Preliminary Exploration Results of the Kalinga Geothermal Prospect, Luzon, Philippines

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ABSTRACT

The Kalinga Geothermal Prospect, located in the eastern flank of the Luzon Central Cordillera has been explored since the late 1970's for its impressive thermal manifestations, faults, and evident Quaternary volcanism. Exploration work conducted in 2010-2012 included limited geologic mapping, literature review, remote sensing acquisition and interpretation, geochemical sampling and geophysical surveys.

Geochemical interpretation suggests the existence of a benign geothermal system with an adjacent younger, acidic system. Geologic interpretation suggests that the neutral reservoir could be hosted by the fractured metavolcanic Basement Complex, with enhanced permeability along structures and intrusive contacts. Magnetotelluric data imaged a shallow low resistivity (20-30 ohm-m) layer, which was interpreted as the clay cap overlying the neutral reservoir, while the gravity data allowed for a range of estimates for depth to the top of the intrusive contact.

Conceptually, two upflow zones are interpreted, one of which feeds a benign exploitable geothermal reservoir, and the other representing an adjacent immature acidic system associated with the young Caigutan Dome. The heat source for the benign upflow is still uncertain, but there are a number of young volcanic domes mapped in the area, beneath which could be sources of conductive heat input.

Introduction

Kalinga Geothermal Prospect (also known as Batong Buhay) is situated in the Luzon Central Cordillera in the Municipality of Pasil, province of Kalinga, approximately 350km north of Manila, Philippines. The prospect is centered at the Batong-Buhay epithermal gold-mining district and has impressive thermal manifestations. The Pasil River is an ENE-trending feature that contains most of the thermal springs. Parallel to this is a ridge defined by Mt. Mossimus, Mt. Binulauan and Mt. Binuwuan (Figure 1). A perpendicular NW-SE structure cutting across the Pasil River contains the fumaroles, which extend on a similar trend beyond the ridge. A young volcanic feature, the Caigutan Dome forms a NW trend with Mt. Binulauan. The dome has a collapsed crater which contains the fumarolic area and acid-altered grounds.

Initial reconnaissance study of the Batong Buhay hot springs and volcanoes was done by the Philippines Commission on Volcanology in 1976. This was followed by a joint preliminary assessment by the Philippines Bureau of Energy Development and ELC- Electroconsult (Italy) in 1978 which included geological and geochemical sampling and aerial photo interpretations. The study concluded that the area has a good geothermal potential. An electrical resistivity survey was conducted and five shallow temperature gradient holes were drilled by GeothemEx Inc for Caltex Philippines in 1982. The resistivity data identified a low resistivity layer and the gradient holes found high heat flow and permeability. In 1996, Philippine Geothermal, Inc. conducted additional geochemical sampling. Chevron Kalinga Limited

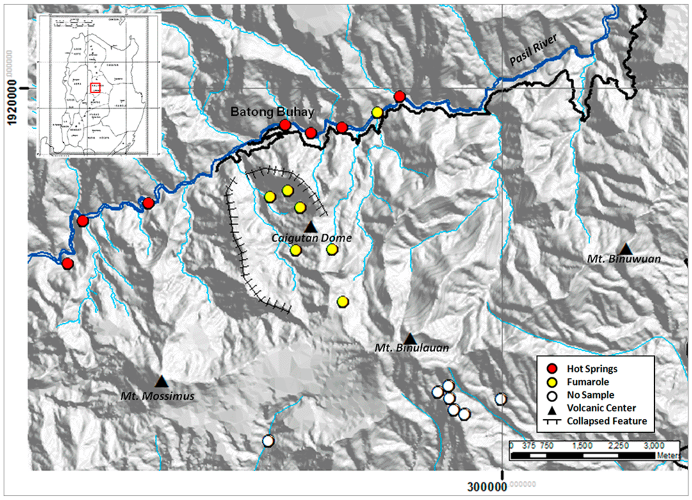

Figure 1. Location Map of Kalinga Geothermal Prospect showing volcanic centers and alignment of surface thermal manifestations.

(CKL), in partnership with Aragorn Power and Energy Corporation (APEC) and Guidance Management Corporation (GMC), is currently exploring the area, under a Philippines Department of Energy service contract held by APEC since 2008, covering an area of 260 km^2. This paper summarizes the results to date of the exploration done in 2010-2012.

Kalinga has also been explored and developed for gold and copper deposits by two local mining companies and a multinational company since the 1970's. Currently one small-scale mine is being operated inside the prospect and additional minerals exploration is ongoing.

Regional Geologic Setting

The prospect is found on the eastern flank of the Luzon Central Cordillera, which is a N-S trending mountain range traversing the western part of Northern Luzon.

The Cordillera formed when the Paleogene Quartz Diorite Batholith, formerly Agno Batholith in Fernandez and Pulanco (1964), intruded into a sequence of precursor basement rocks, the Cretaceous-Paleogene Metavolcanics, during Late Oligocene to Early Miocene. Durkee and Pederson (1961) described the basement lithologies as mafic flows, agglomerates and some thin indurated graywackes and conglomerates. This unit is also reported as the Pugo Formation of the Baguio District *(MGB, 2010).*

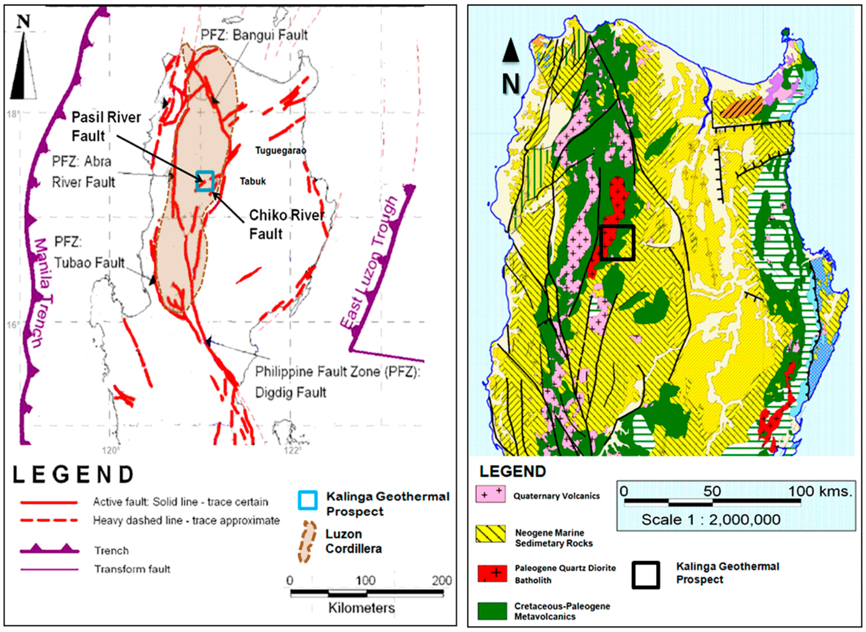

Figure 2. Regional structural and geologic map of Northern Luzon *(MGB, 2010 with minor annotations)*.

The batholithic intrusions of intermediate composition -- diorite, quartz diorite, granodiorite -- is also referred to as the Central Cordillera Diorite Complex *(MGB, 2010)* and according to Fernandez and Pulanco (1964) hosts the mineralization in some places in the district. The intrusion and subsequent uplift exposed the batholith and the basement rocks to the surface while continued erosion and deposition during Mid- to Late Miocene formed the sedimentary rocks at the flanks of the uplift, which were subsequently folded at the on-set of compression.

Later stage intrusions emplaced during the Late Miocene to Pliocene host the porphyry Cu-Au mineralization and the epithermal mineralization *(Subang, et al., 2006)*. Quaternary volcanism is reflected at the younger volcanic centers and likely represents the heat source of the geothermal system.

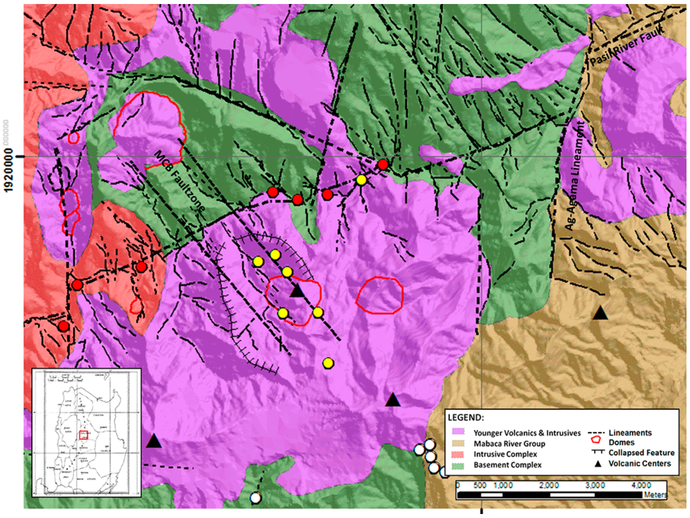

Figure 3. Composite geologic map showing major lithologies and structures.

Two prominent regional structures, both splays of the Philippine Fault Zone, run through the prospect (Figure 2). The NNE-trending Chiko River Fault borders the prospect to the southeast, and the ENE-trending Pasil River Fault runs through the center of the prospect. An E-W compressional regime has dominated much of the tectonic history, which would be consistent with right-lateral motion along both these faults. The E-W compression is also manifested in the folded sedimentary beds east of the prospect towards the Cagayan Valley. N-S trending anticlines and vertical beds are mapped along numerous road and river cuts in the vicinity of Tabuk.

Local Geology and Structures

The local geology is mapped under local formation names which largely correlate with the regional rock units of Figures 2 (Figure 3). The oldest exposed unit is the Basement Complex (known regionally as the Cretaceous-Paleogene Metavolcanics), which outcrops in the north- and south-central portion of the prospect area. The Intrusive Complex (Paleogene Quartz Diorite Batholith), which in Kalinga prospect ranges in composition from gabbroic to granodioritic to tonalitic, outcrops in the western margin of the prospect. The Mabaca River Group (Miocene Marine Sedimentary Rocks) outcrops in the east. The Younger Volcanics and Intrusives outcrop mostly in the center of the prospect area and include the lithologies of the ore-forming intrusive and the Quaternary Volcanics.

Epithermal mineralization is localized at the contacts between these younger intrusions and the older batholith and Basement Complex. Advanced argillic alteration was observed where the younger dikes intrude the batholiths. These contacts may also be good permeability targets. One of the youngest features in the prospect area is the Caigutan Dome, where most of the fumaroles are located.

The Basement Complex is the primary target for a geothermal reservoir. As opposed to most producing Philippines geothermal reservoirs which are hosted primarily in young volcanic rocks, the reservoir here is believed to be in the metamorphosed basement (metavolcanic) rocks. Durkee and Pederson (1961) reported that the thickest section (~3660 meters) is found in Batong Buhay. The five temperature gradient holes of Caltex drilled into the Basement Complex and showed non-linear temperature gradients, with one hole registering a downhole temperature of 178°C at 200m. Three out of the five holes experienced steam flow. These indicate evidence of good permeability and high heat flow.

Lineament analysis using 1-m LiDAR-derived DEM and aerial photo interpretation showed that the Pasil River Fault was offset into at least five segments by NW and NE trending lineaments, suggesting that the fault could be inactive. Another prominent structure is the 1-km wide NW-trending mineralized fault zone referred to as the Malinao-Caigutan-Biyog (MCB) Fault Zone (Figure 3). The fault zone contains the Caigutan Dome at the SE end and another dome feature to the NW, and roughly borders the Intrusive Complex to the east. NW-striking left-lateral faults, NE conjugates and E-W-striking tensional fractures were also mapped within the zone *(Subang, et al., 2006).*

NW and NE trending lineaments are mapped in the Basement Complex. The observed fracturing of the Basement Complex substantiates the probability of hosting the permeable reservoir. The lineaments are not prominent in the Younger Volcanics and Intrusives, but could possibly be buried under the pile of volcanic rocks. Another NE-trending lineament towards the east is the Ag-Agama lineament which acts as a boundary between the Basement Complex and the Mabaca River Group.

Generally, thermal manifestations are located along inferred or mapped fault traces. The Pasil River Fault contains most of the hot springs and alteration in the river bed increases upstream. The collapse feature northwest of the Caigutan Dome, most probably structurally-controlled, contains the fumarolic area. Several other suspected thermal areas are either cut or bordered by lineaments.

Geochemistry

The prospect has numerous boiling springs at low elevation along the Pasil River, including neutral chloride springs, and a number of vigorous fumarole fields in the highlands. There are also a few unsampled thermal features on the southern flank of Mt. Binulauan (Figure 1). The distribution of these thermal features relative to geologic structures and volcanic centers is shown in Figure 3.

Hot Spring Chemistry

Most of the sampled hot springs have neutral-pH chemistry and are at boiling temperatures. Some show cooler temperature west from the Batong Buhay mine site. The chloride concentration of the spring waters varies greatly, from 110 to 6380 ppm, suggesting mixing of the parent fluid with peripheral waters. The best example of the parent fluid (sample #1's, blue circle in Figure 4) is in equilibrium with most mineral parameters but shows higher magnesium than expected. This is consistent with its isotope data being a mixture of ~25% "andesitic water" and local meteoric water (Figure 4).

The Cl-SO_4-HCO_3 ternary plot (Figure 5) shows that most of the neutral Cl samples plot in the chloride apex which is typical for fluids coming from the deep geothermal reservoir in most high-temperature systems. The mixed hot springs plot towards the sulfate apex indicating mixture of the chloride fluids with sulfate waters. One distal warm spring plots towards the bicarbonate apex clearly indicating a bicarbonate type of fluid.

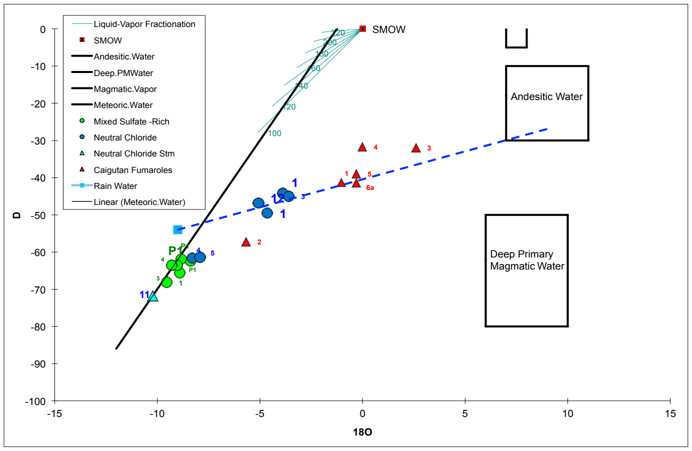

Figure 4. Stable isotope plot of the thermal manifestations.

In the Na-K-Mg Giggenbach ternary plot (Figure 5), neutral Cl samples 1a and 1b plot very near the equilibrium curve and at a projected temperature of about 300°C. This suggests that the sample was in near equilibrium conditions in a high temperature reservoir (280° - 300°C). The slight shift off the equilibrium curve is likely due to minor groundwater contamination. This implies that this hot spring is very near the main hot reservoir and is a

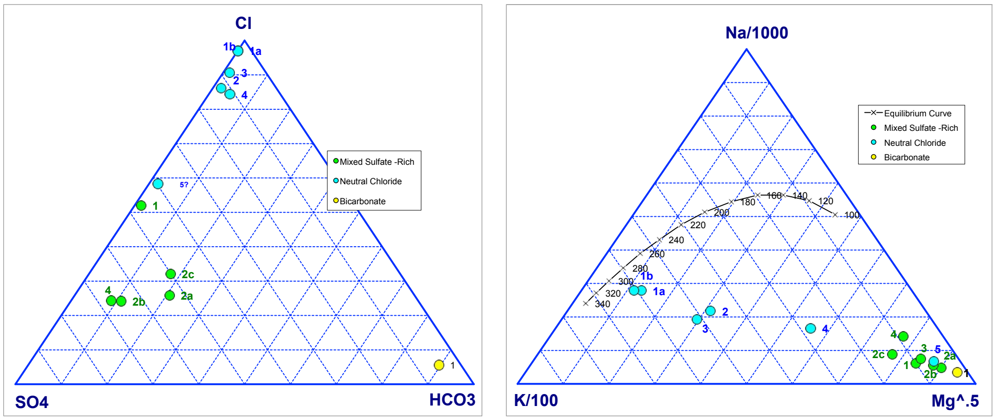

Figure 5. Ternary plots (Cl-SO_4-HCO_3 – left , Giggenbach- right) showing the classification and geothermometry of the hot springs.

very good indication of the presence of a mature, high temperature geothermal system in the area.

Gas Chemistry

Majority of the fumaroles are located at high elevation on the flanks of the inactive Mt. Binulauan volcano south of the chloride hot springs, and are most likely related to the young Caigutan dome. The fumaroles are generally superheated and deposit abundant sulfur. The superheated fumaroles contain significant excess chloride (0.1 to 1370 ppm) and SO_2 (up to 4%). Gas geothermometry temperatures vary significantly or are not calculatable using standard gas grids (CH_4-CO_2-H_2S, FT-HSH, FT-CO_2, HAr-CAr, HYCO-HYCH) (Figure 6). Helium isotope ratios are generally in the mid-range (6.0 – 7.8) near values associated with geothermal systems. The stable isotopes of the steam show a mixture of 50 – 60% "andesitic water" with local meteoric water (Figure 4). This suggests that the source fluid is more enriched in magmatic "andesitic water". A steam vent was also sampled along the Pasil River near one of the neutral chloride hot springs. The gas chemistry from this vent suggested a liquid reservoir with a neutral composition.

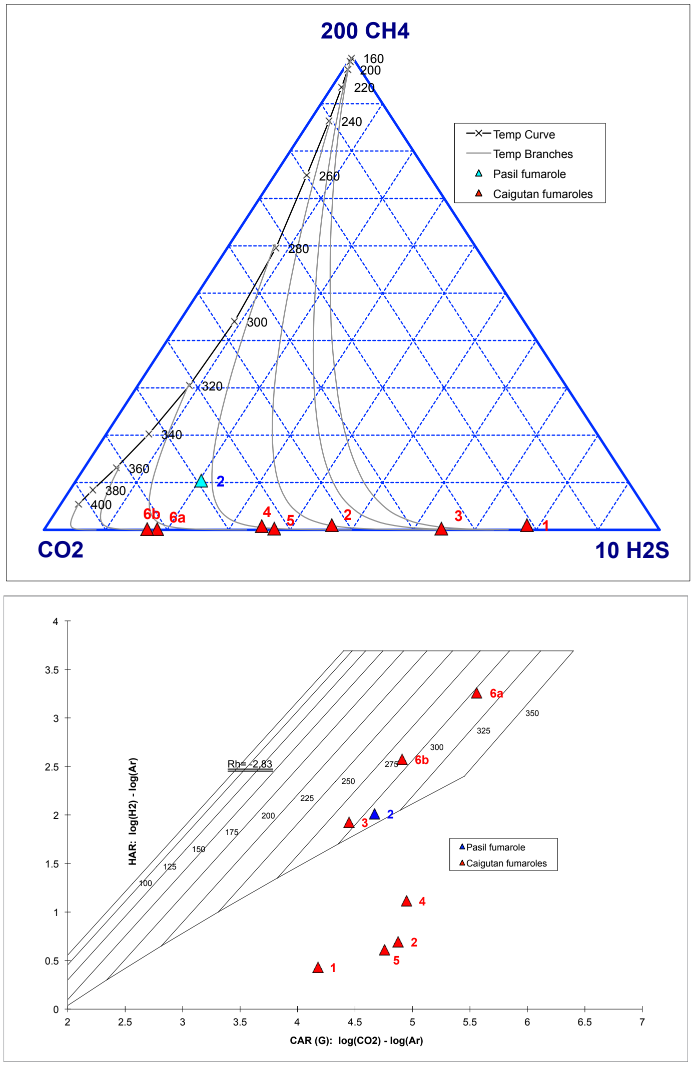

Figure 6. Selected gas geothermometry plots of the fumaroles showing the inconsistencies in their temperatures with some even plotting outside of the grid.

Geophysics

Magnetotelluric (MT) and gravity data show a strong correlation with the mapped lithologic units. The data sets complement each other to show the contrast between high resistivity, low density outcroppings of Intrusive Complex and the low resistivity, low density outcroppings of marine sediments of the Mabaca River Group. Superimposed on this there is a distinct zone of shallow low resistivity interpreted to represent clay alteration overlying the geothermal system. More intense localized low resistivity regions show a strong correlation with active surface alteration within the Caigutan acid fumarolic area. The gravity data complements resistivity correlations with lithology and allowed for estimates of the relative thickness of these units. Variations in relative densities between the clay and the Basement Complex give a range of possible depths to the top of the Intrusive Complex inferred to underlie the Basement Complex.

Magnetotellurics

A new MT survey was carried out primarily to map the location characteristics of the low resistivity clay capping the geothermal prospect area. A 3D inversion was carried out using the MT data. A total of 46 MT stations with a spacing of 300 m to 2.1 km were measured. Stations were occupied on all the major lithologic units within the prospect area, allowing for correlation of resistivity with mapped rock type distribution.

The conductance anomaly of the prospect area is exposed to the surface at the SW and dips to the NE. The conductance map in Figure 6 takes only the layer between 500 and 750 m elevation, which illustrates in plan view the distribution of shallow low resistivity interpreted as clay cap. It shows a good correlation of high conductance in the 500-750 m elevation layer with eastern group of hot springs, which are the neutral chloride-bearing ones. The western margin with lower conductance correlates with the outcropping margin of the Intrusive Complex. Towards the east of temperature gradient hole 5, the conductance increases, corresponding to the Mabaca River Group. The northern margin is characterized by an increase of resistivity associated with the disappearance of <30 ohm-m layer. The conductance anomaly is open to most of the southern portion of the prospect area. A resis-

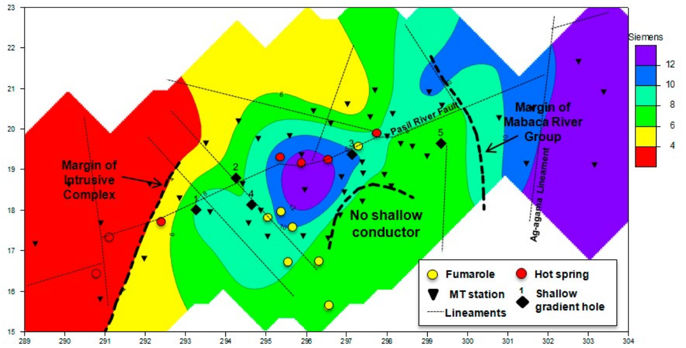

Figure 7. Layered conductance map from 500 m to 750 m elevation (1 tick mark is 1km).

tive plug is inferred at the southern edge of the survey area but was not fully resolved due to limited station coverage.

Most of the thermal areas are located over a zone of < 20 ohm-m as shown in Figure 8. The shape and thickness of the conductive layer is consistent with clay alteration over a geothermal system in the Pasil River valley area with a top that dips to the east. The < 20 ohm-m layer correlates with high surface heat flow and agrees with temperature profiles from the shallow gradient holes. Mineral assemblages from the core holes reveal the presence of argillic alteration within the low resistivity layer. The margins of the geothermal system are indicated in the west by the abrupt resistivity gradient near the outcropping margin of the Intrusive Complex, and in the east with a thickening of the 20 ohm-m and 30 ohm-m layers, associated with the Mabaca River Group, which is interpreted as a regional conductor.

The low resistivity layer mapped by the MT survey is not typical of high temperature volcanic-hosted reservoirs which typically have <10 ohm-m caprocks. The smectite clays, which are normally the primary source for <10 ohm-m resistivity, may have partially eroded away. Because of the different regimes of hydrothermal alteration with the ore mineralization being the oldest, the caprock resistivity may correspond to relict alteration that formed at older higher temperature and then experienced only minor retrograde alteration to smectite clay. The metamorphosed host rocks of the Basement Complex may also not be favorable to altering to smectite.

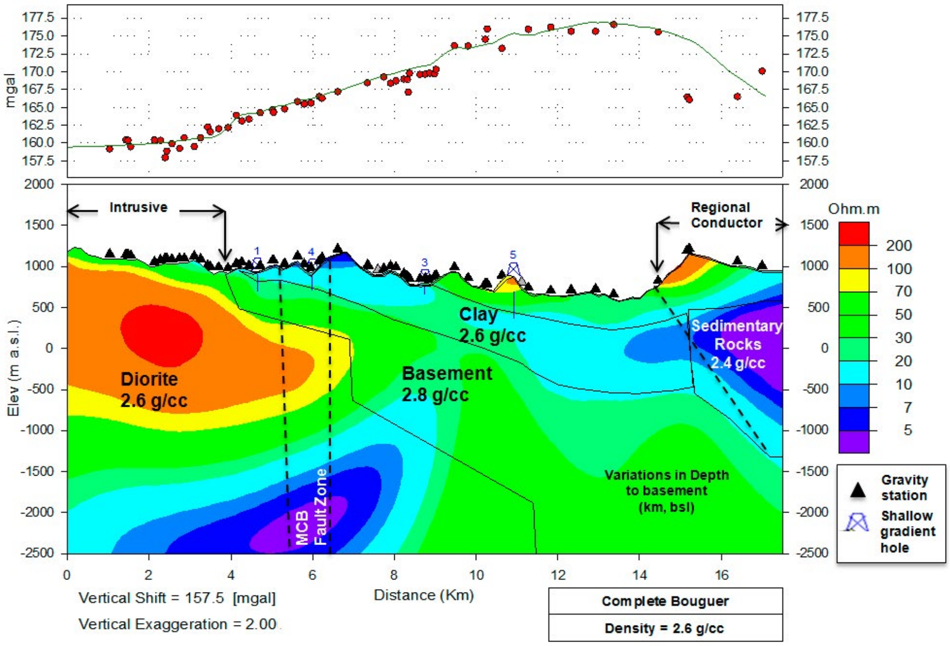

Figure 9. Modeled resistivity along Pasil River valley overlain by 2.5D gravity model and the resulting depth to the Basement Complex-Intrusive Complex contact.

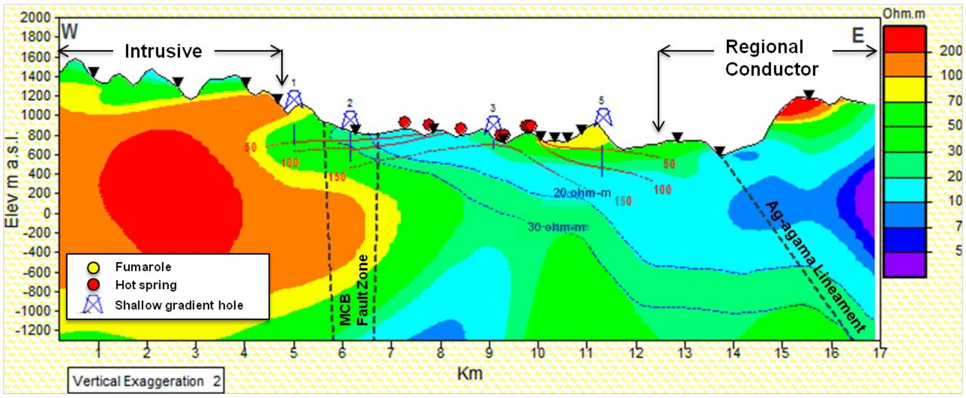

Figure 8. W-E Modeled Resistivity along Pasil River Valley.

The southern area, dominated by acid springs and fumaroles, is characterized by a more intense local low resistivity of <10 ohm-m. The younger volcanics in the area, being not subject to the erosional and lithologic considerations, may have undergone a more typical alteration to smectite which explains the observed lower resistivities extending up to the surface. Localized acid alteration may also explain the area of low resistivities.

In 1982, GeothermEx performed dipole-dipole and other resistivity surveys covering parts of the MT survey the area. The resistivity data generally agree with the MT, and help define part of the north boundary of the low resistivity anomaly, where MT coverage is limited and possibly distorted at high frequencies.

Gravity

A gravity network covering 86 stations at ~300 m spacing was conducted in 2012, including a detailed line at 250 m spacing along the access road paralleling the Pasil River. MT data and location of outcropping Intrusive Complex were used to constrain the 2.5D gravity model (Figure 9). Lacking a suite of rock samples representative of subsurface densities, modeled rock densities were instead based on published values *(Telford, et. al., 1976)* for the mapped lithologies. Densities for the Intrusive, Basement Complex and Mabaca River Group were thereby constrained to a reasonable range, but the density of the altered clay layer, inferred from the MT data, was not easily determined in this way. Another unknown is the cause of the resistivities of <10 ohm-m deeper than 1500 mbsl in the western half of the profile. For the purposes of the gravity modeling this deep conductive unit is treated as part of the Intrusive Complex.

The regional conductor Mabaca River Group in the east, with low resistivity and low density signatures shows a steep gravity gradient. There are some uncertainties in the top elevation and relative thickness of this unit that is exposed at the surface to the east of Ag-agama Lineament. But the 20 ohm-m to 30 ohm-m layer gives insight to the thickness of the formation relative to the low permeability clay to the West of the regional conductor.

The broad westward gravity decrease toward the high resistivity outcropping Intrusive Complex provides evidence that it has lower density than the Basement Complex rocks, as expected based on the lithologies. This provides an opportunity to model the presumed subsurface eastward extension of the top of the intrusive unit. Variations in modeled clay alteration densities from 2.5 g/cc to 2.7 g/cc result to depth to the top of the Intrusive Complex that ranges from 716 m to 1700 m bsl at gradient hole 3. Understanding the uncertainty of these depths would have an impact on well targeting.

Luzon Cordillera Trend Analysis

Within the Luzon Cordillera, five geothermal service contracts have been issued by DOE, of which Kalinga is the northernmost (Figure 10). Calibugan et al. (2011) did a trend analysis for the five prospects. A trend analysis consists of identifying the geologic trend in which the prospect of interest is located, studying every previously drilled well in the trend, and attempting to understand how those results might apply to the subject prospect - i.e. evaluating similarities or differences in particular geologic units, structures, permeability controls and the like, in order to explain possible reasons for the success or failure of the previous drilling programs.

Of the five prospects, only Prospects 3 and 4 have had deep drilling. The wells in both prospects proved non-commercial. Prospect 3 wells were drilled into the sedimentary units, while the Prospect 4 well drilled into the core of intrusive body. Permeability was poor in these two lithologic units. The trend analysis led to the conclusion that Kalinga possibly has an exploitable reservoir in the more permeable metavolcanic basement rocks, which is both exposed in the surface and was drilled by the shallow gradient holes. We infer from the previous drilling results that commercial permeability is less likely to be found in the Intrusive complex and Mabaca River Group at Kalinga.

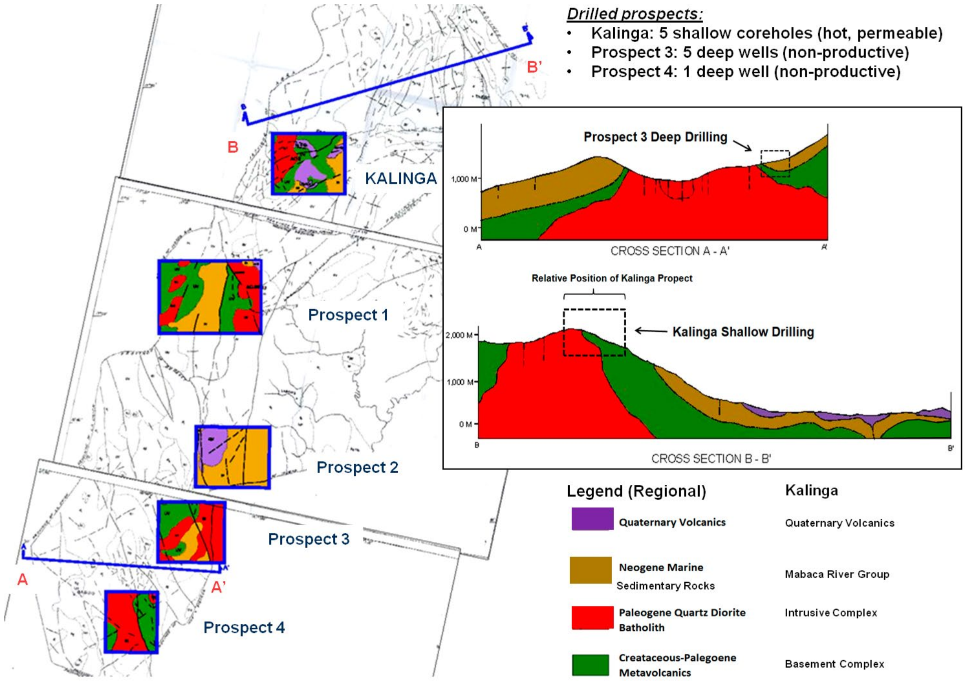

Figure 10. Regional trend of the geothermal prospects in Luzon Central Cordillera and sections showing relative locations of Prospect 3 deep drilling (A-A′) and Kalinga shallow gradient holes (B-B′).

Conceptual Models

The geothermal conceptual model of Kalinga brings together measured and inferred information from detailed studies of the different disciplines- geology, geochemistry and geophysics. Lineament and structural maps interpreted from remote sensing data integrated with local geology allowed for a reasonable geologic interpretation which aided in constructing the model. The chemistry of thermal manifestations reveals the approximate temperature and composition of the reservoir, its potential source, and its hydrological connection. The geophysical anomalies interpreted in the context of geology and permeability controls define the lateral extent and potential depths of the resource. Temperature data from shallow gradient holes helped in constraining the isotherms at least at the shallowest levels. Results of the trend analysis added confidence in discovering a high temperature system hosted in a permeable reservoir rock. Two conceptual models were developed for Kalinga, a distributed permeability model and a fault-controlled model, with the former being the one considered most likely.

Distributed Permeability Model

The distributed permeability model describes a system wherein fluid flow is not restricted to a single structure. It shows a reservoir with a good vertical fracture network that allows upflow from a heat source and subhorizontal fracture network that allows convective flow in a 3-dimensional reservoir. Enhanced permeability could be expected at significant geologic structures, structural intersection and lithologic contacts. The isotherms were constrained mostly near the surface where actual measured data is available. The shallow gradient holes were used to constrain shallow temperatures in the upper few hundred meters. Deeper isotherms were constructed assuming a conductive gradient merging into a more convective profile at a reservoir temperature suggested by the cation geothermometry.

The model shows a benign exploitable reservoir hosted in the Basement Complex between the 250°C to ~320°C isotherms and sealed by the clay cap. The upflow zone in the center outflows to both sides of the section. The rightward outflow is manifested as the neutral chloride springs at the surface (Figure 11). A separate upflow associated with Caigutan dome (where most of the acidic fumaroles are located) is found to the left. As magmatic fluids ascend, some of the fluids that reach the surface condense and flow to the slopes as acid+sufate±chloride fluids and contribute to the mixed Cl-sulfate springs in the vicinity of the dome and even farther left in the Intrusive Complex. The heat source for the benign upflow is still uncertain, but there are a number of young volcanic domes mapped in the area which could reflect deep sources of heat input.

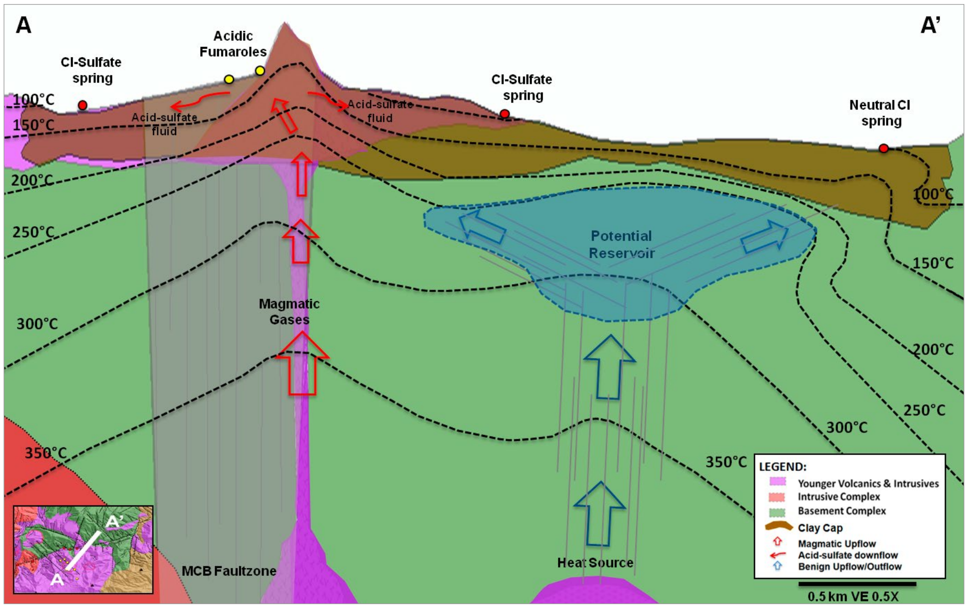

Figure 11. Distributed Permeability Model showing two separate systems- a benign geothermal upflow and an acidic (magmatic) upflow.

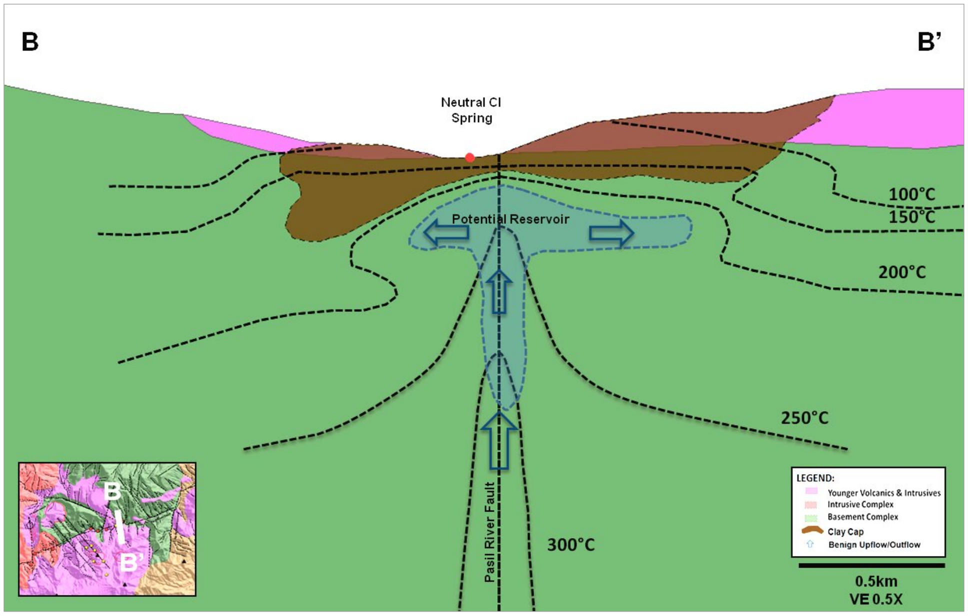

Figure 12. Fault-controlled Model showing a thin upflow centered along the Pasil River Fault and lateral outflows.

Fault-Controlled Model

An alternative conceptual model has the Pasil River Fault as the primary source of permeability (Figure 12). This would imply that the system is restricted to a narrow reservoir centered along the fault, beneath the ENE-trending line of thermal features, and possibly with a shallow outflow plume to cause the MT anomaly. The model became less favorable as evidences pointed to the fault being inactive. Pasil River Fault seems to be cut and offset by younger NW and NE structures. Also the localization of the thermal features along the river valley could be by default since hot springs are normally found on topographically low points. Furthermore, the geophysical anomaly extends away from the fault.

Conclusions

Preliminary exploration results of show good potential for an exploitable geothermal resource in Kalinga. The geochemical data suggest that there are two separate geothermal systems. The prospect is believed to host a mature, equilibrated and benign system as indicated by the high geothermometry and near-equilibrium neutral-chloride chemistry of its primary hot springs along the Pasil River. The higher-elevation fumaroles, on the other hand, suggest the presence of a young, magmatic vapor system around the young Caigutan dome. The magmatic character is indicated by high excess chloride and SO_2 in the superheated fumaroles. The geology of the area combined with regional exploration drilling results suggest that the neutral, benign reservoir is most likely hosted within the fractured metavolcanic rocks of the Basement Complex. Permeability within this rock unit may be enhanced along structures, structural intersections, and lithologic contacts. The geophysical data show a strong correlation with the mapped lithologic units. Superimposed on this is a distinct zone of low resistivity interpreted to reflect clay alteration overlying hot fluids in a geothermal system. The gravity data complements the resistivity data and also correlations with lithology, allowing for estimates of the relative thickness of the lithology units. The most-likely conceptual model is that the young magmatic vapor system in the vicinity of the Caigutan Dome is genetically separate from an older neutral geothermal system that extends north at least beneath the Pasil River. This suggests that there is a good possibility of discovering a benign resource even if an acidic system is adjacent to it, as seen from analogs such as the Tiwi Field and Mt. Apo geothermal fields in the Philippines.

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