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Petrological and Isotopic Characterization of the Tikolob Geothermal Reservoir, Bacon-Manito, Philippines

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ABSTRACT

Tikolob is a potential geothermal expansion area located along the main outflow, northwest of the existing production field in the Bacon-Manito (Bacman) Geothermal Project, Philippines. This study integrates new data from petrology and mineral isotopic chemistry with existing geophysical and reservoir models to provide a glimpse of the subsurface hydrogeologic conditions of the Tikolob resource in relation to the rest of the Bacman geothermal resource. Two-dimensional inverse modeling of magnetotelluric data from past survey campaigns and 3D numerical reservoir simulations provided evidence for a possible heat source beneath Mount Tikolob. Subsurface data from exploration drilling in nearby Mount Kayabon yielded an initial formation temperature estimate of ~240-260 °C based on the alteration mineral assemblage of epidote ± illite, tremolite/actinolite, and wairakite/laumontite from wellbore samples. These results were corroborated by epidote stable isotope chemistry, where calculated temperatures from D/H and ^{18}O isotopic fractionation curves reflect similar temperature ranges of alteration mineral formation. However, evidence of retrograde alteration and mineral paragenesis indicate discordant reservoir conditions, lowering the estimated downhole temperature to ~200-220 °C. Further, isotopic data shows highly distinct signatures of epidotes in the sector (higher δD and lower δ^{18}O) compared with epidotes from other wellbores in Bacman. Together, these datasets point to the existence of a heat source in Tikolob that has cooled down by ~60 °C and has undergone a separate physiochemical evolution from the main Bacman resource.

1. INTRODUCTION

The Bacon-Manito Geothermal Project (BMGP) in the Pocdol Mountains, southeast of Luzon, Philippines hosts the 120 MWe Bacman I geothermal power plant in the Palayan Bayan sector and 20 MWe Bacman II geothermal power plant in the Cawayan sector. Geothermal development in Bacman started in 1977 with surface exploration, followed by drilling of geothermal wells and installation of facilities. Both power plants were commissioned in 1993 (D'Amore et al., 1993). Meanwhile, other sectors were identified as expansion areas and are currently in different stages of development. Expansion projects have been developed to the south in the Tanawon sector, southeast in the Botong and Rangas sectors, and is initiated northwest in the Tikolob sector (Figure 1).

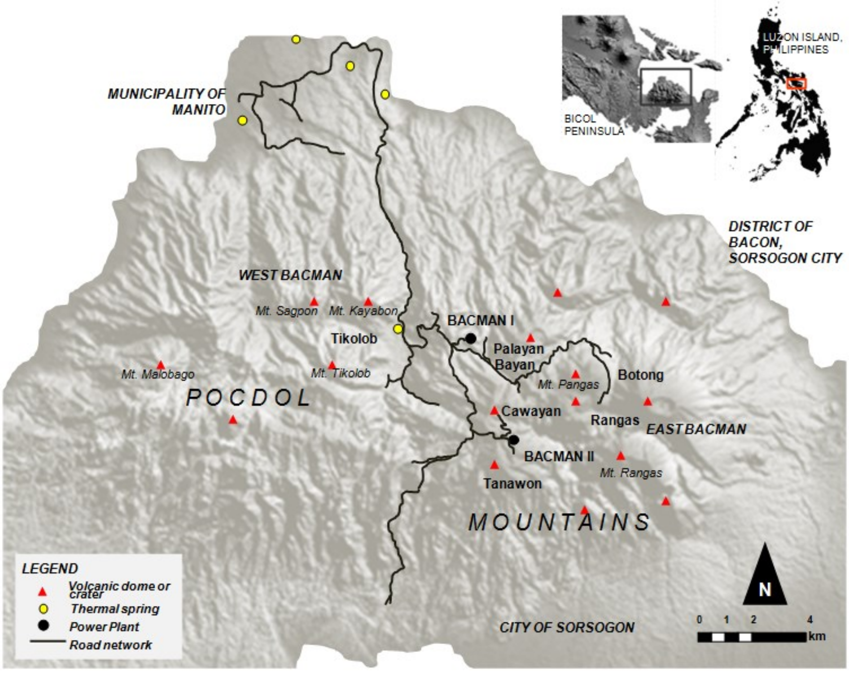

Figure 1: Digital elevation model of the Pocdol Mountains showing the location of the presently utilized sectors of BMGP (Palayan Bayan and Cawayan), the expansion sectors of Tanawon, Botong, and Rangas, and the potential expansion sector of Tikolob located in the northwest part of the area.

In the case of Tikolob, the sector is located northwest along the outflow of the existing Bacman I and II production field in the western portion of the Pocdol Mountain Range, an area commonly referred to as West Bacman. It includes the ancient volcanic centers of Kayabon, Tikolob and Sagpon. The Tikolob geothermal resource was first defined based on the presence of a geophysical magnetotelluric (MT) anomaly right beneath Mount Tikolob (Tugawin et al., 2015). With the onset of "tangible" petrological, geochemical and isotopic datasets from borehole rocks and hydrothermal epidotes in Tikolob, this paper attempts to characterize the present and past conditions of the geothermal reservoir by integrating these with available geophysical datasets and reservoir simulation models. Thus, a better understanding of the Tikolob geothermal resource is crucial in completing the whole Bacman geothermal resource model.

2. BACMAN FIELD OVERVIEW

2.1 Stratigraphy

The surface stratigraphy of the Pocdol Mountains had been undertaken in the pioneering works such as that of Panem and Alincastre (1985) and Tebar (1988), and had been enriched by subsequent exploration and wellbore data during the development of the field. From these studies, rocks found in the Pocdol Mountains are presently classified into three major distinct units: the Gayong Sedimentary Formation, Pocdol Volcanics Formation and Cawayan Intrusive Complex.

The Gayong Sedimentary Formation (GSF), composed of multi-lithologic units of limestone, sedimentary breccia and clastic rocks, is the oldest known unit with an age of Late Miocene to Early Pliocene (Tebar, 1988). These rocks primarily encountered from wellbore drilling in most wells, except in Cawayan and northwest Palayan Bayan. The GSF units encompass a whole range of depositional facies that vary throughout Bacman (Santos and Dimabayao, 2011).

The GSF is unconformably overlain by a thick pile of Early Pliocene to Late Pleistocene volcanic deposits which are composed of intensely altered andesite lava and tuff breccia. These deposits are from the sequence of volcanic centers that erupted throughout this timeframe (Braganza, 2014) and are classified together in a stratigraphic unit called the Pocdol Volcanics Formation (PVF; Panem and Alincastre 1985; Tebar, 1988; DENR-MGB, 2004). Drilling data estimate the thickness of the PVF to be ~2600m (Peña, 2008). Most of the surface volcanic deposits mapped in Bacman and those encountered in the upper portion of wells during drilling are regarded as part of the PVF. Paleosol horizons have been encountered in some wells, indicating breaks in periods of deposition and volcanic activity.

Wellbore data reveals that GSF and PVF are sometimes intruded by the Cawayan Intrusive Complex (CIC). The CIC includes dike swarms composed of porphyritic microdiorite, andesite and diabase with some hornfels (Reyes, 1985), of which the magma source is believed to be the main heat source of Bacman (Ramos and Santos, 2012). Crosscutting relationships reveals that the CIC is younger than the GSF and is coeval with PVF deposits (Santos and Dimabayao, 2011; Braganza, 2014).

2.2 Hydrothermal Alteration

Surface investigation and drilling in Bacman show a suite of hydrothermal alteration minerals formed from the interaction of neutral-pH hydrothermal fluids and reservoir rocks. While mineral assemblages from low-pH hydrothermal fluids and rocks are present in shallow discrete zones in some wells (e.g., alunite, diaspore, pyrophyllite; Lawless et al., 1983; Reyes, 1985; Zaide-Delfin et al., 1989), a propylitic mineral assemblage is observed almost throughout the deeper portion of the Bacman reservoir (e.g., chlorite, epidote, wairakite, secondary biotite). Alteration intensity (i.e., abundance of alteration minerals in the rock) and grade of alteration (temperature-dependent mineral assemblages) vary from different types of rock, although generally increase with depth (Santos, 2014). Volcanic rocks are mostly intensely altered (Ramos and Santos, 2012), while sedimentary and intrusive rocks were observed to be less altered (Zaide-Delfin et al., 1989). Interaction of hydrothermal fluids with original rocks composed of predominantly porphyritic andesite produced these minerals which formed through replacement of original minerals, precipitation of vein minerals that fill up fractures, or in combination (Santos, 2014).

Common alteration minerals can be classified into mineral suites with occurrences that are strongly dependent on the temperature of the reservoir, and thus are utilized as geothermometers (Reyes, 1985). Low temperature (<180 °C to 220 °C) minerals include low temperature silica phases (cristobalite, opal, tridymite), chlorite, laumontite, and clays such as smectite and illite-smectite. High temperature (220 °C to >300 °C) minerals include illite, epidote, wairakite, tremolite-actinolite and secondary biotite. Along with available fluid inclusion data, these minerals provide information on the reservoir temperature variation across the field (Ramos and Santos, 2012).

Epidote in particular is an important index mineral in Bacman. It has been successfully used as an approximate estimator of geothermal reservoir temperature due to its ubiquitous nature in geothermal systems and highly-dependent stability and morphology on temperature (Keith et al., 1968; Patrier et al., 1990), as well as on permeability, fluid composition, silica activity, and CO_2 fugacity (Giggenbach, 1984; Arnason and Bird, 1992). In Bacman and other geothermal fields in the Philippines, epidote is particularly important during geothermal well drilling, as the onset of subhedral epidote in drill cuttings indicates a formation temperature estimated at 220 °C, the minimum temperature required for setting the production casing shoe of a conventional geothermal well (Reyes, 1990). Macroscopically, epidote occurs in euhedral prisms or aggregates, and may form in veins or vugs, or replacing plagioclase, pyroxene, and hornblende (Santos, 2014).

2.3 Bacman Conceptual Model

Geological and geochemical evidence presented by different authors make up the present Bacman conceptual resource model (Figure 2). Hydrothermal alteration zones, mineral geothermometry and fluid inclusion data from geothermal wells (Reyes, 1985; Zaide-Delfin et al., 1989; Ramos and Santos, 2012) suggest that the upflow zone of the geothermal system is located in the heat source beneath Mount Pangas in the Botong sector. Geochemical field trends also agree with this model (D'Amore et al., 1993 and Ruaya et al., 1993). Single-phase hydrothermal fluid upwells in this area and preferentially flows through faults in Palayan Bayan, and eventually northwest towards the Manito lowlands where thermal manifestations are concentrated (Ruaya et al., 1993). Some portions of this fluid also flow west and southwest towards Cawayan and Tanawon, and southeast towards Rangas (Ramos and Santos, 2012).

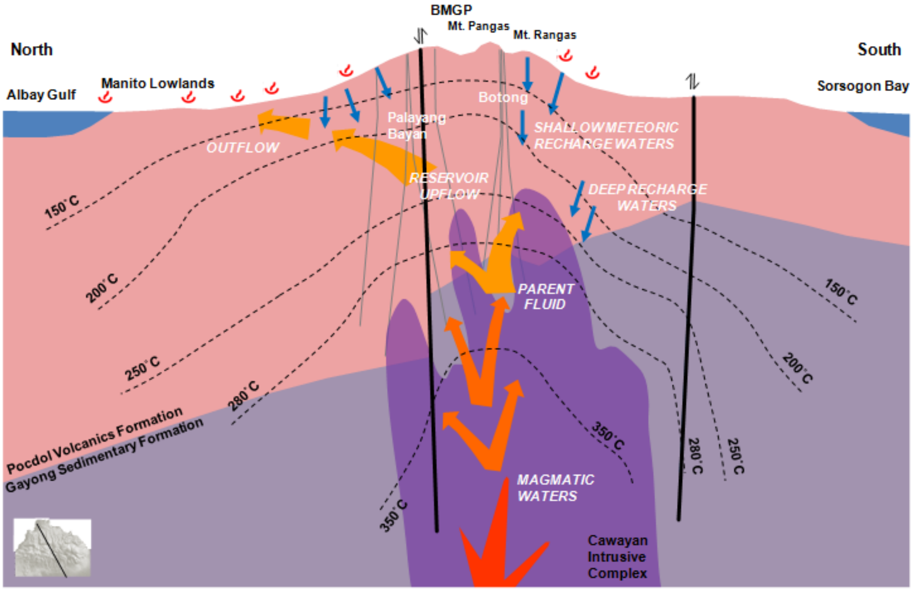

Figure 2: Conceptual hydrogeological model of the Bacman reservoir. Geothermal fluids in Bacman are thought to have come from mixing of meteoric waters with magmatic fluids. The heat source and upflow is located beneath Mount Pangas in the Botong sector. The outflow is located to the northwest towards Manito lowlands (modified from Ruaya et al., 1993).

However, some discrepancies with this model remain when other datasets are considered. Surface geology, hydrothermal alteration and fluid inclusion data from Cawayan and Tanawon sectors and Manito lowlands point out that there could also be heat sources in these areas which are distinct from the Palayan Bayan heat source (Reyes et al., 1995). Recent exploratory drilling in the Rangas sector uncovered a deep and localized hot convective cell that appears to be a distinct heat source from Palayan Bayan and Botong, and is most likely associated with the Rangas volcanic dome (Ramos et al., 2015). Holistic interpretation of geophysical survey datasets in the Pocdol Mountains (mainly two-dimensional inverse modeling of MT, supported by Schlumberger resistivity, vertical electrical sounding, and gravity data) with geologic and reservoir data revealed three distinct geothermal anomalies in Palayan Bayan, Tikolob and Malobago (Tugawin et al., 2015). Resistivity profiles illustrate a high-low-high resistivity signature and an updoming feature beneath Mount Tikolob (Figure 3). This is similar to the geophysical signature of the Palayan Bayan anomaly to the east which is known to contain the present Bacman geothermal resource.

Likewise, natural state modeling of the Bacman reservoir by Villacorte et al. (2015) argued that in order to sustain the temperature profiles from the main upflow in Palayan Bayan all the way northwest to the outflow area in the Manito lowlands, there must be another heat source that provides mass input to the geothermal system. In their model, the heat source was defined as possibly located underneath Mount Kayabon and provides additional 25 kg/s mass flow and 1,350 kJ/kg enthalpy.

The contradictions arising from different datasets are the cause for the unsettled single or multiple heat source model for the Pocdol Mountains. Reconciling these gaps is important and is attempted by providing new insights on the presence of possible heat sources in the Bacman geothermal system such as that in Tikolob based on various older datasets and newly acquired petrological and geochemical data.

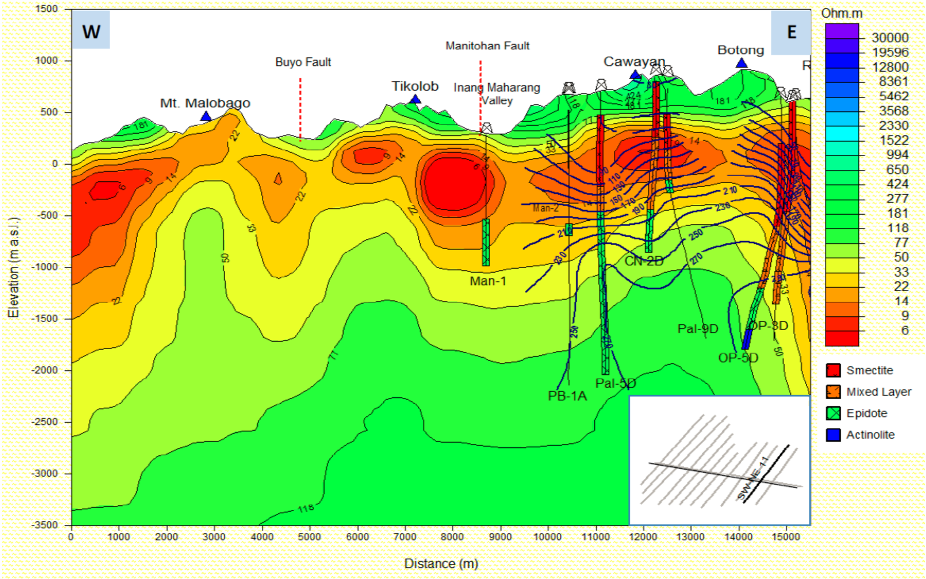

Figure 3: NNW-SSE resistivity profile of the Pocdol Mountains showing three distinct dome-shaped anomalies that represent the heat sources of geothermal systems in the main Bacman reservoir (right), Tikolob (center), and Malobago (left). Superimposed alteration and isothermal data in the existing Bacman geothermal resource show good correlation of the datasets (After Tugawin et al., 2015).

3. METHODOLOGY

In this study, the main purpose of gathering petrological and isotopic data is to characterize the Tikolob reservoir by looking closely at hydrothermal epidotes. This paper describes the occurrence and paragenesis of epidotes in Tikolob vis-a-vis epidotes elsewhere in the Bacman reservoir.

Wellbore cuttings and available core samples where appreciable amounts of hydrothermal epidote can be extracted were gathered from three selected wells in the main Bacman field (Wells 1, 2, and 3) and an exploratory well in Mount Kayabon in the Tikolob sector (Well 4). Alteration mineralogy was described semi-quantitatively from observations of alteration intensity. The cuttings were further ground to a maximum diameter of ~1-2 mm to dislodge epidote crystals from other minerals and groundmass. Epidote grains that were at least 0.2 mm in length, and lacked altered rims, visible inclusions, or other attached minerals, were hand-picked under a binocular microscope.

Following mineral separation, the samples were sent to GNS Stable Isotope Laboratory in Lower Hutt, New Zealand for δD and δ^{18}O analysis. For δD, samples were analyzed in triplicate using a HEKAtech high temperature elemental analyzer coupled with a GV Instruments IsoPrime mass spectrometer. All results are reported with respect to V-SMOW, normalized to international standards IAEA−CH-7, NBS30 and NBS22, with reported δD values of -100 ‰, -66 ‰ and -118 ‰, and waters USGS46, 47, 48, and W62001 (-235.8 ‰, -150.2 ‰, -2.0 ‰, and -41.1 ‰, respectively). The external precision is better than 2 ‰. For δ^{18}O, oxygen extraction was done using a CO_2-laser and BrF_5-laser ablation line following the methods of Sharp (1990). Samples were analysed using a Geo20-20 mass spectrometer with results normalized to NBS-28 (+9.6 ‰), with reproducibility, based on replication of NBS-28 (N=4), at < 0.15 ‰.

Isotope results are expressed in delta notation relative to V-SMOW (‰). Epidote-fluid fractionation factors ($10^3\ln\alpha$) for both deuterium and ^{18}O were determined using Equation 1 following O'Neil (1986). Temperatures for specific sample depths were obtained from well temperature-depth profiles provided by EDC. The δD and δ^{18}O isotope composition of fluids in equilibrium with epidote was calculated using Equations 2 (Chacko et al., 1999) and 3 (Pope et al., 2016; as derived from the results of Matsuhisa et al., 1979; Matthews et al., 1983; and Kohn and Valley, 1998), following the procedure of Pope et al. (2016).

$$10^3 \ln\alpha = 10^3 \left(\frac{1000+\delta_{epidote}}{1000+\delta_{fluid}}\right) \approx \delta_{epidote} - \delta_{fluid} \tag{1}$$

$$10^3 \ln\alpha D_{epidote-fluid} = 9.3000\left(\frac{10^6}{T^2}\right) - 61.90 \tag{2}$$

$$10^3 \ln\alpha^{18}O_{epidote-fluid} = 1.53\left(\frac{10^6}{T^2}\right) - 3.31 \tag{3}$$

4. RESULTS AND DISCUSSION

4.1 Alteration Mineralogy

The wellbore cuttings and core sample obtained from Well 4 in Mount Kayabon, Tikolob sector were petrologically classified as part of the PVF. The cuttings are predominantly made up of tuffaceous volcanic breccias that contain notable amounts of paleosol, while the core sample is an altered porphyritic andesite lava. Alteration intensity is generally observed as moderate to high. The occurrence of secondary minerals is observed typically in veins and fractures, although mineral replacement is also noted on some occasions. For instance, epidote crystals are usually seen in veins. The mineral is often found together with other vein minerals, such as quartz, chlorite, and calcite, and other high temperature minerals such as actinolite, magnetite (at 1850m MD) and clinozoisite (at 2298m and 2388m MD; Table 1).

WELL SAMPLE DEPTH m, MD*	Alteration Intensity[a]	Veins/ Vugs[b]	Shearing[b]	Alteration Mineralogy[b] Illite-Smectite	Illite	Chlorite	Quartz	Calcite	Anhydrite	Incipient Epidote	Subhedral Epidote	Euhedral Epidote	Wairakite/ Laumontite	Tremolite/ Actinolite	Sphene/ Leucoxene	Secondary Biotite	Pyrite	Hematite	Magnetite
1850	▨▨▨	▨▨▨	▨▨		▨	▨	▨▨▨	▨	▨			▨▨▨	▨	▨▨▨	▨		▨		▨
	Lithology: Quartz vein. Sample completely altered and composed of vein minerals, with nil trace of primary rock. Alteration assemblage propylitic. Poikilitic texture prominent on some grains: epidote, actinolite crystals growing in quartz. Relict minerals observed: actinolite and sericite grains retrograding to chlorite or leucoxene. Epidote occurs as abundant euhedral crystals found within quartz veins. Crystals are closely associated with actinolite and magnetite (?)																		
1998	▨▨▨	▨▨	▨	▨	▨▨	▨▨▨	▨	▨	▨			▨▨	▨	▨▨				▨▨▨	
	Lithology: Mixture of tuffaceous volcanic breccia and paleosol. Intensely altered sample, highly hematized due to paleosol (~60% of sample). Alteration minerals mainly occurring as replacement of primary minerals (mainly corroded plagioclase) in clasts, but alteration in veins also present. Lithic matrix usually altered to chlorite, hematite and clays. Epidote crystals are euhedral, drusy aggregates and are found mostly in veins and occassionally as replacement minerals. Crystals are closely associated with quartz, chlorite and calcite.																		
2097	▨▨▨	▨▨	▨		▨▨	▨▨▨	▨	▨	▨		▨▨	▨▨	▨	▨▨			▨	▨	
	Lithology: Tuffaceous volcanic breccia with minor paleosol. Sample similar in alteration mineralogy composition to 1998m, but intensity becomes moderate and paleosol component significantly reduced to ~10%. Epidote crystals are euhedral, drusy aggregates and are found mostly in veins and occassionally as replacement minerals. Crystals are closely associated with quartz, chlorite and calcite.																		
2199	▨▨	▨▨▨	▨		▨▨	▨▨	▨	▨			▨▨	▨▨	▨	▨▨			▨	▨	
	Lithology: tuffaceous volcanic breccia. Sample similar in alteration mineralogy composition to previous two samples, but no paleosol component is observed. Vein minerals become more prominent. Epidote crystals are euhedral, drusy aggregates and are found mostly in veins. Crystals are closely associated with quartz, chlorite and calcite.																		
2298	▨▨	▨▨▨	▨		▨	▨▨	▨	▨	▨		▨▨	▨▨	▨	▨▨			▨	▨	
	Lithology: Tuffaceous volcanic breccia. Sample similar in alteration mineralogy composition to previous 3 samples. Paleosol component is observed at ~5%. Vein minerals are also prominent. Epidote crystals are euhedral, drusy aggregates or interlocking, found mostly in veins. Crystals are sometimes found together with clinozoisite.																		
2388	▨▨▨	▨▨▨	▨		▨	▨▨	▨	▨			▨▨▨	▨▨▨	▨▨				▨	▨	
	Lithology: Tuffaceous volcanic breccia. Sample similar in alteration mineralogy composition to 2298m but intensity of alteration becomes high. Paleosol component is observed at ~5%. Epidote crystals are euhedral, drusy aggregates and are found mostly in veins. Occurrence is abundant throughout the sample. Crystal size also increases (~1 mm width for the largest crystals). Clinozoisite crystals are present but rare.																		
2690	▨▨	▨▨▨	▨			▨	▨▨	▨	▨		▨▨	▨▨	▨▨						
	Lithology: Porphyritic andesite. Phenocrysts composed of plagioclase and quartz, often intact but with altered rims and cleavage planes. Undulose extinction is common. Sample is observed to be cut by unidirectional veins. Mineral paragenesis evident from core sample: epidote, wairakite veins are cut by younger quartz, calcite veins. Epidote crystals are euhedral and occur mostly as aggregates in veins.																		

*MD-measured depth

[a] Intensity of Alteration: ▨ Weak ▨▨ Moderate ▨▨▨ High

[b] Abundance: ▨ Few ▨▨ Moderate ▨▨▨ Abundant

Table 1: Lithology and alteration mineralogy of rock cuttings from Well 4 in Mount Kayabon, Tikolob sector, BMGP.

The mineral assemblage is defined as propylitic and consistent throughout the well since all the samples belong to the illite + chlorite + epidote + actinolite/tremolite + wairakite alteration zone. The estimated reservoir temperature based on this assemblage is 240-260 °C. However, evidence in the texture and mineral paragenesis present temperature incongruence. The sample at 1850m MD is observed to have abundant euhedral epidote and actinolite/tremolite, with some wairakite and sericite. Reservoir temperatures would have been higher based on this mineral assemblage per se, but upon closer observation, the actinolite and sericite minerals are found to be relicts, which often retrograde to chlorite or sphene/leucoxene. Moreover, the core sample at

2690m MD reveals similar disequilibrium conditions. Veins containing epidote are often cut by younger quartz and calcite veins which depict conditions that yields a lower temperature estimate of about ~200-220 °C.

4.2 Epidote Isotope Composition and Epidote-Fluid Disequilibrium

Results of isotope analysis of hydrothermal epidote from selected wells are presented in Table 1. The overall range of epidote δD is from -69.1‰ to -46.4‰, while for $\delta^{18}O$, the field-wide range is from 0.0‰ to +11.6‰. Although sample numbers are limited, the average epidote isotope composition is distinctly different between the four wells sampled. The average δD and standard deviation of analytical results per well ranges from -46.9 ± 0.6‰ (Well 4; n=5) to -64.2 ± 1.1‰ (Well 3; n=3). Inverse to the trend for δD, the average $\delta^{18}O$ varies from 0.7 ± 0.6‰ (Well 4) to 10.5 ± 1.6‰ (Well 3), with an average intermediate epidote isotope composition for Well 1 (δD of -59.0 ± 9.2‰ and $\delta^{18}O$ of 6.2 ± 4.9‰; n=3) and Well 2 (δD of -56.2 ± 0.3‰ and $\delta^{18}O$ of 4.2 ± 0.3‰; n=3). Among the four wells, Well 4 epidote has the lowest $\delta^{18}O$ and the highest δD values. Overall, there is no indication of a systematic change in epidote isotope composition with depth of sampling.

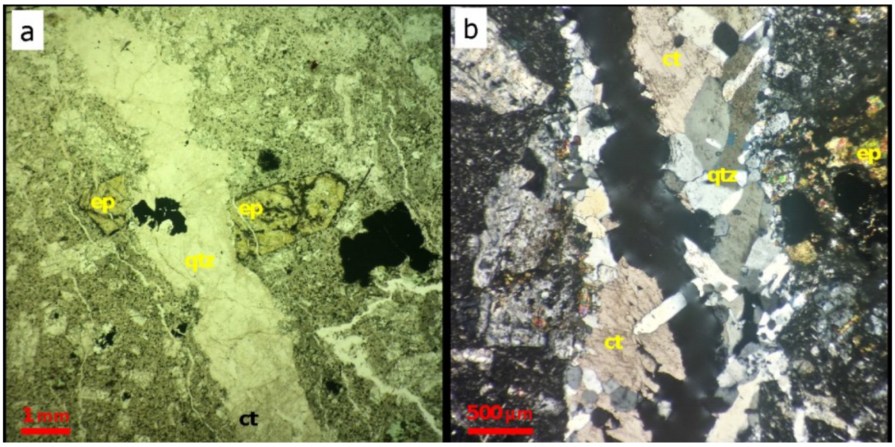

Figure 4: Photomicrographs of core sample at 2690m MD from Well 4. Mineral paragenesis indicates discordant conditions that formed the alteration minerals. Epidotes in the sample are corroded and have formed prior to the quartz and calcite minerals in the vein. Photo (a) taken in ppl at 2x magnification, while photo (b) in xpl at 5x magnification. Ep-epidote, qtz-quartz, ct-calcite.

Well	Depth	Elevation	Discharge fluid (δ_{fluid})		Epidote		Fluid in equilibrium with epidote ($\delta_{fluid(eq)}$)		
	m MD	m RSL	δD	$\delta^{18}O$	δD	$\delta^{18}O$	Temperature (°C)	$\delta D_{fluid(eq)}$	$\delta^{18}O_{fluid(eq)}$
Well 1 Location: Palayan Bayan sector	1850	-1012	-23.0	-0.6	-51.1	+0.5	277	-19.9	-1.3
	2425	-1518			-56.8	+9.8	276	-25.8	+8.0
	2530	-1620			-69.1	+8.2	271	-38.6	+6.3
Well 2 Location: Palayan Bayan sector	1700	-850	-21.0	-2.4	-56.4	+4.0	257	-27.6	+1.9
	1900	-1010			-56.0	+4.0	261	-26.7	+1.9
	2395	-1442			-	+4.5	242	-	+2.1
Well 3 Location: Rangas sector	2185	-1353	-23.5	+7.2	-64.7	+11.3	295	-31.6	+9.9
	2359	-1498			-65.0	+11.6	301	-31.3	+10.3
	2413	-1544			-62.9	+8.6	292	-30.1	+7.1
Well 4 Location: Mt. Kayabon, Tikolob sector	2097	-1542	-	-	-46.6	+1.3	-	-	-
	2199	-1618			-46.7	+1.2	-	-	-
	2298	-1693			-46.9	+0.7	-	-	-
	2388	-1761			-48.0	+0.3	-	-	-
	2690	-1990			-46.4	0.0	244	-19.3	-2.4

Table 2: δD and $\delta^{18}O$ isotopic composition of reservoir fluids from discharge data, epidotes, and fluids in equilibrium with epidote ($\delta D_{fluid(eq)}$, $\delta^{18}O_{fluid(eq)}$; Dimabayao et al., 2019). Depth and elevation are expressed in mMD (meters, measured depth) and mRSL (meters, relative to sea level), respectively. Baseline discharge isotopic compositions (δD_{fluid}) were obtained from Ruaya et al. (1993, for Well 1) and Energy Development Corporation (Wells 2 and 3), with the exception of Well 4 which does not have fluid discharge data. The $\delta D_{fluid(eq)}$ and $\delta^{18}O_{fluid(eq)}$ values were calculated using Equations (2) and (3) given the downhole temperature and δ_{fluid} values per well, which were applied to every depth. Temperature values were obtained from downhole measurements from EDC data, except for Well 4 which was obtained from fluid inclusion homogenization temperature estimates from Doma (2015).

From the calculated equilibrium fluids ($\delta_{fluid(eq)}$), variations in both δD and $\delta^{18}O$ are evident when compared to δ_{fluid}. The discharge fluid samples represent a modern, “final” or average fluid composition and do not necessarily represent the heterogeneity of fluids at depth as recorded by epidote, or potential changes in the composition of fluids over time. Intra-well variations thus reflect the effectivity of epidote in recording vertical isotope variations of the fluids in equilibrium with the mineral (Dimabayao et al., 2019). Currently, the fluids discharging from wells are isotopically distinct from the calculated epidote-equilibrium fluids (Table 2).

By comparing the fractionation factors between the epidote and well discharges to isotope equilibrium for δD (Chacko et al., 1999) and $\delta^{18}O$ (Pope et al., 2016) as a function of temperature, we can assess the current relative epidote-fluid disequilibrium in isotopic space (Figure 5). Fractionation factors are skewed away from the theoretical isotope equilibrium based on modern downhole well temperatures, to a lesser extent for D and more significantly for ^{18}O, consistent with partial fluid-rock re-equilibration (i.e., rock has high O/H while water has low O/H). In addition, calculated fractionation values are out of thermal equilibrium as defined by the temperature range where the occurrence of hydrothermal epidote is expected in Bacman or in other geothermal fields (180–320 °C; Reyes, 1985, 1990; Bird and Spieler, 2004). However, based on the established ±10‰ uncertainty in δD fractionation by Chacko et al. (1999), most data points could still be included within the theoretical range of hydrogen isotope equilibrium space. Given that proportionally hydrogen is far less abundant in rocks than the fluid, the disequilibrium of fluid based on hydrogen may readily reflect changes in fluid isotope composition. Meanwhile, the $\delta^{18}O$ fractionation factors are skewed to a greater degree from isotope equilibrium, which suggest greater fluid-epidote disequilibrium when looking at ^{18}O as compared to D (Figure 5). This likely reflects the significant oxygen buffering by the host rock, wherein δD reflects potential changes in fluid composition while $\delta^{18}O$ likely instead reflects the complexity of variable fluid-rock interactions (Dimabayao et al., 2019).

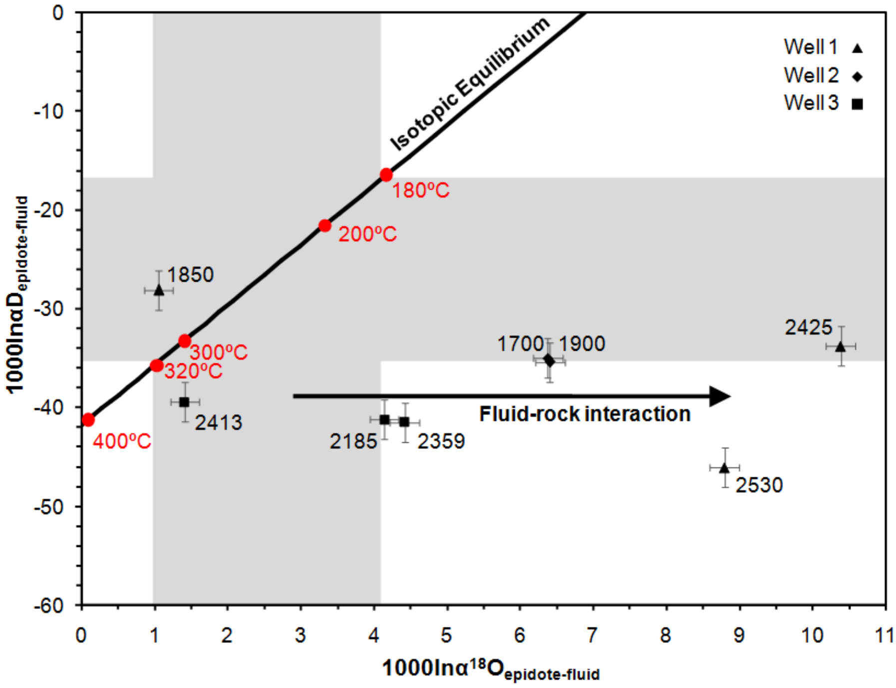

Figure 5: δD (from Chacko et al., 1999) vs. $\delta^{18}O$ (from Pope et al., 2016) isotope fractionation values between Bacman epidotes and fluids as a function of temperature. The plotted values are the difference in isotopic composition of epidote and corresponding well discharges. Sample depth in mMD is indicated next to each symbol. The blackline delineates the isotopic equilibrium with respect to the δD and $\delta^{18}O$ isotope fractionations as a function of temperature. The vertical and horizontal gray fields delineate the temperature range where epidotes typically occur in geothermal systems, and the corresponding isotope fractionation values D and $\delta^{18}O$ (modified from Dimabayao et al., 2019).

4.3 Tikolob Reservoir Evolution

Compared with hydrothermal epidote elsewhere in the Bacman system, the epidote from Well 4 in the Tikolob sector retain isotope signatures in equilibrium with a distinct fluid composition. The petrogenesis of the Tikolob sector epidotes is interpreted to have formed from a higher temperature source, prior or contemporaneous with when fluids in the main Bacman reservoir were still more isotopically enriched than shown by their present compositions (Ruaya et al., 1993; Martinez-Olivar et al., 2005). Also, the calculated epidote-equilibrium fluid has a similar isotope composition to that of Palayan Bayan sector discharge fluids (Well 1 and Well 2). The depleted $\delta^{18}O$ of Tikolob epidotes and the calculated equilibrium fluid composition relative to the other three wells suggests a different source from the main Bacman reservoir.

Furthermore, the elevated δD values of the same epidotes and fluids relative to the other wells in this study are unusual. One possible explanation is that host rocks rich with pre-existing hydrous silicates influenced water-rock reactions in the Tikolob sector, thereby producing epidotes that already have an enrichment in D/H. Subsequent interactions of the altered rock with meteoric water in modern reservoir conditions may have resulted in further enrichment to produce the present-day δD compositions. A similar interpretation has been put forward for the Hakone geothermal system where substantial groundwater recharge fluids led to the long-term δD enrichment and $\delta^{18}O$ depletion in both fluids and host rock (Matsuo et al., 1985; Giggenbach, 1992).

The isotopic composition of the ancient fluids in Tikolob could also give some insights on the reservoir conditions, particularly as a geothermometry tool to estimate its temperature prior to what it is today. Table 3 shows the calculated temperatures of the reservoir. These were derived from the D/H and ^{18}O isotopic fractionation curves between epidote and water by using the available

$\delta D_{fluid(eq)}$ and $\delta^{18}O_{fluid(eq)}$ values (from Table 2) on each sample depth in the wellbore. The D/H fractionation curve gives higher and more consistent temperature estimates (251 to 265 °C) compared to the ^{18}O fractionation curve (192 to 244 °C). The range of temperatures obtained from the former also falls within the typical reservoir temperatures where epidote occurs in its euhedral and prismatic form, and thus, is deemed accurate. Similar to the discussions in epidote-fluid disequilibrium, the discrepancy in the resulting temperatures when both fractionation equations are used could be due to the higher sensitivity of oxygen isotopes to the effects of water-rock interaction. This renders the ^{18}O isotopic fractionation inaccurate in depicting the original temperature conditions of epidote formation in Tikolob.

Well/ Sector	Depth		Fluid in equilibrium with Epidote		Epidote composition		Calculated Temperature (°C)	
	(mMD)	(mRSL)	δD (‰)	$\delta^{18}O$ (‰)	δD (‰)	$\delta^{18}O$ (‰)	D fractonation	^{18}O fractionation
Well 4 Tikolob	2097	-1542			-46.6	1.3	253	192
	2199	-1618			-46.7	1.2	253	195
	2298	-1693			-46.9	0.7	255	214
	2388	-1761			-48.0	0.3	265	229
	2690	-1990	-19.3	-2.4	-46.4	0.0	251	244

Table 3: Calculated wellbore temperatures of Well 4 using δD and $\delta^{18}O$ isotopic fractionation curves (Equations 2 and 3, respectively).

The calculated temperatures from the epidotes are anomalously high and cannot be explained by simple fluid convection along the main northwest fluid outflow path. Such a long distance from the reservoir upflow in BMGP would have significantly reduced the temperature in this part of the reservoir (Villacorte et al., 2015). A possible explanation is that there must be a heat source somewhere beneath in the Tikolob reservoir in order for fluids to have sustained such high temperatures along the outflow path (Figure 6). As discussed, this hypothesis has been corroborated by geophysical interpretations and presented in numerical models formulated for the Bacman reservoir (Tugawin et al., 2015; Villacorte et al., 2015). However, this has been largely unsupported by geological or geochemical evidence, until recently.

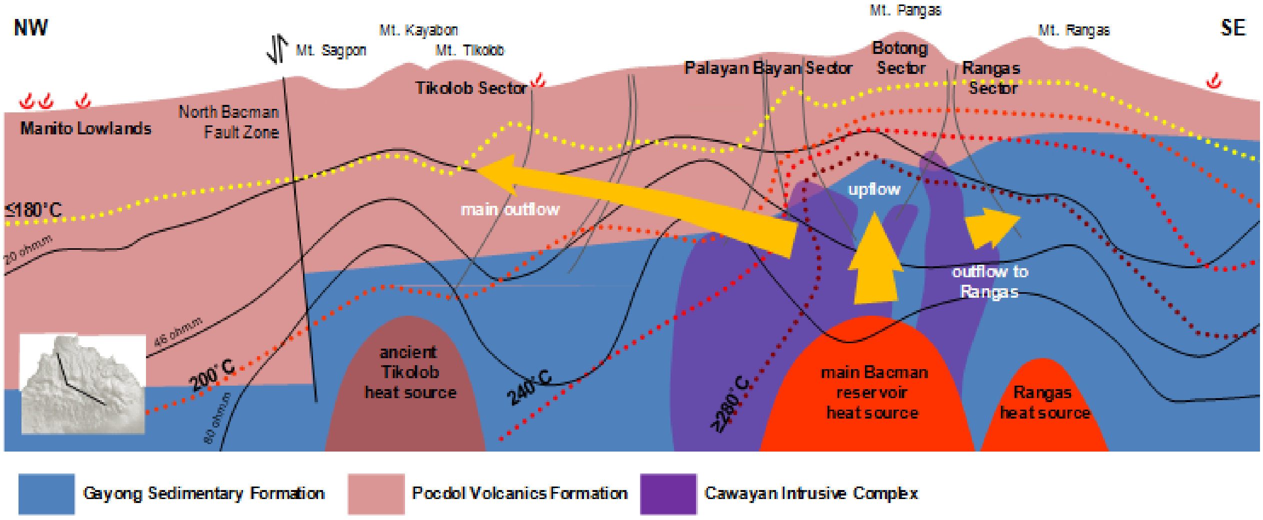

Figure 6: Revised conceptual hydrogeological model of the Bacman Geothermal Project which includes the main Bacman geothermal reservoir, the postulated ancient Tikolob geothermal reservoir, and the localized heat source in Rangas as discussed by Ramos et al. (2015). Isoresistivity contours from geophysical data (black lines) and isothermal contours from hydrothermal alteration and wellbore data (colored dotted lines) are also integrated. Profile not drawn to scale.

Evidence from actual downhole measurements and fluid inclusion data, along with isotopic and petrological data from this study indicate that the heat source in Tikolob has been continuously waning ever since. This study does hereby reaffirm the premise that Tikolob has a heat source that is separate from the main Bacman heat source, but the aforementioned new data suggest that it has since cooled down by ~60 °C to its present downhole temperature of ~200 °C.

5. SUMMARY AND CONCLUSIONS

Investigating the petrological and isotopic data from epidotes in the Tikolob reservoir reveal a geothermal system with a distinct evolution from the main geothermal producing reservoir in the Bacon-Manito Geothermal Project. A closer look at hydrothermal epidotes and their morphology has been particularly important in estimating the past and present reservoir temperatures in Tikolob. Mineral paragenesis of epidotes has also revealed the anachronistic nature of mineral formation in this sector when compared with the rest of Bacman. Unlike the epidotes gathered from the other wells, petrologic evidence indicated that the epidotes found in Well

4 in the Tikolob sector are not representative of present borehole conditions, making these alteration minerals in Tikolob sector relict from a previously hotter reservoir.

Meanwhile, isotopic data also reveal that the $\delta D_{epidote}$ values were found to be generally in equilibrium with present-day geothermal fluids based on fractionation factors and downhole temperatures. On the contrary, $\delta^{18}O_{epidote}$ values were not, which reflect the huge effect of water-rock interaction processes on final $\delta^{18}O$ compositions. Compared to the other wells in Bacman, the unique isotopic signatures of Tikolob sector epidotes (higher δD and lower $\delta^{18}O$) reveal a different origin and evolution of the reservoir. Furthermore, the isotopic compositions helped constrain the past temperature conditions of the reservoir at around 251 to 265 °C, which was significantly hotter than its present condition. This suggested that there was once a hotter heat source and has since cooled down by up to 60 °C. These findings still pose further questions on the nature and potential of the Tikolob sector for geothermal development, and this can only be answered by additional data from drilling, downhole measurements and discharge fluid chemistry.

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