PROCEEDINGS, Twenty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2002
SGP-TR-171

POTENTIAL CONSTRAINTS TO THE DEVELOPMENT OF THE RANGAS SECTOR BASED ON PETROLOGIC EVALUATION OF THE BACMAN GEOTHERMAL FIELD, PHILIPPINES

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ABSTRACT

At production levels below -600 m RL, the reservoir in the Palayang Bayan sector of the Bacman Geothermal Production Field is hosted by andesitic lavas, tuffs and breccias of the Plio-Pleistocene Pocdol Volcanics, while the Botong-Rangas sector is dominated by calcareous sediments of the Late Miocene-Early Pliocene Gayong Sedimentary Formation. Alteration mineralogy and fluid inclusion homogenization (T_h) data are generally consistent with geochemical and stable measured temperatures indicating a maximum reservoir temperature of 320°C at the upflow zone located in the vicinity of wells PAL-10D and OP-4D. The isotherms dip towards the southeast in Rangas where maximum temperatures of 300°C lie at -1800 mRL. Freezing point depression temperatures (Tm) of fluid inclusions with corresponding apparent salinities of ~7,000-9,000 ppm Cl_{equi} approximate Cl_{res} of 8,000 mg/kg. Higher T_h and apparent salinities are attributed to trapped CO_2 gases contributed by Gayong sediments in PAL-8D, PAL-14D and OP-6D, while progressively low salinities in PAL-14D and OP-6D suggest dilution of reservoir fluids by invading cooler waters. Fluid flow towards Rangas is channeled by the southeast-trending Makabug, Botong, and Dome faults. The low permeabilities and high NCG levels of the Botong reservoir will likewise prevail in Rangas and may impose critical constraints on the future development of this sector.

INTRODUCTION

The Bacon-Manito (Bacman) Geothermal Production Field, (Fig. 1) has a total installed capacity of 150 Mwe from Palayang Bayan (Bacman-I, 110 MWe), Cawayan (Bacman-II, 20 MWe), and Botong (Bacman-II, 20 MWe). Bacman-I has been in commercial operation since September, 1993 while Cawayan and Botong were commissioned in 1994 and 1998, respectively. An earlier evaluation on the Rangas-Tanawon sector (PNOC-EDC, 1992) shows an upflow zone in the vicinity of OP-4D with a major

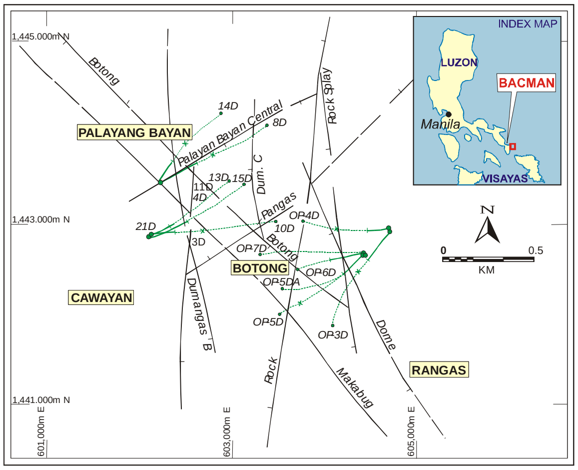

Figure 1. Location map of Bacman.

outflow towards the northwest and minor outflow paths to the west, southwest, and east-northeast. Although a well has yet to be drilled in Rangas, this sector was considered part of the upflow zone as there were no indications of pressure and temperature decline south of OP-3D. On the other hand, geochemical baseline studies (Ruaya et al., 1994) and magnetotelluric interpretations (Los Baños et al., 2000) both indicate that Rangas lies within a possible outflow path.

The present study focuses on the extent of hot geothermal resource from the Palayang Bayan-Botong production field towards the southeast in Rangas through a detailed petrologic evaluation of production wells in Palayang Bayan (PAL-8D, PAL-10D, PAL-13D, PAL-14D, PAL-15D) and Botong (OP-3D, OP-4D, OP-5DA, OP-6D, OP-7D). These petrologic data are integrated with available magnetolelluric, geochemical and other reservoir parameters to a model showing the location of Rangas relative to the existing production field and to assess the viability of this frontier sector for future expansion.

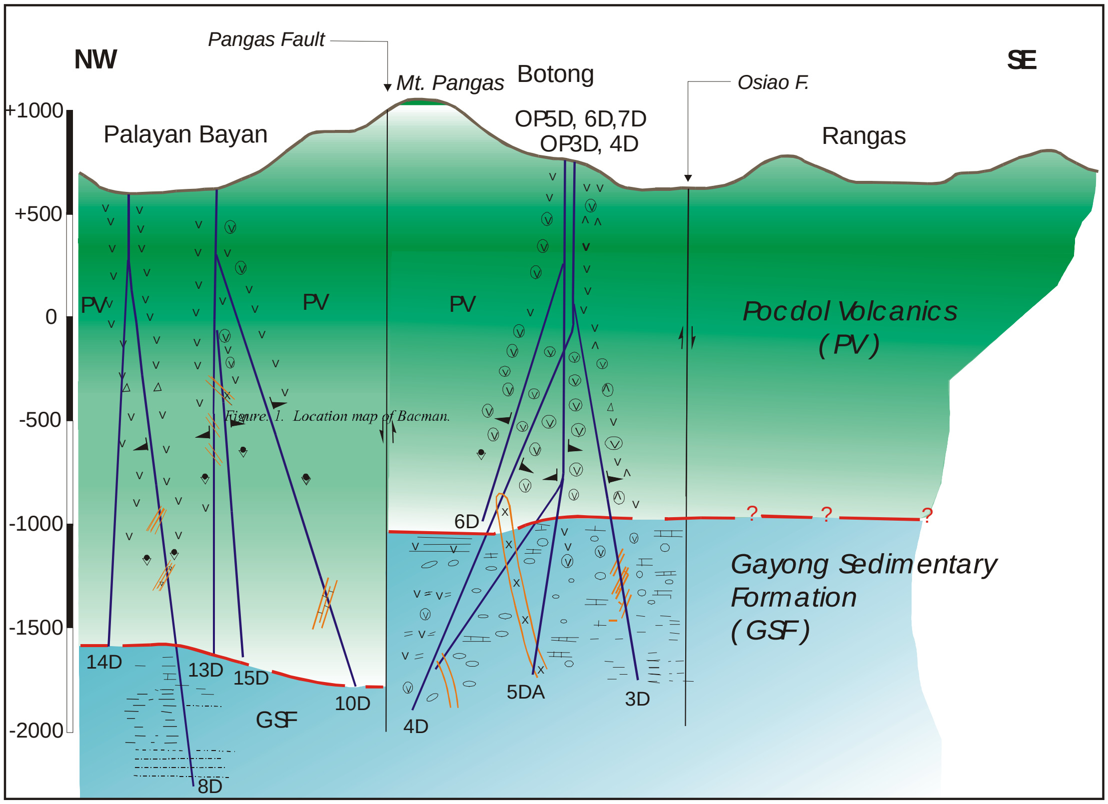

Figure 2. Reservoir rocks in Palayang Bayan-Botong, Bacman.

SUBSURFACE PETROLOGY

Reservoir Rocks

The Bacman geothermal production field 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). Paleosol horizons made up of hematized and argillized rocks are common at the basal unit of PVF near the PV-GSF contact. Both rock units are intruded by microdiorite, andesite and diabase dikes starting at -200 m RL in PAL-15D down to deep levels at -1585 m RL in OP-4D. Garnet-amphibole-biotite-carbonate hornfels develop as local contact metamorphic aureoles along the margins of these dikes. The carbonaceous siltstone facies of GSF was intersected in Palayang Bayan by PAL-8D only starting at -1550 m RL. In contrast, its shallow occurrence in Botong (-960 m RL in OP-5DA) makes the calcareous facies of GSF the dominant reservoir rock in this sector (Fig. 2).

Distribution of Alteration Minerals

Clays. The smectite, interlayered illite-smectite, and illite zones commonly overlap but generally occur shallower in Palayang Bayan relative to Botong (Fig. 3). Smectite defines a thick zone from surface down to -140 m RL in PAL-8D and until -520 m RL in OP-3D. Illite-smectite is a thin layer (160-220 m thick) between PAL-8D and PAL-15D, but reaches a maximum thickness of 520 m in OP-5DA, then peters in OP-3D towards Rangas. These clay zones correspond to the low resistivity layers of <20 Ω-m and serve as a clay cap above the reservoir (Los Baños et al., 2000).

The illite zone occurs below -220 m RL in Palayang Bayan and -780 m RL in Botong.

Epidote. The three crystalline morphologies of epidote: incipient-anhedral, subhedral, and euhedral show a similar shallow occurrence in Palayang Bayan and a dipping trend towards the southeast in Botong (Fig. 4). A profile showing the first occurrences of the various forms of epidote defines a consistent uphill trend in PAL-13D and PAL-15D in Palayang Bayan. Their shallowest occurrences were observed in PAL-13D at +55 m RL for anhedral epidote, -52 m RL for the subhedral type, and -302 m RL for euhedral crystals.

In Botong, all three forms are found at deeper levels in OP-4D at -451 m RL, -771 m RL, and -901 m RL, respectively. The contours generally dive towards the southeasterly wells and in the direction of Rangas. The deepest occurrences of epidote were observed in

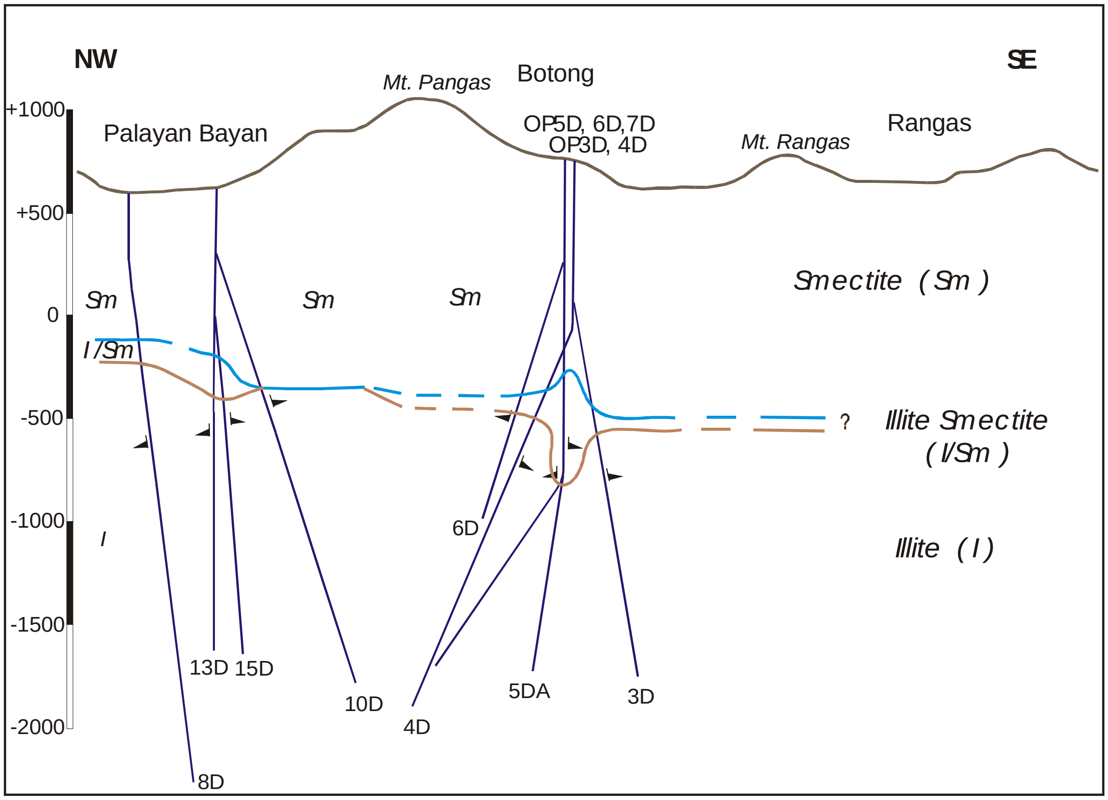

Figure 3. Clay zonation in Palayang Bayan-Botong, Bacman.

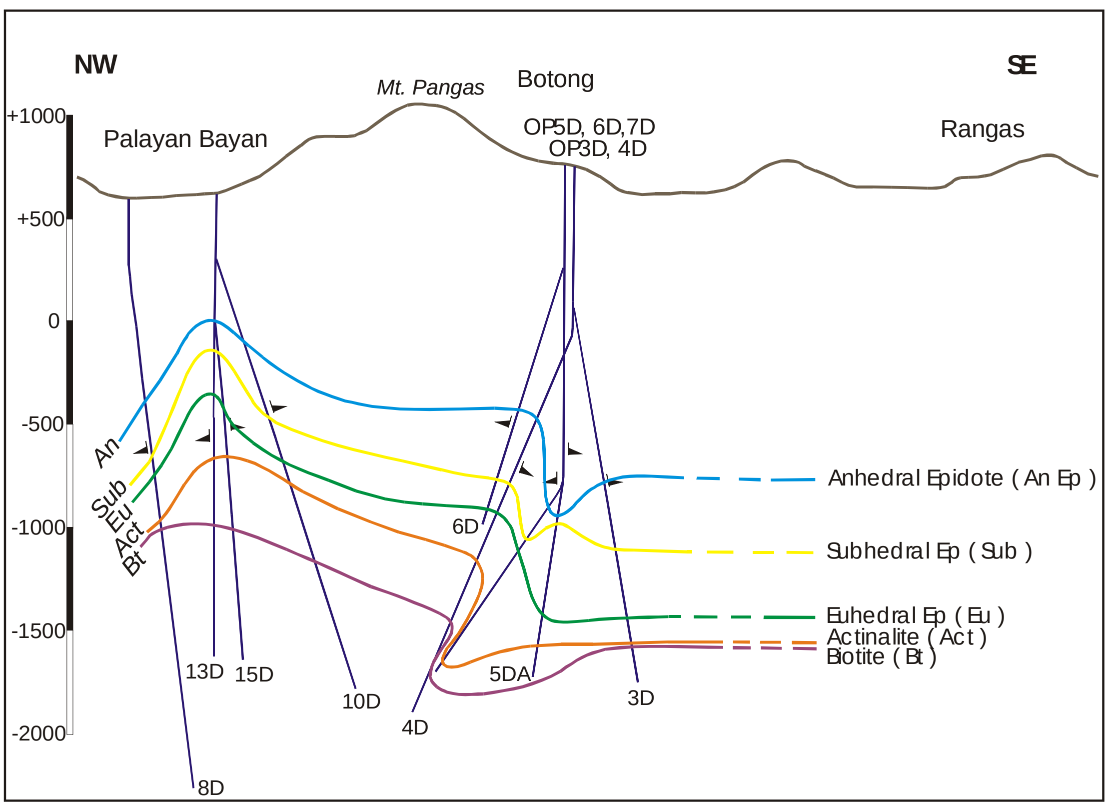

Figure 4. Epidote-Actinote-Biotite zonation in Palayang Bayan-Botong, Bacman.

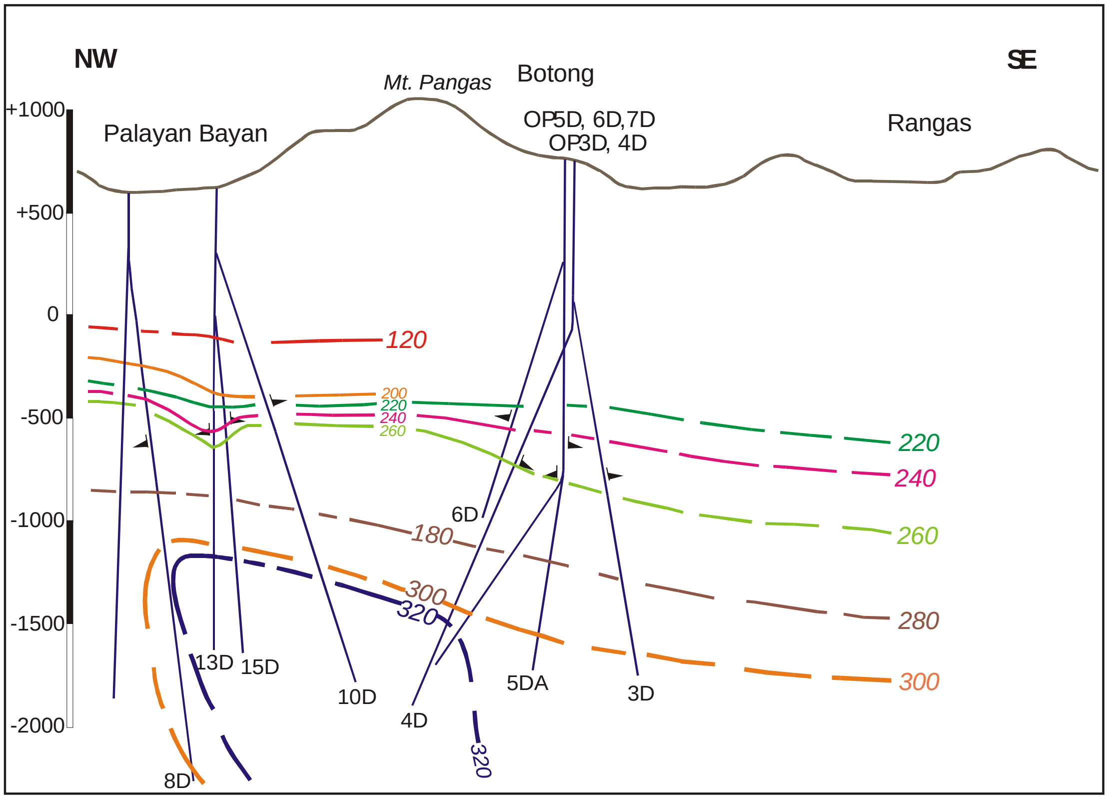

Figure 5. Fluid inclusion homogenization temperatures (Th) in Palayang Bayan-Botong, Bacman.

OP-5DA (-960 m RL and -1440 m RL for the anhedral and euhedral forms, respectively) and OP-3D (-1100 m RL for subhedral crystals).

Actinolite. Actinolite generally follows the epidote trend. It was first observed at -653 m RL in PAL-13D and dips to -1550 m RL in OP-3D and OP-5DA (Fig. 4).

Biotite. Biotite was noted in PAL-8D (-913 m RL) and similarly occurs at deeper levels in the Botong wells OP-3D (-1570 m RL) and OP-4D (-1430m RL). It approximates the occurrence of actinolite in OP-3D (Fig. 4).

Structural Flow Paths

Faults serve as the major pathways for the vertical and lateral flow of hot geothermal brine. The main arteries connecting Palayang Bayan, Botong and Rangas are Makabug, Botong, and Dome faults (Fig. 1). Their northwest-southeast-structural grain define the major flow direction of fluids in Bacman. These are dispersed via Palayang Bayan Central, Dumangas A, Dumangas B, Dumangas C, and Rangas faults within Palayang Bayan and via Botonga fault in the Botong sector. These faults are manifested by the presence of veins and sheared rocks along their well intercepts. Vein minerals are commonly composed of quartz, anhydrite, wairakite, and calcite, with epidote and actinolite at deeper levels.

Lithologic contacts at the PV-GSF and dike-country rock boundaries, together with bedding planes within GSF provide additional permeabilities.

Fluid Inclusion

Homogenization temperature (T_h) measurements on anhydrite, quartz and calcite veins are available from PAL-8D (Reyes, 1984), PAL-13D, PAL-14D (Zaide-Delfin, 1990), PAL-15D, OP-4D (Reyes, in Maturgo, 1990), OP-5DA, and OP-6D (Fig. 5). The data provide critical temperature information on the deposition of these minerals and on the quality of fluids passing along the fractures. The fluid inclusions are commonly two-phase and liquid-rich while some are vapor-rich and contain daughter minerals. The available average T_h values clearly define the distribution of temperatures between 220ºC and 320ºC across Palayang Bayan and Botong. The 300ºC and 320ºC contours plunge sharply near the bottoms of PAL-8D, PAL-13D, PAL-15D, PAL-10D, and OP-4D outlining a dome-like feature in this sector. The isotherms generally dip gently from the northwest in Palayang Bayan towards OP-5DA and OP-6D in Botong. In OP-6D, the 220ºC, 240ºC, 260ºC contours are at -460 m RL, -580 m RL, and -720 m RL, respectively. On the other hand, the

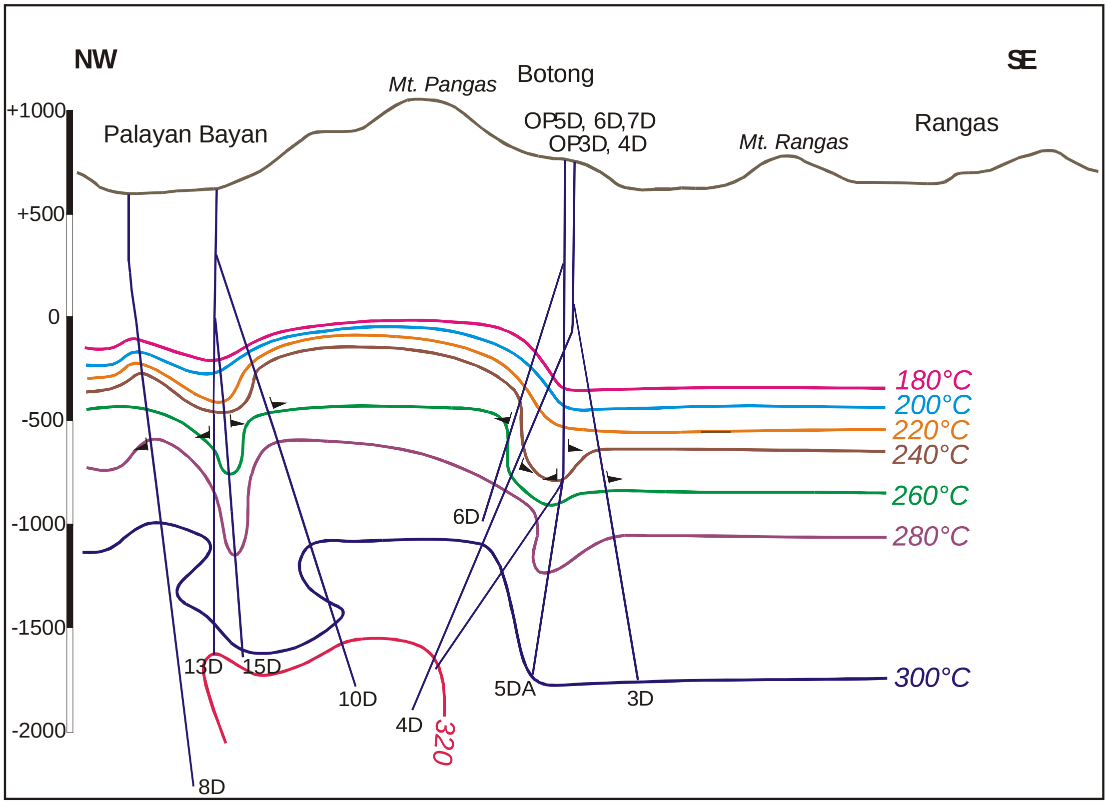

Figure 6. Stable measured temperatures (Tmeas) in Palayang Bayan-Botong, Bacman.

280ºC and 300ºC contours are found at depths of -1200 m RL and -1580 m RL in OP-5DA.

THERMAL HISTORY

Mineralogic and T_h Contours vs. Stable Reservoir Temperatures

Temperature contours based on mineral geothermometers and fluid inclusion T_h are compared with stable measured temperatures (T_{meas}) (Fig. 6) to better understand the thermal history of the Bacman geothermal field. Mineral geothermometers are typical hydrothermal alteration minerals whose range of temperature of occurrence has been firmly established in Philippine geothermal fields (Table 1).

Table 1. Common mineral geothermometers in Philippine geothermal fields

Mineral	Temperature Range of Occurrence (°C)
Clays Smectite	≤ 180
Illite-smectite	180-220
Illite	≥ 220
Epidote Incipient - anhedral	180-200
Subhedral	200-240
Euhedral	≥ 240
Actinolite	≥ 280
Biotite	≥ 300

Mineral geothermometers, T_h, and T_{meas} all indicate maximum reservoir temperatures of about 320ºC. T_{meas} contours starting at 180ºC show the occurrence of high temperatures at relatively shallow depths in the vicinity of PAL-10D and OP-4D. Geochemical data such as T_{quartz} and chloride-enthalpy plots similarly suggest that hot, geothermal brine with temperatures of 300ºC-320ºC are presently originating from this sector called the Palayang Bayan-Botong upflow zone (Solis et al., 1999, Ruaya et al., 1994). The highest CO2/N2 ratio (1460) and CO2 content (2.0 wt %) likewise show that OP-4D taps the hottest original liquid phase (Ruaya et al., 1994). The 220ºC T_{meas} show that the production zone in Palayang Bayan starts at -300 m RL, -400 m RL in OP-4D and OP-6D, but is much deeper at -600 m RL towards the southeast in OP-3D and Rangas.

The distribution of geothermometers and T_h contours are consistent with the trend of T_{meas} across the field suggesting that both alteration and vein minerals were deposited by fluids presently circulating in the system. The illite zone (Table 1) and 220ºC T_h contours indicate production levels below -400 m RL in Palayang Bayan, and -600 mRL in the Botong well OP-3D. This zone corresponds to the high resistivity zone of >50 Ω-m which represent the Bacman reservoir (Los Baños et al., 2000).

In Palayang Bayan, downflowing cooler fluids shown in the T_{meas} of PAL-13D and PAL-15D (Fig. 6) are likewise reflected in the T_h and illite contours between -200 m RL and -700 m RL. The shallow occurrence of epidote and actinolite in these wells probably reflects localized contact metamorphic effects of dikes intruded in the past (Fig. 2).

In Botong, the epidote contours dip steeply from OP-4D towards the southeast. The calcareous nature of the GSF in this sector and the attendant high NCG levels of up to 9% (Solis et al., 1999) probably suppressed crystalline growth of epidote. The first appearance of its anhedral and subhedral forms is ~300 m deeper, while the euhedral type occurred ~700 m deeper relative to the T_{meas} contours. On the other hand, the steeply dipping trend demonstrated by the T_{meas} contours may have been influenced by the limited fluid circulation due to inherent low permeability of the reservoir rocks in this sector. Most Botong wells are characterized by low injectivity indices of ≤12 L/s-Mpag, low transmissivities from 0.3-1.6 d-m, and generally positive wellhead pressures. At deeper levels below -1400 mRL, however, high temperature minerals such as actinolite and biotite (Table 1) are in equilibrium with T_{meas} in OP-3D, OP-4D, and OP-5D suggesting that these were deposited by fluids related to the present geothermal system. Thus, the Botong sector also hosts temperatures up to 300ºC which are found at deeper levels relative to Palayang Bayan.

Fluid inclusion T_h data generally show several episodes of mineral deposition. There are high T_h values (>350ºC) with occasional vapor-rich inclusions which indicate boiling during ascent of the geothermal fluids. Other T_h values correlate with the T_{meas} and represents the average temperature of the geothermal reservoir. Lower temperature (≤200ºC), liquid-rich fluid inclusions were deposited by cooler, meteoric fluids presently invading the reservoir. This latest episode is already manifested in the T_{meas} of PAL-13D and PAL-15D where such invasion may reach as deep as -1500 mRL. However, such invasions have not resulted in critical temperature decline in the reservoir.

T_m vs. Reservoir Fluid Chemistry

Freezing point depression temperatures (T_m) are available from PAL-8D at -378 m RL and -2188 m RL (Bueza and Reyes, 1987; Reyes, 1984;), PAL-14D at -198 m RL to -514 m RL (Zaide-Delfin, 1990), OP-5DA at -1260 m RL, and OP-6D at -465 m RL and -848 to -877 m RL. T_m may be used to approximate the apparent salinity of the fluids in terms of ppm chloride equivalent (Cl_{equi}). However, trapped gases in the inclusions may affect T_m measurements and result in values higher than the true salinitiy of the reservoir fluids (Zaide-Delfin, 1990).

T_m values suggest salinities of 50,000 ppm Cl_{equi} and 25,000 ppm Cl_{equi} in PAL-8D; 17,000 ppm Cl_{equi} in PAL-14D, 12,400-14,400 ppm Cl_{equi} in OP-6D. These are higher compared with actual Cl_{res} of 8,000 mg/kg. The high salinity estimates likely represent unboiled fluids which still contain high amounts of trapped CO_2 gas. PAL-8D, PAL-14D, and OP-6D intersected the GSF which is the probable source of high NCG levels in Bacman. On the other hand, salinity values of 9,000 ppm Cl_{equi} in OP-5DA and 7,400-8,400 ppm Cl_{equi} in OP-6D approximate reservoir chlorides of 7,500-8,500 mg/kg Cl based on the Cl- $\delta^{18}O$ plot (Ruaya et al). In contrast, lower values of 6,300-2,100 ppm Cl_{equi} in OP-6D and 1,000 ppm Cl_{equi} in PAL-14D may be related to the progressive dilution of boiled, saline reservoir fluids by cool, meteoric waters percolating down to reservoir depths.

FLUID FLOW PATHS

Correlation with Structures and Lithologic Contacts

Most of the permeable zones in Bacman are associated with faults (Fig. 7). In Palayang Bayan, the main permeable zones in PAL-8D and PAL-10D are correlated with Palayang Bayan Central and Dumangas C faults, respectively. These two structures each account for >20% of the permeable zones in the Palayang Bayan wells. Multiples faults may also be present in a single permeable zone such as in PAL-13D and PAL-15D where the permeable zone between -700 m RL and -1000 m RL correlates with Botong, Makabug, and Dumangas-A faults.

In Botong, the main permeable zones of OP-4D and OP-3D are each related to Dome and Botonga faults, respectively. The other significant structure is Botong. Both Dome and Botong faults are each responsible for 23% of the permeable zones in this sector. Other structures which account for ≤10% each of the permeable zones in Botong are San Lorenzo, Rock Splay, and Makabug faults.

Lithologic permeability also contributes to well production. In Palayang Bayan, the permeable zone at -1520-1620 m RL in PAL-8D is also correlated with the PV/GSF stratigraphic contact. In Botong, 15% of permeable zones are attributed to lithologic permeability within Pocdol Volcanics. Dikes are likewise associated with the major permeable zones in PAL-8D and OP-3D, and minor permeable zones in PAL-10D and OP-4D.

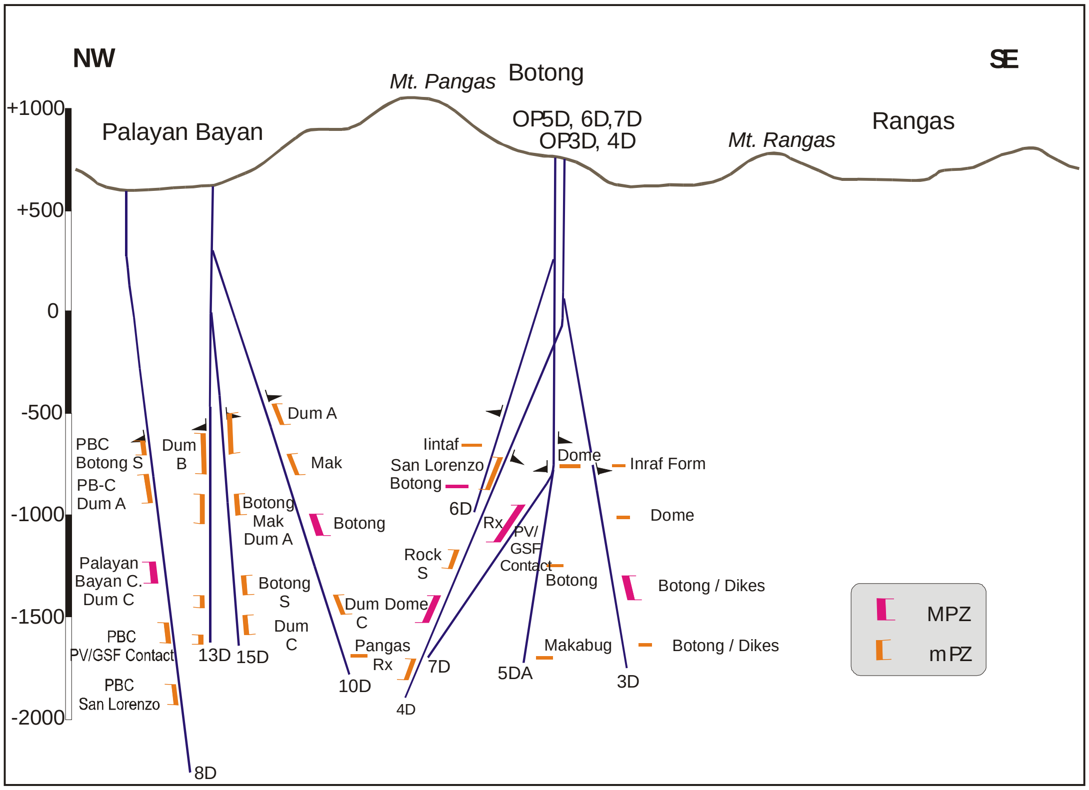

Figure 7. Structural correlation of permeable zones in Palayang Bayan-Botong, Bacman.

Only one structure, Dumangas B is likely associated with downflowing, cooler fluids in PAL-13D and PAL-15D.

PETROLOGIC MODEL

The hot, neutral geothermal brine in Bacman originates from the Palayang Bayan-Botong upflow zone beneath Mt. Pangas. (Fig. 8). A maximum temperature of 320ºC is found at the bottoms of PAL-10D and OP-4D where the center of resource is located. The preferential major outflow direction is towards the north-northwest where fluids travel at least 10 km and emerge as springs in the Manito lowlands. The southeasterly fluid flow direction towards Rangas is facilitated by structural permeabilities related to Makabug, Botong, and Dome faults (Fig. 9). These fluid flow directions are consistent with magnetotelluric and geochemical data which define major outflows to the northwest and southeast towards Manito lowlands and Sorsogon, respectively. Rangas thus lies along the southeasterly outflow of the hot, neutral geothermal brine with a maximum temperature of ~300ºC at ~-1800 m RL.

IMPACT ON FUTURE DEVELOPMENT OF RANGAS

The future development of Rangas will be constrained by the same reservoir characteristics of Botong considering the proximity of these sectors. Production levels lie below -600 mRL and temperatures as high as ~300ºC are available at about -1800 mRL. High NCG levels should be expected below -1000 m RL where the reservoir is hosted by GSF calcareous sediments. Low permeabilities characterize such reservoir and acidizing work may be needed to enhance productivity. Silica levels as high as 1,300 ppm in Botong (Garcia and Mejorada, 2001) may extend to Rangas and use of silica inhibitor should be considered to prevent rapid scale deposition along the pipelines.

Production pads in Rangas should be sited south of the bottomholes of OP-3D and OP-5D. Wells should be directed towards the east, south, and southeast to intersect the structural permeabilities of Rock, Makabug, Dome and Rangas South faults. Drilling should reach a total depth of -1500 m RL to tap a high temperature resource of 280ºC while the production casing shoe should be set at a minimum depth of -600 mRL. A Rangas well is expected to have a power potential of about 5 MWe based on the average output of the Botong wells. Thus, a total of 20 MWe may be produced from four wells drilled from a single pad. On the other hand, the reinjection sector may be located east of Botong and wells should drilled towards the east to target Sampaloc, Pulog, and San Lorenzo faults.

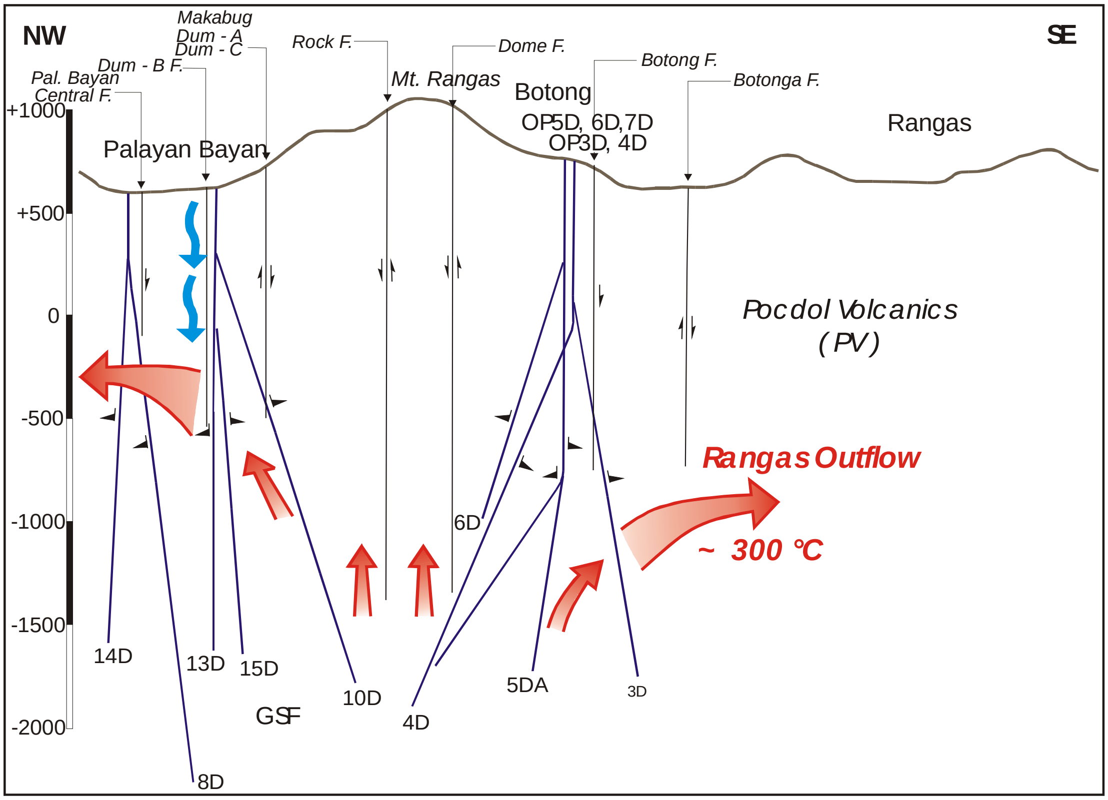

Figure 8. Petrologic model for Palayang Bayan-Botong-Rangas, Bacman.

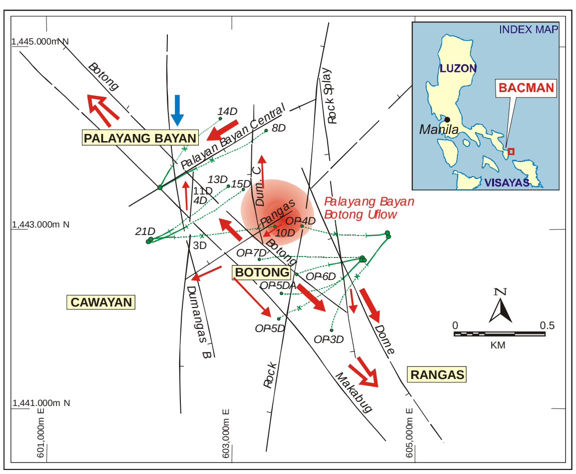

Figure 9. Petrologic model (plan view) for Palayang Bayan-Botong-Rangas, Bacman.

ACKNOWLEDGEMENTS

I am most grateful to H. P. Ferrer and M. C. Zaide-Delfin for the critical review of the manuscript. C. V. Melo prepared the final lay-out, while our cartographers patiently worked on the figures.

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