PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

UPDATED HYDROGEOLOGICAL MODEL OF THE BACON-MANITO GEOTHERMAL FIELD, PHILIPPINES

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ABSTRACT

Recent deep drilling in the Bacon-Manito Geothermal Field (BGF), Philippines, provided enough additional information on subsurface stratigraphy and hydrothermal alteration mineralogy to come up with an updated hydrogeological model for the field. Two major rock units underlie the Bacman Field: Late Pliocene-Late Pleistocene Pocdol Volcanics (PV) composed of andesitic lavas, tuffs, and breccias; and the underlying carbonate-volcano-clastic sequence of the Late Miocene-Early Pliocene Gayong Sedimentary Formation (GSF). Both the PV and GSF are intruded by dikes of the Cawayan Intrusive Complex which serve as the heat source for the geothermal system. A field wide correlation of the PV and GSF was done for a better understanding of their distribution and petrologic characteristics.

Based on added subsurface information from drilling, hydrothermal alteration zones and their corresponding isothermal contours, based on mineral geothermometers and fluid inclusion homogenization temperatures, were drawn across the field. The secondary biotite alteration zone at deep levels indicates upflowing fluids of ≥300°C beneath the Palayang Bayan and Botong sectors. These fluids preferentially outflow towards the Manito lowlands to the northwest, Cawayan to the southwest, and Rangas to the southeast.

INTRODUCTION

A drilling campaign was recently implemented in the Palayang Bayan sector of the Bacon-Manito (Bacman) Geothermal Field (BGF) as part of the Bacman Steam Augmentation Program for the 150 MWe power plants (Figure 1). This activity provided additional subsurface information allowing an updated evaluation of the petrologic data on stratigraphy and hydrothermal alteration in the field, and bridging these with a previous resource assessment. Other wells drilled in the other production sectors of Botong, Cawayan and more recently in the expansion area of Tanawon also allowed insights into their subsurface geology and petrology, allowing for a clearer correlation with the main Palayang Bayan production field.

A field wide correlation of the two main underlying main rock formations, Pocdol Volcanics and Gayong Sedimentary was done for a better understanding of their distribution and petrologic characteristics.

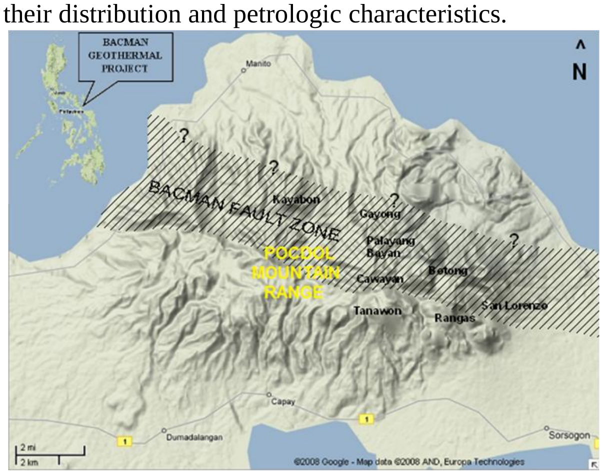

Figure 1. Location Map of the Bacman Geothermal Field, Philippines. .

Key hydrothermal alteration geothermometers, together with available fluid inclusion homogenization temperatures, were also used for correlation to be able to construct field-wide isothermal contours and trends to refine and update the hydrogeological model for Bacman.

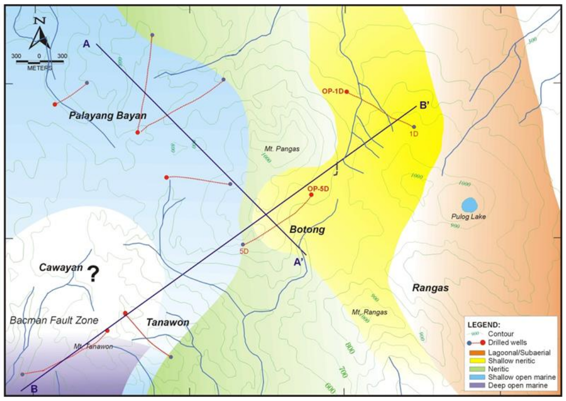

Figure 2. Sectoral map of Bacman showing the Palayang Bayan, Botong, Cawayan, Tanawon and Rangas sectors and location of cross sections. The colors represent the various rock units of GSF.

SUBSURFACE STRATIGRAPHY

BGF is underlain by andesitic lavas, tuffs and breccias of the Late Pliocene-Late Pleistocene Pocdol Volcanics (PV) and by carbonate-clastic sediments of the Late Miocene-Early Pliocene Gayong Sedimentary Formation (GSF) (Ramos, 2002).

Pocdol Volcanics

PV is characterized by two-pyroxene andesite and basaltic lava flows, andesitic tuff breccias, tuffs and basaltic breccias (Figures 2 –4). The breccia clasts, commonly composed of andesite, basalt, scoria and those derived from older terrains of microdiorite and dacite, are held together in a tuffaceous matrix of broken plagioclase or clinopyroxene crystals. This formation has an approximate maximum thickness of 2,000 m. It is assigned a Plio-Pleistocene age and reflects the extensive volcanism during this period. The basal unit of Pocdol Volcanics is usually the water-lain andesitic lava flows or hyaloclastite.

Old soil beds or lenses called paleosols are made up of hematized and argillized rocks with a general thickness of about 20 m. These are common at the basal unit of PV near or at the PV-GSF contact and serve as the marker horizon for their stratigraphic boundaries in most of the Bacman wells. There are cases, however, when the PV-GSF contacts appear to be transitional. In Botong and Tanawon, this is shown as an intercalation of hyaloclastite with the sediments or the partial calcareous cementation in the sedimentary breccias. The paleosol horizon thus signifies a regressive stage and end of marine sedimentation in this part of the Bicol Basin during the Early Pliocene, and onset of aerial, subaerial to partly sub-aqueous depositional conditions for PV.

Gayong Sedimentary Formation

GSF is predominantly composed of carbonaceous and fossiliferous limestones, reefal carbonates, calcareous sedimentary breccias and fine-grained clastic rocks (Figures 2-4). In Botong, fossiliferous calcarenites show echinoid spines, red algae and larger foraminifera. In addition, andesitic clasts with occasional basalt admixed with bioclasts of coral, algae, shells and foraminifera are all cemented by calcite. On the other hand, a recent core in Palayang consists of a clast-supported volcanic sandstone. Its age, based on paleoanalysis of core samples ranges from Late Miocene to Early Pliocene (N18-21 undifferentiated) coincides with widespread deposition of carbonates in the shallow neritic to open marine setting of the Bicol basin. Lithofacies characterization indicates a paleoenvironment gradation – from shallow neritic to shallow open marine - in Botong and Palayang Bayan sectors, and deepening towards the south in Tanawon, possibly reaching the abyssal plains of deep marine setting (Figure 4). Observed lateral and vertical changes in lithofacies of GSF are attributed to natural deepening of ocean basin morphology, historical sea level fluctuations, and tectonic activities (Santos and Dimabayao, 2011).

This sedimentary formation has widespread occurrence in Bacman except in Cawayan sector where this unit was not observed within the sampled intervals of the wells. Most of the production wells were blind drilled at shallow levels but a core cut at deeper levels showed an intensely altered volcanic rock belonging to PV. A reinjection well drilled towards the west likewise intersected tuff breccias and andesitic hyaloclastite of Pocdol Volcanics.

CAWAYAN INTRUSIVE COMPLEX

Both rock units are intruded by multi-lithologic dikes ranging in composition from gabbro, monzogabbro, monzodiorite, pyroxene to quartz microdiorite and diabase and microdiorite, andesite and diabase collectively called the Cawayan Intrusive Complex (CIC) (Figures 3-4). Their compositional and textural variations may be an indication of their emplacement in various stages of magmatic differentiation and rejuvenation. K-Ar radiometric dating gave an Early Pleistocene age (1.71 Ma) for the outcropping Rangas Intrusive and a comparable age (1.79 Ma) for a core sample from a Cawayan well. These ages possibly represent the older intrusive event. Most Bacman wells intersected the CIC, where local contact metamorphic aureoles develop along the margins of these dikes. These hornfels display a distinct sugary texture and consists of various suites usually reflecting the composition of the original country rock. The garnet-amphibolebiotite-carbonate and biotite-actinolite-muscovite suites are more likely derived from the calcareous and clastic facies of the GSF, respectively. On the other hand, the actinolite-epidote-clinozoisite are related to the volcanic rocks of Pocdol Volcanics.

HYDROTHERMAL ALTERATION AND TRENDS

The neutral-pH alteration suite is the dominant secondary assemblage in the deeper levels of Bacman wells. Geothermometry is based on recent replacement alteration and vein mineralogy which generally show good correlation with measured reservoir temperatures indicating deposition by present day fluids. Table 1 shows the important mineral geothermometers in Bacman ranging in temperatures from ~ ≤180°C to >300°C. These geothermometers, together with some available fluid inclusion homogenization temperatures, were used as basis for constructing the isothermal contours across the various sectors of BGF.

Table 1. Key Mineral Geothermometers in Bacman wells.

Mineral	Estimated Temperature (°C)
Smectite	≤ 180
Illite-smectite + incipient-anhderal epidote	180 – 200
Illite + subhedral epidote	220
Illite + euhedral epidote +/- wairakite	240
Actinolite + abundant epidote/clinozoisite + veins	260
Abundant actinolite/tremolite + veins	280
Biotite	≥ 300

Palayang Bayan-Botong Section

The hottest sector in Bacman, enclosed by the secondary biotite isothermal contour correlative with temperatures exceeding 300°C, is at deep levels of Palayang Bayan and Botong (Figure 3). A distinct arching of the isothermal contours starting from 220°C (subhedral epidote + illite) to shallow levels until 280°C (abundant actinolite + tremolite) indicates the presence of hot, upflowing fluids. This extends a bit to the northwest where the measured temperature reached about 360°C in one recent well. On the other hand, fluid inclusion average homogenization temperature on calcite veins from a recent core was 290°C. Recent drilling has thus confirmed that hot, neutral-pH fluids upflow beneath the central part of BGF as originally defined in previous reports (i.e., Ramos, 2002).

In Botong, the 200°C- 280°C isotherms dip steeply towards the southeast and appears to be structurally controlled, possibly by Botonga Fault. This implies that production temperatures of ≥220°C may be intersected at deeper levels southeast of Botong towards Rangas.

In the northwest, the 240°C- 280°C contours plunge at deeper levels. In contrast, the 200°C- 220°C isotherms dip gently indicating that the geothermal fluids preferentially outflow in this part of the field (Figure 3).

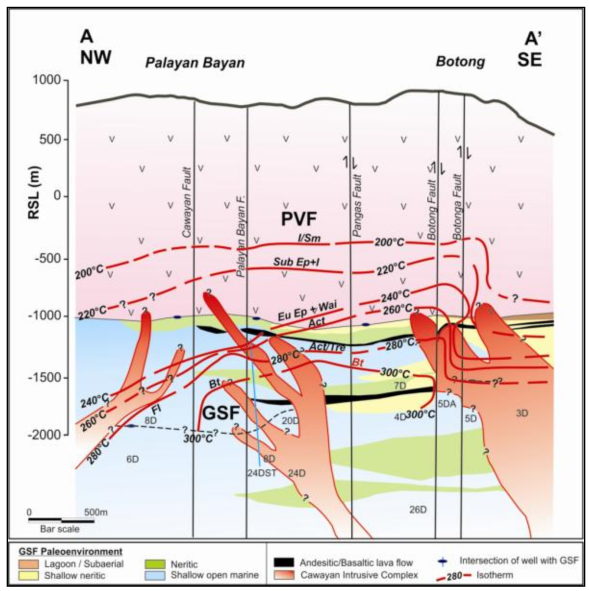

Figure 3. Stratigraphy and Isothermal Contours in Palayang Bayan and Botong sectors.

Tanawon-Botong Section

In Tanawon, the 180°C (incipient epidote + illite-smectite) to 240°C (subhedral epidote + wairakite + illite) isothermal contours occur at relatively shallow depths (Figure 4). However, the 260° isotherm (abundant euhedral epidote + veins + actinolite) occurs deeper near the bottom of a Tanawon well. The wide separation of ~800 m between the 240°C and 260°C contours suggests that a low thermal gradient exists in the southwest sector, and Tanawon possibly represents the periphery of the Bacman resource.

The 180°C - 220°C isotherms plunge towards the northeast in Botong as these contours intersect Rangas South Fault and appears to mimic the distribution of the GSF on the downthrown block of the said structure (Figure 4). The 220°C - 260°C contours are closely spaced beneath the Botong wells suggesting a sharp increase in the thermal gradient in this sector. The 280°C contour, represented by abundant tremolite/actinolite takes an upward trend in the Botong wells. The heat flux is more likely associated to the younger intrusives of the CIC in this sector.

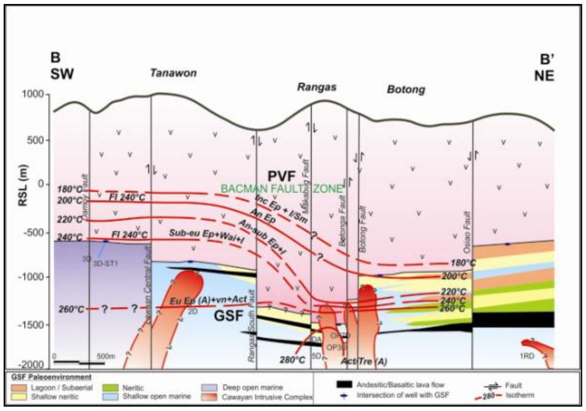

Figure 4. Stratigraphy and isothermal contours in Tanawon and Botong sectors.

HYDROGEOLOGICAL CONCEPTUAL MODEL

Subsurface data from wells drilled since 1989 in Palayang Bayan, Botong, Cawayan and Tanawon affirm the 1989 hydrogeological model where hot neutral-pH fluids upflow mainly in the central part of BGF within Palayang Bayan and Botong sectors. Secondary biotite and actinolite alteration and vein mineralogy define high temperature isothermal contour exceeding 300°C in this part of the field. These upflowing fluids take a preferential outflow direction to the northwest and a minor one to the southeast towards Rangas along permeable structures (Figure 5).

In addition, a third outflow direction towards Cawayan in the southwest is suggested and supported by Cawayan well discharge chemistry indicating temperature not exceeding 270°C. The lower temperature in Cawayan, despite the presence of CIC suggests that these dikes are possibly part of older intrusive events. It is more likely that the apophyses of the younger dikes, intersected by the Botong and Palayang bayan wells, are the near surface extension of the deeply rooted, youngest intrusive events in Palayang Bayan and Botong and are the direct heat source driving the current geothermal system in Bacman.

Recent drilling has also revealed low permeabilities in the north-northeast sector and Tanawon in the southwest possibly demarcating the boundaries of the Bacman geothermal resource. In Tanawon, this postulated boundary coincides with marine-deposited GSF fine-grained clastics which possess inherent low permeability.

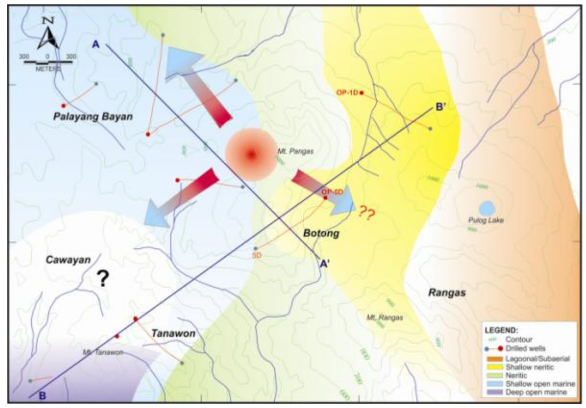

Figure 5. Plan view of the hydrogeological conceptual model for Bacman

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