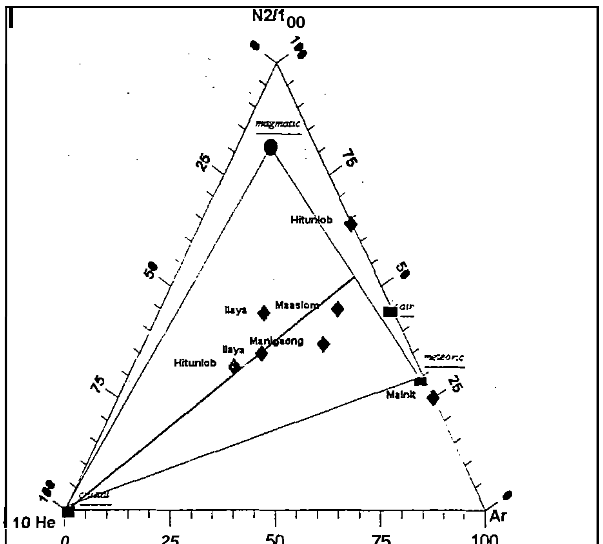

Figure 6. N2-He-Ar ternary plot of SLGP gas samples

If solute geothermometers are strictly applied to SLGP samples: then only the Mainit HS sample can be utilized, since this is the only sample which comes close to primary Cl water composition (Fig. 4). For comparison, however, reservoir temperature estimates using Mahalo and Tabunan WS were also calculated. Results indicate that temperature

The Na/K geothermometer gave the highest temperature estimate among all geothemometers used. Temperatures range from 214-246°C using the equation developed by Fournier (1981), 184-224°C with the Truesdell formula (1979), and 230-259°C using Giggenbach's (1981) equation. Tabunan HS consistently gives the highest temperature, and Mainit HS the lowest. Highest temperature estimates using T Na/K are expected because of the proven slow exchange rate between Na and K bearing constituents, and therefore may be reflective of temperatures at deeper levels of the hydrothermal system. The alignment of springs along one dilution line in Figure 5 suggests a source temperature of 240°C. Because of the high Ca concentration in water samples, the Ca-corrected Na-K-Ca geothennometer (Fournier and Truesdell, 1973) was also applied. The resultant temperature estimates range from a high of 202°C in Tabunan to about 175°C in the vicinity of Mahalo. Silica geothermometer applied to the analyzed waters is that for alpha cristobalite. 'and temperatures range from 87°C in Mahalo to 110°C in Mainit.

Gas geothermometry yielded calculated temperatures of 150 (H_2S/H_2) to 209°C (CO_2/H_2) for the knipohan samples. The latter gas geothermometer is considered to be more reliable than the former. and the temperature range of 202-209°C given by the CO_2/H_2 geothermometer is similar to the range from solute geothermometry, reinforcing the interpretation that the parent fluid temperature of the Mt. Cabalian system is at least about **200°C.**

The Na/K temperature is taken to provide the best estimate of the deep reservoir temperature, while the Na-K-Ca and cristobalite temperatures may be taken as reflecting temperatures in the shallower portions of the system. **As** such. and considering that Mainit HS is the most representative sample. the deep fluid is estimated to have a minimum temperature of 200°C. As the deep fluid rises towards the surface. boiling and water-rock interaction results in cooling of fluid before mixing with groundwater to produce the hernial **springs.** At the point of **mixing of** deep fluid and groundwater. fluid temperature is only about 100°C based on cristobalite geothermometry (subsurface boiling *is* at shallow levels), which may be taken as a record of boiling temperature.

There is strong evidence indicating that subsurface boiling is extensive in the Cabalian hydrothermal system. One is the occurrence of kaipohans around the Cabalian edifice. Another is the high SO_4 and HCO_3 contents in hot springs suggesting extensive boiling and dissolution of H_2S and CO_2. Apparent equilibrium of the waters with cristobalite. with resulting temperatures estimated at 90-110°C implies boiling at this temperature. It **may** be assumed that spring discharge waters are derived from **a** residual liquid formed by the flashing process and then mixed with meteoric waters. Mixing between geothermal ana meteoric waters is shown in the Cl vs. enthalpy diagram (Fig. 7). Assuming a parent fluid temperature of 200°C. the reservoir fluid is estimated to have a Cl content of about 2500 mgikg. The residual liquid has about 3000 mg/kg Cl at a temperature of about 100°C.

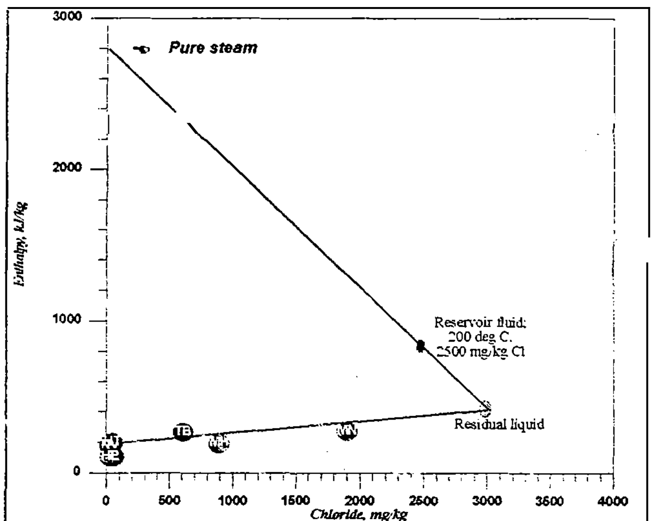

Figure 7. Chloride-enthalpy diagram, SLGP water samples

The distribution of "kaipohans" in Mt. Cabalian makes the prospect interesting, since very few other geothermal areas in the Philippines (i.e., Palinpinon) exhibits such **an** array of cold acid altered grounds. With subsurface boiling considered **a** natural-state occurrence, the area defined **by** the "kaipohans' to the north, west and *east* **may** be reflective of the extent **of** the geothermal system. Beyond the **'kaipohans,"** fluid flow is dependent totally on structural control; the main geothermal reservoir may be confined within what *can* be called the "kaipohan block".

4.0 CONCEPTUAL MODEL

A conceptual model of the SLGP geothermal system is envisaged based on geological and geochemical data (Fig. 8). The resource is postulated to be centered beneath the coalescing cones of Mt. Cabalian and Mt. Cantodoc based on the distribution of the thermal springs and kaipohans. The heat is probably being supplied by cooling dioritic plutons, the depth of which can not be ascertained. Various sedimentary rocks consisting of conglomerates, sandstones, siltstones and limestones act as the reservoir of the system with fluids being supplied by deeply-circulating meteoric waters. The reservoir fluid has a calculated temperature of about 200-240°C and a chloride concentration of about 2500 mgkg. The fluid upwells to the shallow subsurface, where flashing occurs to produce the kaipohans and high-SO_4 springs in the vicinity of the Cabalian crater lake. Residual fluid flows laterally toivards the west through Nava. Hitunlob and Anislag faults and towards the northeast along Mahalo, Mahalo-A and Mahalo Splay faults. Mixing between outflowing geothermal and shallow meteoric waters occurs at or very near surface, producing the high-Cl springs of Tabunan. Mainit and Mahalo.

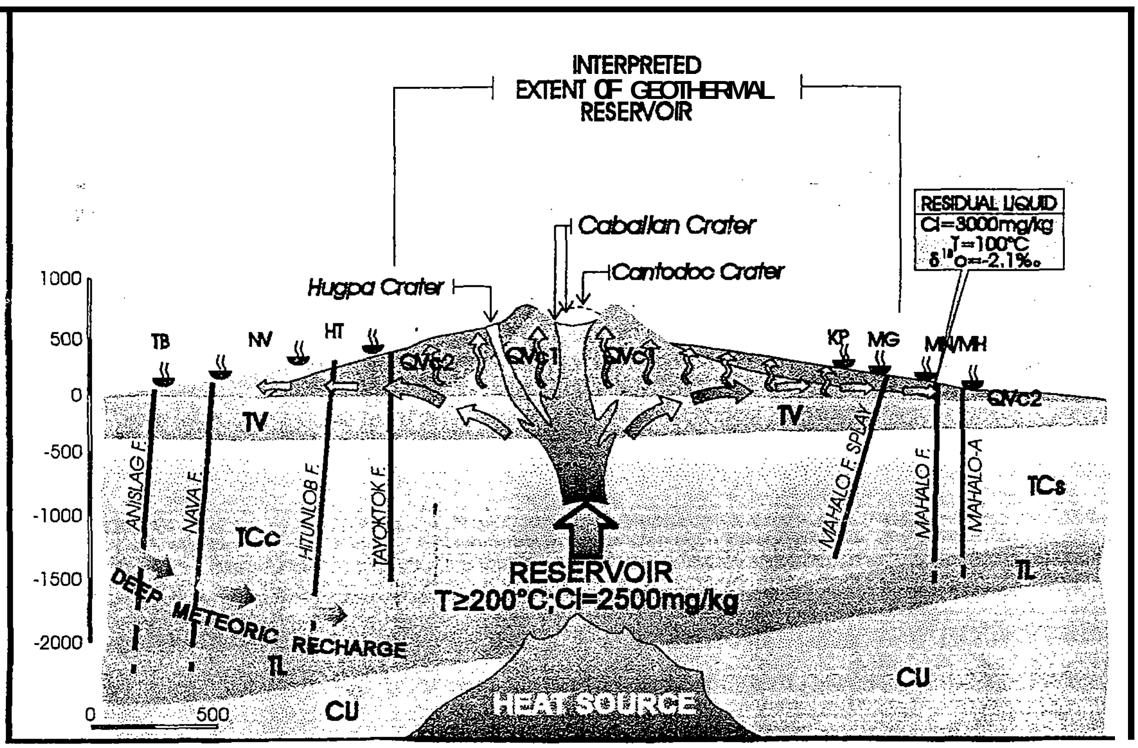

Figure 8: Geological/Geochemical model of the Southern Leyte geothermal system

REFERENCES

Bayrante, L. F. and Apuada, N. A., 1983. Reconnaissance geology of the Anahawan geothermal prospect, Southern Leyte. Unpublished PNOC-EDC Report, 10 pp.

Bureau of Energy Development-Electroconsult (BED-ELC), 1979. Inventory of the thermal areas in the Philippines. Phiiippine-Italian Technical Cooperation on Geothermics stage II, Annex-I, 50 pp.

Datuin, R. T., 1982. An insight on Quaternary volcanoes and volcanic rocks of the Philippincs. Journal of the Geological Society of the Philippines, vol. 36, no. I, pp. 1-11.

Lubas, L. L., De Guzman, A. M., and Revilla, A. P.. 1996. Micropaleontological analysis of field samples from Cabalian, Leyte, for PNOC-EDC, 5 pp.

Maturgo, O. O., and Sanchez, D. R., 1996. Stable isotope investigation in the Northern Negros Geothermal Project, Philippines. PNOC-EDC Internal Report.

PNOC-EDC, 1989. Geoscientific exploration and evaluation of the Mt. Cabalian geothermal Prospect, Southern Leyte. PNOC-EDC Unpublished Internal Report, 106 pp.