REMOTE SENSING APPLICATION IN EVALUATING THE SOUTHERN LEYTE GEOTHERMAL PROJECT (SLGP), SOUTHERN LEYTE, PHILIPPINES

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ABSTRACT

Remote Sensing (RS) approach was applied to refine the existing geological and hydrological models of the Southern Leyte Geothermal Project (SLGP). Landsat thematic mapper and radar imageries were processed mainly for geological and structural interpretations. The spectral classification of altered grounds and/or thermal springs was extracted from the Landsat TM imagery using the Normalized Difference Vegetation Index (NDVI) and the Principal Component Analysis (PCA) methods.

This study revealed the spatial relationship between faults, lineaments, stratigraphic contacts and hydrothermal manifestations in the project area. The northeast and east-northeast structures dissect the Cantodoc-Tamar volcanic edifice and control the distribution of most hydrothermal manifestations (i.e. Mahalo-Mainit thermal area to the east and Tabunan thermal area to the west). Mount Cabalian harbors predominant NW structures that are believed to channel hydrothermal fluids at deeper levels of the reservoir (i.e. Hugpa kaipohan). This study indicates the existence of more than one geothermal system in the Southern Leyte Geothermal Project (SLGP). These include (1) Cabalian, (2) Cantodoc and (3) Tamar system. Geophysical (e.g. resistivity and gravity anomalies), geochemical and petrological (i.e. thermoluminescence data) data are consistent with this geological evaluation.

1 INTRODUCTION

The study area covers the Southern Leyte Geothermal Project (SLGP). It includes the Quaternary volcanoes of Cabalian and Cantodoc and Tamar (Figure 1). The study area is bound to the west by Sogod Bay, to the east by the Philippine Trough and to the south by Cabalian Bay.

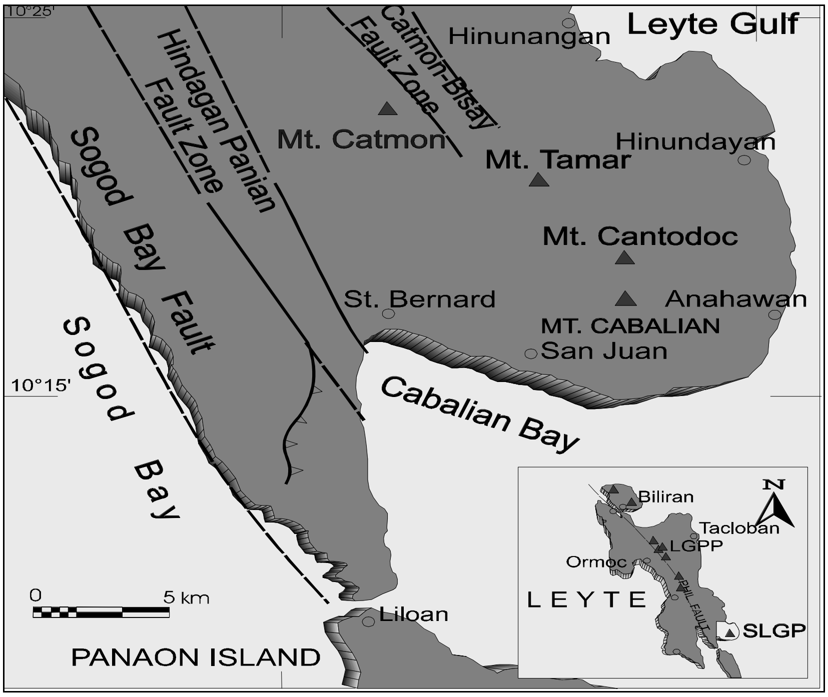

Figure 1. Location map of So. Leyte Geothermal Project (SLGP).

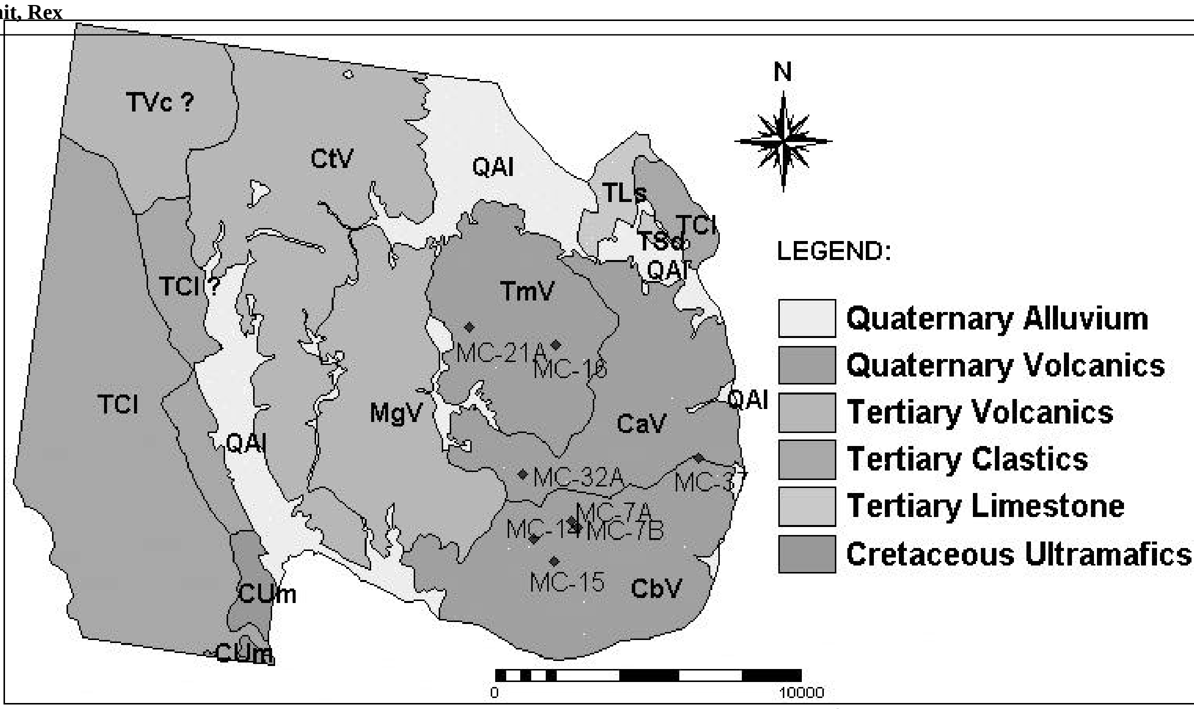

Figure 2. 1999 general geology based on Landsat TM and SAR imagery.

Previous geothermal studies were conducted at SLGP by Bureau of Energy Development together with Electroconsult of Italy (BED-ELC, 1979). This was followed by a series of integrated geoscientific studies by PNOC Energy Development Corporation (PNOC EDC, 1989; Leynes et al., 1997; and Catane and Apuada, 1998). These latest geoscientific studies postulate the presence of a neutral-pH resource located between Hugpa and Kapakuhan Kaipohan with a temperature range of 188 - 205 °C (Leynes et al., 1997). Resistivity surveys, on the other hand, delineated distinct low resistivity anomalies to the west (Nava-Magcasa anomaly) and northeast (Mainit-Mahalo anomaly) of Mt. Cabalian which are indicative of outflowing geothermal fluids.

This study aims to: (1) supplement the previous structural and other geologic interpretations and (2) assess the location of the proposed (i.e. Hugpa) and additional drilling target in the area through the application of remote sensing technique using Landsat TM and Radar imageries.

2 METHODOLOGY

The study utilizes a 30-m resolution Landsat TM image and a < 10-m resolution Radar image georeferenced to a 1:50,000 scale topographic map. The images were radiometrically- and geometrically-corrected wherein the general geology and regional structural lineaments were drawn by heads-up digitizing. The results initially were delineated from the enhanced false color composite of Landsat TM bands 7, 5 and 2 (Figure 2). In combination with the interpreted Synthetic Aperture Radar (10-m resolution) data, spatial discrimination of said lithologic units and lineaments were confirmed. Processing of the Landsat TM and Radar imageries were performed using the Integrated Land and Water Information System (ILWIS) version 2.1 and Environment for Visualizing Images (ENVI) version 3.0 (evaluation software), respectively.

In addition, the combined use of the Normalized Difference Vegetation Index (NDVI) and Principal Component Analysis (PCA) methods were applied to the Landsat TM image to pinpoint bare grounds as probable hydrothermal signatures. Landsat TM bands 1, 4, 5, and 7 were inputted in the PCA method while Landsat TM 4 and 5 were set in the NDVI method. The NDVI method initially classifies the various ground classes (e.g. bare, vegetated, rocky grounds, water bodies, etc.) while the PCA method filters the previously identified bare grounds as probable hydroxyl-bearing surfaces indicative of hydrothermal alteration. The resulting principal component 3 image obtained the highest eigenvector loading (0.55, -0.49) which represents hydroxyl-bearing surfaces associated with either epithermal or hydrothermal areas. This theory works mainly on "strained" vegetation/ground where hydrothermal activity is believed evident. The ILWIS 2.1 software was used in processing said Landsat TM imagery.

Interpretations done in this study were based mainly on integrating Remote Sensing (RS) data with the Geographic Information System (GIS) data. Interpreted remotely-sensed altered grounds/thermal springs mostly coincide with the locations of ground-validated thermal manifestations of SLGP

3 SURVEY RESULTS

3.1 Lithology and Structural Geology

There were six major lithologic units interpreted from the Landsat TM and radar imageries (from oldest to youngest): (1) Cretaceous ultramafics; (2) Tertiary sediments (limestone); (3) Tertiary clastics; (4) Tertiary volcanics (Catmon/Mahayag volcanics); (5) Quaternary volcanics (Tamar/Cantodoc/ Cabalian) and (6) Quaternary alluvium (Figure 2). The chronological ordering and lithologic discrimination is based on the apparent spectral signature, tone, texture and pattern exhibited by each unit. These morphological features have been extracted from both the Landsat TM and Radar imageries. However, the information from these imageries can only establish relative ages and not absolute ages of each lithologic unit. This study's stratigraphic interpretation closely resembles the lithologic correlation done by Leynes et al. (1996). However, new thermoluminescence dating by Ramos et al. (1998) had constrained the absolute ages of Tamar (490-670 ka.), Cantodoc (510 ka.) and Cabalian (17 ka.) volcanic units to Pleistocene age. This result was adopted in the chronology of the different geologic units (Figure 2).

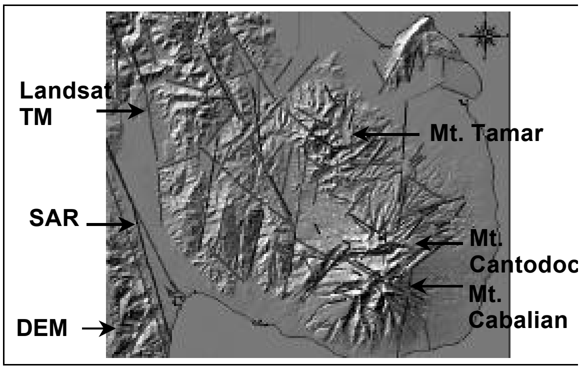

Figure 3a. Composite lineament map at SLGP.

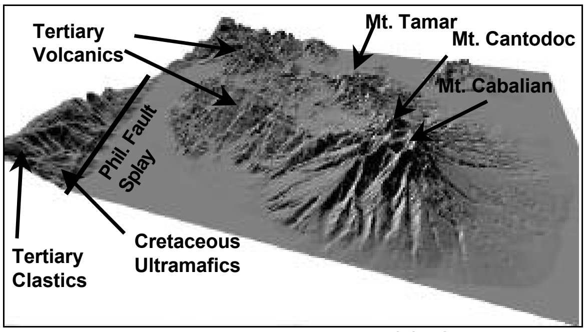

Figure 3b. Hill-shaded DEM of SLGP.

Structural lineaments that were drawn using the Landsat TM and Radar imageries (Figure 3a) were based on stream offsets, linear valleys/ridges, ridge offsets, stratigraphic contacts and crosscutting faults. A three-dimensional view of SLGP with NW hill-shading is shown in Figure 3b. Three structural blocks (Figure 3c) were discerned from the imagery: (1) Cretaceous ultramafics/Tertiary clastics fault block (Western block); (2) Tertiary to Quaternary volcanics fault block (NE block); and (3) Quaternary Cabalian/Cantodoc fault block (SE block). The western block is dominated by WNW structural lineaments while the NE block contains mostly NE-striking lineaments. However, the SE block covering Mts. Cabalian and Cantodoc are dominated by NW-trending fault sets. The occurrence of WNW to NW fault sets could have been strongly influenced by the active, generally sinistral Philippine Fault and splays (along the Hindagan-Panian and Catmon-Bisay vicinities). The fault set analyses conducted by Leynes et al. (1996) is interpreted in this study to favor localized ENE-trending compressional regime on observed NW fault sets. This, therefore, implies that NE to ENE-trending fault sets at the NE and SE structural block (Tertiary/Quaternary volcanics and sediments) have extensional properties which are potential channels for hydrothermal fluids.

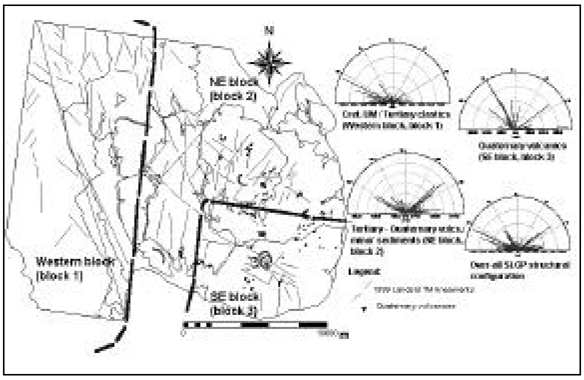

Figure 3c. Structural blocks at SLGP based on Landsat TM.

Leynes et al. (1996) identified high occurrences of NE to ENE fault sets within the SE block (Quaternary Cabalian and Cantodoc volcanics) based on aerial photo and later field ground-truthing. This is validated in this study using the NW-directed hill-shading interpretation (Figure 3a and 3b). These structures could have been passageways of hot, hydrothermal fluids outflowing towards the ENE at Mainit thermal area (i.e. Mahalo Fault Splay).

Well SL-1D encountered partial and total circulation losses at depths 788-999 m along Mahalo Fault Splay (Rosell and Zaide-Delfin, 1997). In relation to this, well SL-1D intersected veneers of hematized/goethized, weathered volcanics down to 241 m of the upper member of the Quaternary volcanics. Partial circulation losses were encountered within these depths which are indicative of either an aquifer or paleosol (Leynes and Bien, 1998). Shallow permeability probably exist along the NE portion of Mt. Cabalian and extends towards the Mainit thermal area through interconnected primary (i.e., lithologic contacts between the Tertiary volcanics and underlying Tertiary clastics and limestones) and secondary (i.e., Mahalo fault splay) sources of permeability (Rosell and Zaide-Delfin, 1997).

Despite the regional scale of lineaments delineated from the 30-m resolution Landsat TM imagery, a distinct younging pattern (through crosscutting relationships) of NW-trending structures relative to the NE and ENE-trending lineaments can still be observed. This suggests that these NW-trending lineaments have possible direct connection with hydrothermal fluids beneath Mts. Cabalian and Cantodoc and are probably deep-seated like the Philippine Fault. Its intersections with NE to ENE-trending fault sets could have localized fluid flow at shallow levels (i.e., Mainit thermal area to the NE, Tabunan thermal area to the west). In addition, localized structures drawn from aerial photographs and ground-checked lineaments (Leynes et al., 1996) show a variety of fault sets at the Cabalian-Cantodoc-Tamar volcanic edifices which are not visible from the structurally-interpreted Landsat TM imagery (Figure 3a). This is probably due to the Landsat imagery's 30-m spatial resolution. Structural lineaments extracted from the radar imagery confirmed the occurrence of these localized structures (Figure 3a). This advantage of radar is due to its < 10-m spatial resolution and its ability to penetrate cloud-covers.

3.2 ALTERATION MAPPING RESULT

Ground-mapped major altered grounds and springs (e.g. Mainit thermal area, Ilaya kaipohan and Tabunan thermal area) are all located in proximity to the interpreted alteration zones (Figures 4 and 5). It is worthy to note the occurrence of springs and altered grounds (e.g. Liptong altered grounds, Tabunan thermal area and Hitunlob springs) along faults and fractures and lithologic contacts. Their occurrence and distribution seem to suggest three- (3) probable geothermal systems: Cabalian, Cantodoc and Tamar systems.

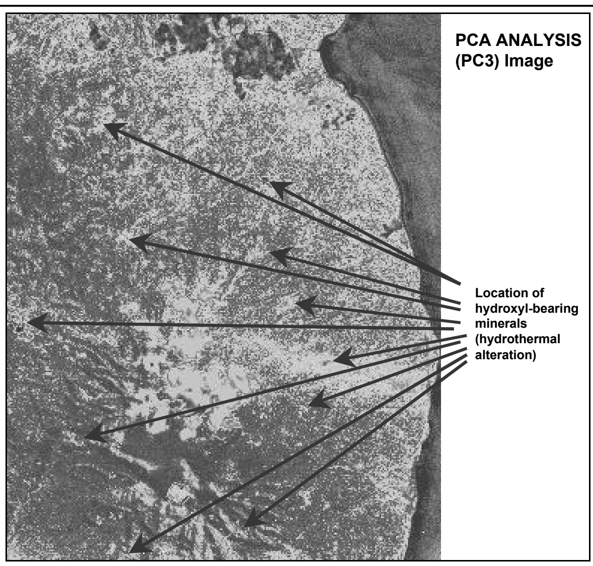

Figure 4. Alteration mapping of SLGP using Normalized Difference Vegetation Index (NDVI) and Principal Component Analysis (PCA).

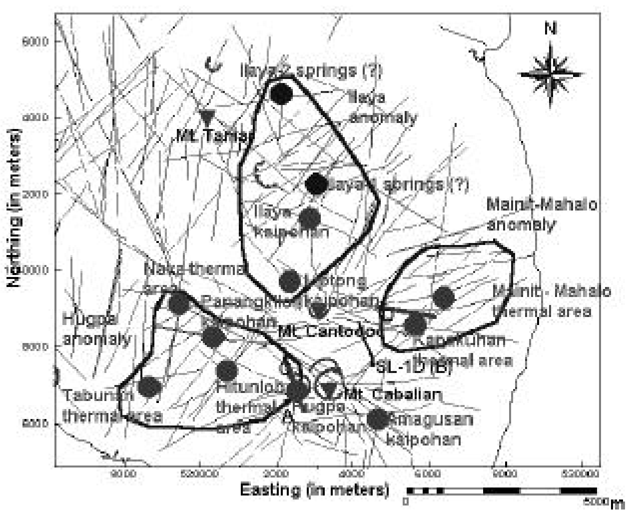

Figure 5. SLGP Interpreted composite geophysical anomaly showing current and proposed drilling pad locations.

The Cabalian hydrothermal system is centered within the Hugpa Kaipohan and Amagusan cold altered grounds. Hence, hydrothermal fluid outflows were inferred to migrate WSW by faults trending NNE to NE towards Tabunan thermal area and Hitunlob springs (Figure 5).

The Cantodoc system harbors the Liptong and Manigaong kaipohan which in turn outflows NE accommodated by faults trending ENE towards the Mainit-Mahalo and Kapakuhan thermal areas (Figure 5).

The Tamar system is manifested by the ground-truthed Ilaya kaipohan. This kaipohan indicate the upwelling portion of the Tamar hydrothermal system that is inferred to be associated with predominant sets of NE- and ENE-trending faults dissecting this relatively older Quaternary volcanic unit. Further N and NNW of Ilaya kaipohan, suspected group of altered grounds and springs (i.e. Ilaya-1 and Ilaya-2 springs) also follow a NE-trending structural grain which could have favored outflow of hydrothermal fluids (Figure 5).

The overlapping hydrothermal system boundaries of Cabalian, Cantodoc and Tamar are possible at Mainit-Mahalo thermal area. This assumption is based initially on the available thermoluminescence data of Ramos et al. (1998). The thermoluminescence data implied that the Cantodoc system has an age of 5-6 ka. for its latest hydrothermal event. It was also noted that the Cantodoc volcanic system (510 ka.) is relatively older than the Cabalian volcanic system (17 ka.). Tamar volcanic system has an age range of 490-670 ka.

The use of the PCA and NDVI methods has manifested clearly the approximate locations and spatial distribution of probable altered grounds and springs within the study area. The results based on these methods imply probable communication between primary (i.e., lithologic units/contacts) and secondary (i.e. faults) sources of permeability.

4 GEOSCIENTIFIC MODELS

4.1 Post-1996 Model

Previous geological, petrological, geochemical and geophysical data support a single hydrothermal system for SLGP (Leynes et al., 1996; Rosell and Zaide-Delfin, 1997; Bayon, 1996; Los Baños, 1998; Catane and Apuada, 1998). Geology data points only to Quaternary Cabalian and Cantodoc volcanoes as probable heat source thereby representing the Cabalian- Cantodoc system (Leynes et al., 1996). While petrology data of well SL-1D indicate passage of geothermal brine at shallow levels (depths 200 to 400 mBSL) believed to be associated with the Cabalian-Cantodoc system along channels of Mahalo Fault Splay (Rosell and Zaide-Delfin, 1997). These affirmed the assumptions based on the Na-K-Mg (for water chemistry data) and N_2-He-Ar (for gas chemistry data) ternary plots of SLGP thermal manifestations (Bayon, 1996). Also, two-dimensional representations of the < 5 ohm-meter anomalies at Hugpa and Mainit-Mahalo vicinities were delineated WSW and NE, respectively, of Mt. Cabalian through magnetotelluric survey results (Los Baños, 1998; Catane and Apuada, 1998).

These previous studies deduce a single Cabalian-Cantodoc system which channels hydrothermal fluid flow towards the WSW at Tabunan/Hitunlob thermal areas and to the NE at Mainit-Mahalo thermal areas. This initial geothermal model is consistent with their findings that fluid flows are evident along lithologic contacts, faults and permeable hostrocks (i.e. Tertiary volcanics).

4.2 1999 Model

Review of the post-1996 geoscientific data, especially geological (this study) and geophysical (Apuada, in prep.) data, delineated significant findings favoring a three-system geothermal model for SLGP. Based on the spatial distribution of thermal springs and kaipohans (ground-truthed and remotely-sensed data); clustering of these thermal features along associated NE to ENE (for the Ilaya kaipohan and Mainit-Mahalo thermal areas) and NNE to NW (for Hugpa kaipohan, Nava, Hitunlob and Tabunan thermal areas) fault sets suggest the probable influence of three geothermal systems. Moreover, isolated NE fault sets (i.e. Anislag and Hitunlob faults), located west of Mt. Cabalian, possibly extend towards the NE. These observations were similarly duplicated in the refined interpretation of the geophysical data by Apuada (pers. comm.). Using the same MT result of Los Baños (1998), a shallow Mainit-Mahalo anomaly was instead interpreted to exist only until 350 mBSL.

Broad anomalies (< 10 ohm-meters) covering the NW part of Mt. Cantodoc and SE of Mt. Tamar extends down to depth 1000 mBSL. This anomaly (called "Ilaya" anomaly) is associated with Mt. Tamar (termed in this report as "Tamar system") through the predominant NE/ENE structures that dissect the area. The Hugpa anomaly (< 10 ohm-

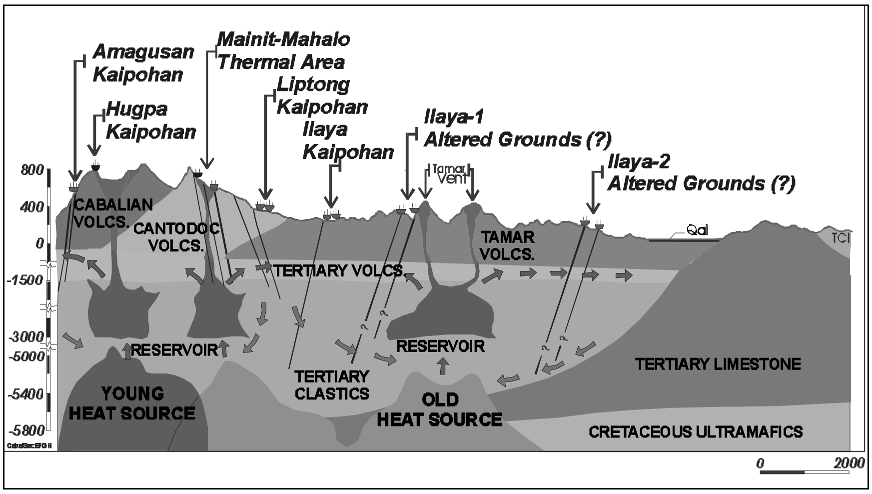

Figure 6. 1999 Conceptual model of SLGP.

meter), located WSW of Mt. Cabalian, is consistent with previous geophysical interpretations (Los Baños, 1998; Catane and Apuada, 1998) and was associated with the Cabalian system.

In this study, the previously identified Tamar and Cantodoc system supply the kaipohans (i.e. Ilaya, Kapakuhan and Liptong) and thermal springs (e.g. Ilaya-1/2 springs?, Mainit-Mahalo and kapakuhan thermal areas) at the northern and northeastern sector of SLGP, respectively, while the Cabalian system is represented by Hugpa kaipohan, Panangkilon kaipohan, Amagusan kaipohan, Tabunan, Nava and Hitunlob thermal areas (Figure 5 and 6). Mainit- Mahalo thermal area is believed to be the result of the overlapping boundary of Cabalian, Cantodoc and Tamar hydrothermal systems.

5 DISCUSSION

The integrated 1999 geoscientific model (Section 4.2) envisaged by this study supports the existence of three hydrothermal systems (i.e. Cabalian, Cantodoc and Tamar systems). These systems are responsible for the occurrence of the Ilaya, Mainit-Mahalo and Hugpa geophysical anomalies within SLGP (Figure 5). These potential systems are believed to be centered beneath the cones of Mts. Cabalian-Cantodoc and Mts. Cantodoc-Tamar, respectively. The volcanic roots of these Pleistocene volcanic units are probably supplying the heat. Tertiary volcanics, non-clastics (i.e. limestones) and clastics (i.e. conglomerates, sandstones and siltstones) act as reservoir rocks of the system. Kaipohans and high-SO_4 springs generally dominate the upflow portion of the systems (i.e. Cabalian, Cantodoc and Tamar systems). While high-chloride springs to the west and NE (i.e. Tabunan and Mainit-Mahalo thermal areas, respectively) outflow to the distal flanks of Mts. Cabalian and Cantodoc.

The one-geothermal system model interpreted from previous geologic, petrologic, geochemical and geophysical data (Leynes et al., 1996; Bayon, 1996; Rosell and Zaide-Delfin, 1997; Los Baños, 1998; and Catane and Apuada, 1998) was observed to be located within the conductive zones of Hugpa and Mainit-Mahalo anomalies. These anomalies were previously interpreted to be related to an upflow zone within vicinities beneath Mts. Cabalian and Cantodoc. However, the authors observed isolated anomalies (from D.C resistivity and magnetotelluric surveys) ranging from 10-30 ohm-meters evident to the N and NNE of Mts. Cabalian and Cantodoc (PNOC EDC, 1989; Los Baños, 1998; and Catane and Apuada, 1998). Previous workers correlate those anomalies (10-30 ohm-meters) to the Hugpa and Mainit-Mahalo anomalies (evident down to depths of 2000 mBSL) but recent interpretations of Apuada (in prep.) using the same magnetotelluric data delineated it as a separate anomaly (i.e. Ilaya anomaly). Incidentally, remotely-sensed Landsat TM and radar imageries show clustering of springs or altered grounds along Ilaya anomaly and in proximity with dominant NE-trending fault sets within vicinities of the Cantodoc and Tamar volcanics. These evidence discern a probable existence of a separate geothermal system based mainly on remotely-sensed structural geology and re-assessed geophysical interpretations.

This study's 1999 geothermal model (Figure 6) is consistent with previous geoscientific studies' contention of a combined effect of channeling hydrothermal fluids along permeable lithologic contacts/units (e.g. Tertiary volcanics and sediments) and faults. These primary and secondary permeability controls, respectively, contribute to the circuitous migration of thermal fluids at subsurface levels.

Indirectly, Landsat TM imagery interpretations deduced probable relationship between the occurrence of springs and altered grounds with said permeability controls. This observation proves that spectral signatures of thermal areas can still be detected even in highly vegetated areas in a volcanic terrain. This approach relies heavily on strained vegetation caused by seepage of thermal fluids at surficial levels.

The results of this study suggest the need to probe the established Hugpa anomaly to the west and Mainit-Mahalo anomaly to the NE. The current location of drilling pad C is preferred here to target the former anomaly where deep-seated NW-trending faults dissect the western Hugpa crater (Figure 5). However, the next well (site D) should be located east of Mt. Cantodoc (~1.5 kilometers east of Mt. Cantodoc) in proximity to the latter anomaly where NE to ENE fault sets predominate. These drilling strategies will validate this study's model of an upflow origin within the vicinities of Mts. Cabalian, Cantodoc Tamar.

6 CONCLUSIONS

This study dealt with the concept of integrating remote sensing and geographic information system. Use of the imageries (i.e. Landsat TM and SAR) refined the previous structural interpretations and established its relationships with SLGP thermal manifestations. Primary and secondary permeability controls (i.e. hostrocks/lithologic contacts and faults) were important factors that influenced the hydrothermal system at SLGP. This study favors the existence of more than one geothermal system (i.e. Cabalian, Cantodoc and Tamar system).

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