PETROLOGICAL IDENTIFICATION OF MULTIPLE HEAT SOURCES IN THE BACON-MANIT0 GEOTHERMAL SYSTEM, TIIE PHILIPPINES

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ABSTRACT- The positions of upflow zones and heat sources in the Bacon-Manit0 geothermal system do not necessarily coincide. Water chemistry and measured well temperatures suggest a single upflow zone, centred near wells OP-3D and OP-4D in the Botong-Pangas area. However, surface geology, subsurface alteration patterns, detailed fluid-inclusion studies in well cores and cuttings, and measured pressure gradients in 40 wells point to the existence of at least **two** major heat sources: Botong-Pangas, related to the major Palayangbayan upflow, and Tanawon-Cawayan south of Palayangbayan. Another localized heat source may be located 10 km north of Palayangbayan, in the Manito Lowlands. Alteration and fluid-inclusion patterns suggest high temperatures in the south, where the presence of a kaipohan and young craters (<40 ka) already point to the possible existence of additional heat sources. Directional wells drilled towards these intersected temperatures of 276°C at a depth of 1400 m. Thus a heat source may remain hidden from fluid geochemistry and may reveal itself only in detailed petrological studies.

Key words: Bacon-Manito, Philippines, hydrothermal mineralogy, heat source

1. INTRODUCTION

Most high-temperature (>250°C at depths <2500 m) geothermal systems in the Philippines are associated with active volcanic arcs. Bacon-Manit0 is one of four geothermal systems along the Bicol Volcanic Arc in southern Luzon, related to subduction along the Philippine Trench at about 100 km depth (Divis, 1980).

The Bacon-Manit0 geothermal system (BMGS) is divided into West and East Bac-Man. East Bac-Man is further subdivided into the northern Manito Lowlands and the Pocdol Highlands, about 10 km to the south. Within the Pocdol Highlands, eight geographical sectors are distinguished: Inang Maharang (IM), Putingbato (PB), Palayangbayan (PAL), Cawayan (CW), Tanawon, Osiao, Pangas and Botong (Fig. 1).

Thermal manifestations cover an area of about 225 km^2 and consist of warm to boiling springs, solfataras, areas of copious gas emanations (kaipohans), and cold altered ground. Neutral Cl hot springs with temperatures of 89-96°C occur in the Manito Lowlands, with Cl values from 1400-4400 mg/kg. Most of the springs in the Pocdol Highlands are acid-SO_4 and neutral Na-SO_4-HCO_3 in composition, with minor HCO_3 seepages. Spring temperatures vary from 22°C to as high as 95°C, and Cl values are low, <370 mg/kg (Ruaya, *et al.*, 1994; Solis, pers. comm., 1993). Solfataras are found in Cawayan and Pangas, with a kaipohan in Tanawon, south of Cawayan (Fig. 1). In West Bac-Man, there are only cold to warm acid-SO4 springs and cold altered ground.

About 76 km^2 of the BMGS have been explored by drilling, with 40 deep wells (1500-3000 m) since 1979: three wells in the Manito Lowlands, and the rest in the Pocdol Highlands. Most of the geothermal exploration and development are presently centred on East Bac-Man, where more than 85% of the wells are directional due to the rugged terrain. Maximum measured temperatures in the wells range from 195 to 325°C, at depths of >700 m; discharge enthalpies range from 800 to 2560 kJ/kg, with mass flows from producing wells of 15 to 100 kg/s. The power potential of the wells averages about 8 MWe (PNOC-EDC, 1993). In 1993, three power plants totalling 140 MWe were installed in the Pocdol Highlands.

2. EPISODES OF VOLCANISM AND HYDROTHERMAL ACTIVITY

The Pocdol Highlands formed through the coalescence of several volcanic centres of Early Pliocene to Holocene age (Tebar, 1988), and are composed of two-pyroxene andesites (73%), basalts (17%), and dacites (10%). In general hydrothemial and volcanic activity shifted with time from West to East Bac-Man. The oldest dated volcanics, at 500 ka, were sampled from Lison dome (Fig. 1) in West Bac-Man (Tebar, 1988). Here, hydrothermal manifestations consist of cold altered ground and cold acid-sulfate springs, likely to be associated with receding hydrothermal activity and a waning heat source.

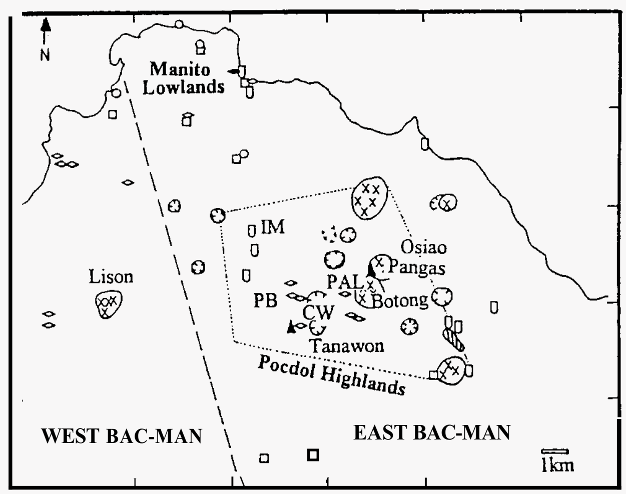

Figure 1. Map of the Bacon-Manito geothermal system, showing place names mentioned in the text. IM: Inang Maharang, PAL: Palayangbayan, PB: Putingbato, CW: Cawayan. Legend: dome , crater , intrusive , solfatara/kaipohan .Springs: neutral Cl , acid SO_4 , acid SO_4-Cl , bicarbonate , neutral Na-SO_4-HCO_3

The most recent volcanic events over the Pocdol Highlands occurred <40 ka ago. They are related to the formation of the Tanawon and Cawayan craters (Fig. 2), and the extrusion of the Botong and Pangas domes (Tebar, 1988). Solfataric activity and kaipohans on some of these structures also reflect their young age and probable association with the geothermal system. The youngest volcanics occur generally in regions of high subsurface temperatures, permeable formations, and active thermal manifestations. Even in the absence of data for the age **of** volcanism, the presence of kaipohans and solfataras in rugged terrains such as in Cawayan, Tanawon, and Pangas are good indicators for the existence of a young heat source.

Wells intersected, from top to bottom, andesitic to basaltic lava flows and hyaloclastites, Late Miocene to Early Pliocene limestones and calcareous breccias, and an intrusive complex. The latter is a sequence of cross-cutting dikes intruding the volcanic and sedimentary formations. There are about six distinct dike compositions: monzogabbro, pyroxene gabbro/diabase, hornblende and/or pyroxene microdiorite, hornblende quartz microdiorite, monzodiorite and rare aplite. Cross-cutting relationships among the dikes indicate multiple intrusive events. Among these, the pyroxene microdiorite and hoi·nblende quartz monzodiorite dikes appear to be related to the present hydrothermal system. This is implied by the arching to shallower depths of subsurface temperatures, as indicated by mineralogical and fluid-inclusion data.

Stratigraphic evidence and the dike swarm intersected by wells reveal the highly complex volcanic, intrusive and hydrotliermal history of the BMGS and point to the superimposition **and** juxtaposition of multiple potential heat sources of different ages.

3. DISTRIBUTION OF FLUIDS

Mixing of local meteoric waters and waters associated with andesitic magmatism was invoked by Giggenbach (1992) to explain oxygen shifts in fluids discharged from volcanoes and hydrothermal systems along convergent plate boundaries. The ^{18}O-^{2}H data of well discharges correspond to an "andesitic water" contribution of up to 50% to the BMGS reservoir, with the highest amount found in the Botong wells (Ruaya *et al.*, 1994).

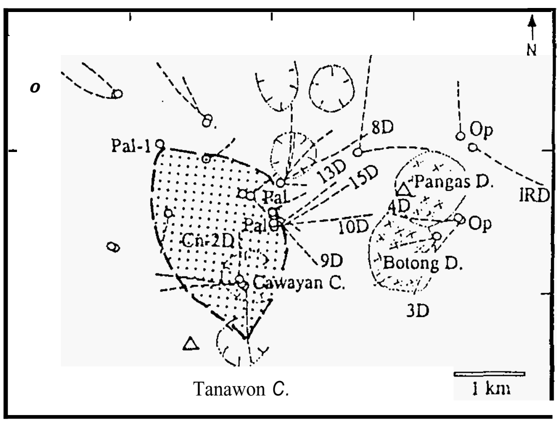

Figure 2. Map of Pocdol Highlands showing the extent of deep acid alteration in the drillholes Legend drillhole , crater , dome solfatardkaipohan , area of deep virulent acid alteration .

Dissolved silica contents show that the highest temperatures, 300-320°C, are centred on wells PAL-SD, 10D, 12D, 15D, and OP-3D and 4D (Ruaya *et al.*, 1994). A similar concentric pattern is indicated by chloride contours (PNOC-EDC, 1989). The K/Na temperatures, based on analyses reported in Ruaya *et al.* (1994) and Solis (pers. comm., 1993) suggest >320°C in the vicinity of OP-3D and 4D. Most of these wells are deviated towards the youngest volcanic features in the area, the Botong and Pangas domes (Fig. 2).

Using chemical analyses from Ruaya *et al.* (1994), the deep reservoir fluid in the BMGS is characterized by plotting measured well enthalpies against total discharge Cl contents (Fig. 3). The parent water PA suggested by Fig. 3 is a single phase 300°C liquid with a Cl content of 7500 mg/kg, similar to that derived by Ruaya *et al.,* (1994). Discharges from OP-3D (03) and 4D (04) are nearest this water composition. Most well discharges deviate from the parent water by mixing with a 140°C (C) to 240°C **(S)** condensate, followed by either addition with vapor having **an** enthalpy of 2700 kJ/kg (PV) or adiabatic cooling. Dilution with 20°C groundwaters (GW) appears to be a relatively insignificant process in the BMGS. Wells OP-SD (05) and 6D (06) in Botong have the highest vapor contents. Wells in the Manito Lowlands, 10 km away (M1, M2, M3), plot along a line indicative of adiabatic cooling after parent water PA has cooled and mixed with condensate (C). The plot of enthalpy vs total Cl concentrations suggests that the Inang Maharang, Cawayan, Palayangbayan, Osiao, Botong and the Manito Lowlands well discharges are associated with a single parent water, upflowing near OP-3D and 4D. Of the wells drilled into this major upflow, those reaching beneath the Botong and Pangas domes (Figs. 2 and 3) show the highest proportion of "andesitic water".

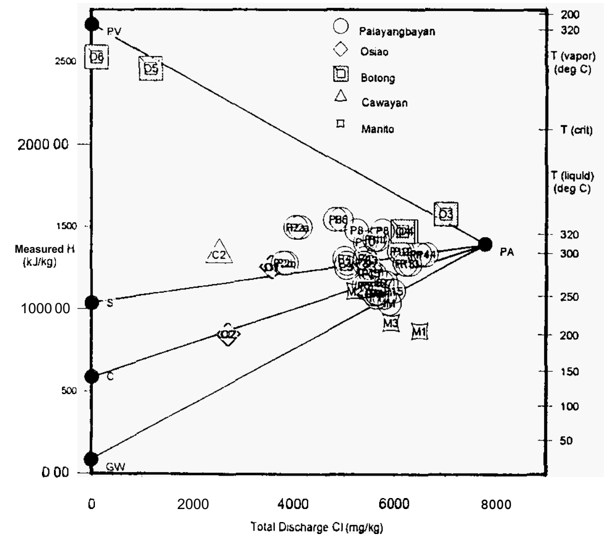

Figure 3. The total discharge Cl of water discharges from **wells** are plotted against measured enthalpies. PV: parent vapor, **PA:** primary parent water, S: 240°C condensate, C: 140°C condensate, GW: groundwater. Points connected with lines indicate mixing.

The same data set (Ruaya *et al.*, 1994) is plotted on a triangular graph featuring total discharge H_2O, CO_2 and Cl contents. **All** the waters in the BMGS can be assumed to represent mixtures of a common deep liquid (PA) having a Cl content of 7500 mg/kg, and a CO_2-rich vapor (VA) with a CO_2 content of 3.5 mmol/mol. At a temperature of 300°C, the corresponding CO_2 content in the liquid phase is 0.10 mmol/mol. The CO_2/Cl ratio for the parent fluid of BMGS is 0.035, much lower than tlie value of two at the probably much younger hydrothermal system of Alto Peak (Reyes *et al.*, 1993). Both Figs. 3 and 4 agree with tlie findings of Ruaya *et al.,* that tlie fluids discharged from the BMGS are derived from a common parent water.

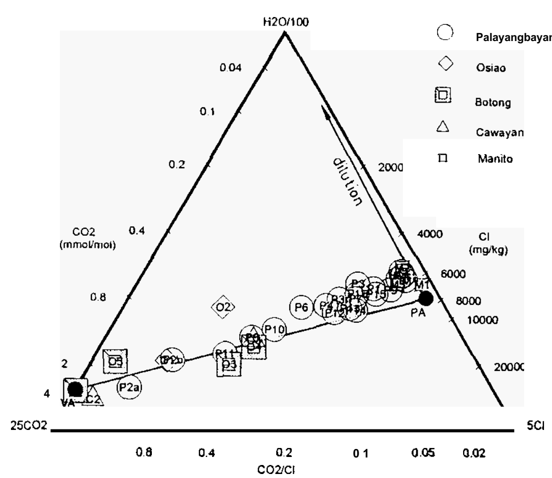

Figure 4. Fluid compositions of wells are plotted on a H_2O-CO_2-Cl triangular graph. PA: parent water, VA: parent vapor.

4. ALTERATION TYPES

Alteration studies in geothermal systems basically yield results pertaining to changes in the geological environment caused by variations in permeability and temperature, and the influx of magmatic fluids or groundwaters. In conjunction with fluid-inclusion (F.I.) homogenization (T_h) and freezing (T_m) data, well geology, gas and water well-discharge compositions, and measured reservoir characteristics, the study of hydrothermal mineral occurrences assists during exploration of new geothermal areas and drilling operations, is able to decipher changes in the hydrothermal system with time, allows modelling of the hydrology of a geothermal reservoir, and may help to identify future problems.

The pervasive alteration in the BMGS is due to the action of hydrothermal fluids at temperatures varying from ambient to 330°C. Apart from hydrothermal processes, contact metamorphism, diagenesis, and weathering produced distinct mineral associations. Hydrothermal alteration grades to "wet" or "dry" contact metamorphism at or near dikes. The association actinolite-tremolite ± biotite ± magnetite is typical of the former, whereas clinopyroxene ± plagioclase ± wollastonite ± magnetite ± rare cordierite characterize the latter.

"Wet" contact metamorphism associated with the youngest microdiorite dikes suggests that they were intruded into a water-saturated rock formation, which in turn implies that a hydrothermal system had pre-existed. Furthermore, the fact that contact metamorphism is still extant and that previously hydrothermally altered rocks are intruded by dikes, also points to continued intrusive activity and replenishment of heat for the hydrothermal system.

Prograde, neutral-pH, hydrothermal alteration occurs in most wells. However, alteration reversals are caused by cold water influx along faults and near the margins of the system, and the inhibition of fluid flow by impermeable horizons at depth. Although present measured temperatures bear little relation *to* dike occurrences in Palayangbayan (PAL), the amphibole and epidote alteration subzones, typical of high temperatures (Reyes, 1990), extend towards shallower levels above microdiorite or quartz monzodiorite dikes, showing that these may be partly responsible for elevated temperatures in this sector.

Acid sulfate alteration is prominent in the BMGS, occurring in 93% of the wells. In addition to mineral zonations, acid alteration assemblages can be divided, according to the virulence and corrosivity and their tendency to rejuvenate fluid acidity, into: virulent acid associations defined by the occurrence of elemental **sulfur** ± alunite/natroalunite ± abundant iron sulfides, and relatively benign assemblages characterized by the absence **of** sulfur and alunite/natroalunite, and the presence of various amounts of kaolinite, dickite, pyrophyllite, diaspore, anhydrite and pyrite (Reyes, 1990).

Within Palayangbayan, Cawayan, and the Manito Lowlands nearly 60% of the wells intersected generally short-lived and, therefore, young acid alteration below 500 m, suggesting that recent magmatic input is responsible for continued production of acid fluids and virulent acid alteration at deep levels in the Cawayan wells, some of the Palayangbayan boreholes (Fig. 2) and two **of** the wells in the Manito Lowlands. Elemental sulfur from 1200 m was discharged by a well directionally drilled into the Cawayan crater.

Of these, only five wells actually discharge acid waters; in others, the acid zones are cased off. Actively forming deep acid alteration and deep occurrences of elemental sulfur emanate from the youngest craters, Tanawon and Cawayan, and acid solutions flow to the north via faults, where they become increasingly neutralized (Fig. 2).

The widespread occurrence of obviously recent acid alteration and deep-seated elemental sulfur provide an important tool in locating young and viable heat sources.

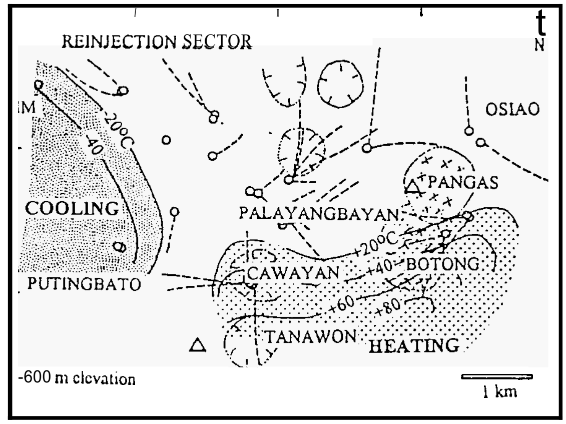

Figure 5. Heating and cooling trends in Pocdol Highlands at an elevation of -600 m. Numbers indicate the degree of heating or cooling observed in the secondary mineral occurrences. The unshaded area shows alteration in equilibrium with present conditions.

5. COOLING AND HEATING TRENDS

Cooling and heating trends, based on mineralogical geothermometers such as opal, quartz, sphene, epidote, actinolite-tremolite, anhydrite, garnet, vermiculite, chlorite, illite and biotite (Reyes, 1990), are shown in Fig. 5 at an elevation of -600 m. **At** this depth a large percentage of production zones are intersected. Measured temperatures, lower by 20°C than mineralogical temperatures, suggest cooling; higher by 20°C, heating. Cooling is widespread and persistent through all depths in Putingbato (PB), where a previous hydrothermal regime appears to have collapsed. It is presently on the margins of the main geothermal system.

Most Palayangbayan and Inang Maharang boreholes, and the reinjection wells north of Palayangbayan, show equilibrium with present conditions at **all** depths. However, heating by up to 80°C appears in some wells in Palayangbayan, Botong, and Cawayan, suggesting that mineral assemblages in the wells have not yet adjusted to the present-day high temperatures. This suggests that other, but younger, heat sources exist in the **S,** related to the Tanawon volcanism, dated <40 ka, and the formation of the Tanawon and Cawayan craters. High temperatures predicted for this area were subsequently proven by the 276°C encountered at 1400 m by **a** well deviated towards Tanawon, from Cawayan. The complex pattern of heating and cooling clearly points to the existence of several episodes of intrusive and hydrothermal activity.

6. FLUID INCLUSIONS

Homogenization and freezing temperatures of fluid-inclusions were measured in quartz, anhydrite and calcite. For neutral-pH alteration, T_h ranges from 190-400°C, whereas for quartz and anhydrite in acid assemblages, temperatures range **from** 195-370°C. In general, homogenization temperatures are multi-modal, with the lowest temperatures clustering around present measured data, suggesting the superimposition of several heating events in the BMGS.

Cooling trends based on mineralogy are corroborated by fluid-inclusion data. In general, the BMGS has cooled by as much as 160°C in Putingbato, and about 65°C in the upper 1000 m of Palayangbayan. Within Putingbato however, the decrease in temperature with time is accompanied by a decrease in salinity in the fluid inclusions, from an earlier highly mineralized regime (as indicated by the presence of daughter salt minerals) to a relatively dilute one. Boiling, as indicated by the presence of vapor-rich fluid inclusions and vein minerals such as drusy quartz, wairakite, and anhydrite, was observed in Cawayan well CN-2D, PAL-8D in Palayangbayan, OP-4D in Botong, and MO-1 in the Manito Lowlands. In MO-1, CN-2D, and OP-4D, clathrates in fluid inclusions indicate high gas contents.

Nearly SO% of fluid-inclusion salinities are within the range of the total discharge reservoir Cl contents of about 7000-8000 mg/kg. Some F.I. salinities are lower than the reservoir Cl, especially in the peripheral wells at depths where faults channelling cold groundwaters are intersected. About 35% of the F.I. equivalent salinities are 3-7 times greater than the reservoir Cl content, attributed mainly to the contribution of CO_2 to the freezing temperatures. Fluid-inclusion equivalent salinities increase from west to east, from PAL-1 to PAL-8D, and reverse in OP-1RD, mimicking present-day Cl trends and outlining the main upflow and outflow regions of the system.

Fluid-inclusion results also show that several heating events have occurred in Bacon-Manito. In general, F.I. equivalent salinities in the youngest vein minerals are similar to present-day trends and confirm that the main upflow occurs at Palayangbayan. The presence of high gas and vapor pockets, however, point to the existence of subsidiary upflow zones in Cawayan and in wells deviated into the Pangas and Botong domes. On a macroscopic scale, the vapor pockets in Botong can be discerned in the fluid discharge chemistry, typified by OP-SD and 6D. These are high enthalpy, high temperature wells with a high CO_2/Cl ratio of about 4.8 (Figs. 3 and 4).

7. AGE DISTRIBUTION OF THE SYSTEM

Repeated episodes of dike intrusions and volcanism are likely to have led to multiple hydrothermal pulses as recorded by alteration overprinting. The Bacon-Manito hydrothermal sytem may have been initiated as early as Late Pliocene, when volcanism became active in the area, with high reservoir temperatures sustained by intermittent dike intrusions until now. A large portion of tlie BMGS houses mature fluids and is dominated by **a** neutral chloride upflow. These waters are likely to be considerably older than the less mature acidic fluids being generated in Cawayan, Tanawon, and parts of Palayangbayan. The more mature system within East Bac-Man may be about 65-80 ka old, and the younger immature fluids are probably associated with <40 ka volcanism in Tanawon and Cawayan.

8. MEASURED FIELD ISOTHERMS AND ISOBARS

Measured isotherms show that the highest temperatures in the Pocdol Highlands encompass the Palayangbayan, Cawayan, and Botong sectors, where temperatures >270°C are encountered. **A** similar pattern is shown by silica temperatures (Ruaya *et al.*, 1994). Temperatures in the Manito Lowlands are lower. The isobars at -1000 m elevation show a break where they cross from Palayangbayan to the Botong and Cawayan sectors (PNOC-EDC, 1989), indicating a rapid change in the thermal regime and probably low permeabilities.

9. FIELD MODEL

Interpretations of well fluid compositions suggest a predominant upwelling of 300°C alkali Cl (7000-8000 mg/kg), single-phase liquid in the vicinity of OP-4D and OP-3D. It undergoes changes due to dilution, vapor loss, vapor gain, steam condensation and degassing, as it outflows to the NE towards Osiao, to the WNW towards the Palayangbayan wells, Cawayan and Inang Maharang, to the S towards Botong, and 6-10 km to the NW towards the Manito Lowlands. Measured isotherms and reservoir Cl contours across the field uphold this model of a single upflow associated with apparently only one heat source, related to the Botong **and** Pangas domes.

Detailed petrology and fluid-inclusion observations however show a more complex picture. Several hydrothermal regimes are interspersed in the BMGS: relict at West Bac-Man, dying at Putingbato, and active at Palayangbayan, Botong, Pangas, Osiao, Inang Maharang, and Cawayan. Within the active system, the pervading and more voluminous regime is that dominated by mature fluids as represented by the OP-4D-type neutral high-Cl waters. It dominates all sectors of the BMGS. The confluence of structures channelling hot, alkali Cl aquifer fluids controls the Palayangbayan upflow.

Interposed within the mature system are younger, localized systems characterized by the occurrence of deep (>500 m) virulent acid sulfate alteration and immature fluids, found in Cawayan and adjacent Palayangbayan wells north of Cawayan (Fig. 2); and in two of the Manito Lowlands drillholes. Fluid-inclusion petrography indicates the presence of of gas- and vapor-rich zones in some wells, reminiscent of those penetrated by the Alto Peak wells (Reyes *et al.*, 1993), showing that there are small, highly localized upflows related to the younger heat sources such as Cawayan and Tanawon craters and the Pangas dome.

Young volcanic structures and active thermal manifestations such as a kaipohan or a solfatara are associated with most immature systems as at Cawayan and Tanawon, but not in the Manito Lowlands, where any surface evidence of a localized heat source may be swamped by a shallow water table. Heating trends point to three major heat sources in the BMGS: one associated with the Manito Lowlands wells in the north, another with high temperatures in Palayangbayan and Inang Maharang and the last with Cawayan and Tanawon. The latter is the most recent one, as alteration assemblages in the wells have not yet adjusted to the present high-temperature conditions. A break in field isobars indicates that a barrier exists between Palayangbayan and the areas south of it, which is also observed in the alteration trends.

Apparently, magmatic fluids that actively form acid waters at levels >500 m in Palayangbayan and Cawayan are associated with the Cawayan and Tanawon heat source and are channelled to the north by faults, where they are neutralized and entrained into the major upflow.

The petrological perturbations caused by young heat sources in tlie Bacon-Manito geothermal system are not reflected in the fluid chemical compositions, which are surprisingly uniform. This may be due to the pre-existence of a large reservoir of mature neutral Cl water that absorbs heat from intermittent intrusions of new magmatic material and buffers any chemical disturbances associated with them.

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