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Conceptual Hydrogeological Model of the Rangas Sector, Bacman Geothermal Field, Philippines

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ABSTRACT

Recent deep drilling in the Rangas sector of the Bacman Geothermal Field (BGF), Philippines provided new information for delineating the extent of the current resource block towards the southeast. The subsurface stratigraphy and hydrothermal alteration mineralogy intersected by the three new wells, together with geological structures and their associated permeabilities were evaluated to come up with an updated conceptual hydrogeological model for the Bacman 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). An older sedimentary unit beneath the GSF, characterized by quartz-rich sandstone was encountered in two Rangas wells. This was dated Late Miocene using nannoplankton fossil analysis. The shift in the clastic framework composition from dominantly andesitic in GSF to quartzose in the underlying unit indicates a change in the provenance of sediments from a volcanic terrain to a plutonic-metamorphic basement. The term Rangas Sedimentary Formation (RSF), is proposed for this new rock unit. An in-depth correlation of the various rock units within the PV, GSF, and RSF were done for a better understanding of their lithostratigraphy and reservoir characteristics. Both the PV and GSF are intruded by the Cawayan Intrusive Complex, and by relatively younger magmatic dikes which are deemed to provide the heat source for the Bacman geothermal system. On the other hand, hydrothermal alteration mineralogical assemblages were used as geothermometers to be able to draw their corresponding isothermal contours across the Rangas sector. The secondary biotite alteration zone at deep levels suggest temperatures of ≥ 300°C beneath one well in Rangas, indicating the persistence of hot fluids and the probable extension of the resource block in the southeastern sector of Bacman.

1. INTRODUCTION

Three (3) directional wells, RS-1D, RS-2D, and RS-3D were drilled in 2012-2013 to probe and confirm the extent of the geothermal resource towards Rangas in the southeastern sector of the Bacman Geothermal Field (Figure 1). This geothermal resource was earlier delineated by magnetotelluric geophysical survey (Tugawin et al., 2015) Each of these three wells were drilled to a total depth of ~3 km.

Petrological analysis of rock cutting samples from the three (3) wells provided detailed information on the lithologic characteristics, stratigraphic relationships, hydrothermal alteration mineralogy and indications of permeabilities from faults. Hydrothermal alteration mineralogical assemblages were used as geothermometers to indicate subsurface temperatures and were correlated with measured reservoir temperatures. These recent subsurface petrologic data were used to refine the conceptual hydrogeological model of the Bacman field in relation to the southeastern Rangas sector.

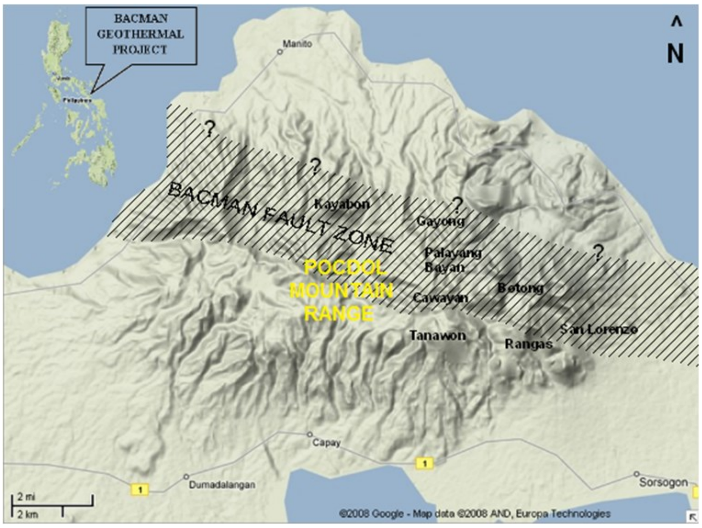

Figure 1. Location Map of the Bacman Geothermal Field, Philippines.

2. SUBSURFACE STRATIGRAPHY

The Bacman Geothermal Field is underlain by two (2) main rock units: 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) (Ramos and Santos, 2012). An older sedimentary unit beneath the GSF, characterized by quartz-rich sandstone was encountered in two Rangas wells RS-1D and RS-3D. This was dated Late Miocene using nannoplankton fossil analysis and a new formation name, Rangas Sedimentary Formation is proposed for this unit. These three rock units are intruded by dikes of variable composition and are collectively called the Cawayan Intrusive Complex (CIC). Figure 2 is a cross section along Rangas showing the underlying rock units and their stratigraphic correlation, while Figure 3 shows the stratigraphic correlation of Rangas to the northeastern sectors Botong and Palayang Bayan.

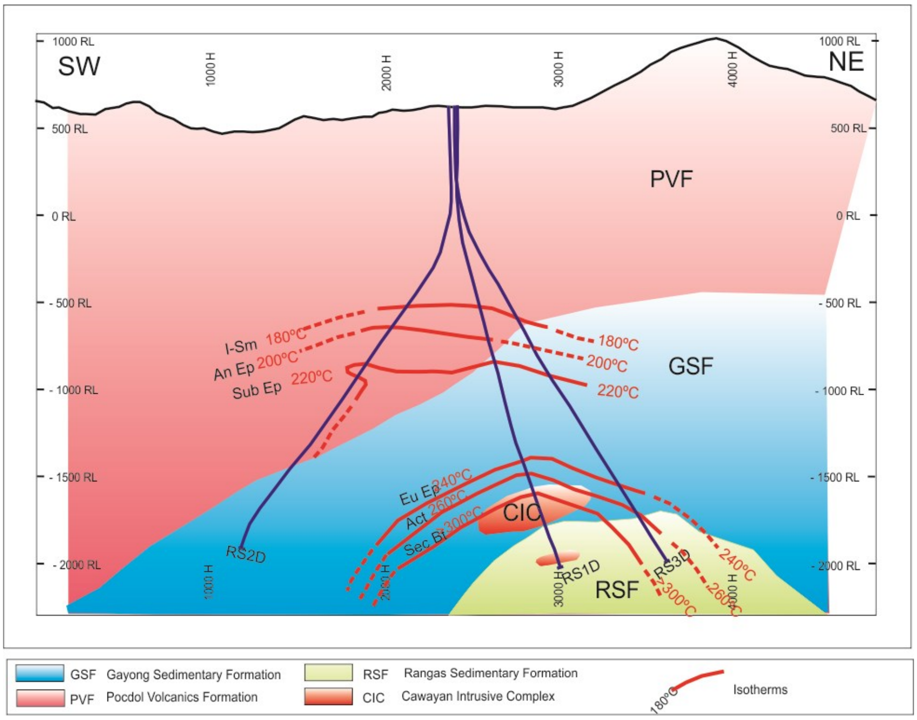

Figure 2. Stratigraphic and Hydrothermal Alteration Correlation along Section AA' (NE-SW) in Rangas, Bacman Geothermal Field

2.1 Pocdol Volcanics

Pocdol Volcanics (PV) is composed of andesitic tuff breccias and lava flows. In the shallower depths of RS-1D well, fresh basaltic breccia was also noted. The tuff breccias in the upper 900 m contain clasts mostly of andesites of oxyhornblende and biotite varieties, with subordinate two-pyroxene andesites, and rare reworked carbonate and hornfels clasts. These clasts are held together by a tuffaceous matrix composed of angular fragments of feldspars and oxyhornblende. Below 500 m, clinopyroxene andesitic clasts start to dominate over hornblende variety until clinopyroxene andesite becomes the characteristic framework composition of the breccia. At midsections at about 1500 m in RS-1D, fine-grained sedimentary rocks together with rare basalts occur as clasts as the PV-GSF is approached.

In both RS-2D and RS-3D, the entire section of PV is generally characterized by fresh to completely altered andesite tuff breccia which is typically fragmented and composed of plagioclase, pyroxene, rare oxyhornblende, volcanic glasses, magnetite, basalt, rare diorite and andesite clasts enclosed in cryptocrystalline to microcrystalline tuffaceous matrix. The andesite and basalt clasts sometimes show amygdaloidal texture where vesicles are rimmed or filled with low temperature minerals opal/tridymite, smectite, vermiculite or calcite. Occasional carbonaceous siltstone lenses were also noted in RS-2D. Sedimentary conglomerate composed of rounded clasts of siltstone, mudstone and volcanics in a matrix of smectite, chlorite-vermiculite and hematite was encountered at about 800 m. Weak amounts of paleosol fragments is distributed discretely at ~1, 300 m suggesting that these are possibly lenses or reworked from a paleosol horizon.

In RS-3D, moderately altered andesitic tuff breccia with occasional calcareous matrix and embedded fossils possibly marks the transition zone between PV and the underlying GSF.

PV has a maximum thickness of ~2,000m in RS-2D which is its average thickness in most Bacman wells (Ramos and Santos, 2012). In contrast, PV is thinner in both RS-1D and RS-3D wells ($\leq$1500 m).

2.2 Gayong Sedimentary Formation

The stratigraphic boundary of PV and GSF in the Rangas wells is marked by the onset of calcareous matrix and presence of fossils in the breccias. Minor paleosol fragments were noted in RS-1D and RS-3D. In RS-1D, the stratigraphic demarcation was based on the appearance of altered andesitic sedimentary calcareous breccias with occasional fossils (corals, larger foraminifera, echinoid spines) and carbonaceous sandstone. The entire GSF section is characterized by interbedded andesitic sedimentary breccias and calcareous/fossiliferous breccias with minor dacite lava, tuff, breccias, calcareous sandstone, sandy siltstone, and rare calcareous siltstone. The volcanic framework composition of the clastics is dominated by biotite-bearing hornblende pyroxene andesite and intermittent hornblende dacite and basalt. At about 2,000 m and 2,300 m, pure bioclastic limestones with partial recrystallization were observed . At ~2,400 m, GSF is metamorphosed into its contact hornfels equivalent with the first occurrence of a microdiorite dike.

In RS-2D, the andesite tuff breccia near the PV-GSF boundary becomes intensely argillized or silicified and cut by abundant veins of quartz, calcite and weak to moderate epidote, with minor veinlets of chlorite, illite-smectite, anhydrite and chlorite. The drusy character of some vein minerals suggests that this section is highly permeable. The siltstone lenses and conglomerate layers within the GSF are generally composed of sub-rounded clasts of andesite and rare diorite; and fragmental crystals enclosed in clayey or oxidized matrix with very little calcite. Towards deeper levels, the matrix becomes increasingly calcareous, some with fossils that are noticeably intact. Near the well bottom, limestone fragments prevail within the conglomeratic sandstone with minor siltstone lenses.

The upper section of GSF in RS-3D is composed of sandy conglomerate with fine to coarse-grained sandstone interbeds. The boundaries between beds are defined by hematite-rich laminations. Clasts of porphyritic andesite, hematized rocks, and completely altered rocks together with foraminiferal fossils are set in a matrix of smectite, calcite or hematite. Fossilferous carbonate units are found in the deeper sections below ~2,000 m characterized by foraminifera, mollusk and coral fragments which have retained their original morphology despite intense recrystallization. The associated clastic units at these depths are calcareous, medium-grained to conglomeratic sandstones. The clasts of mostly andesites with subordinate amounts of pyroxene basalt lie in a matrix ranging from fossiliferous, calcareous to finely silicified. Sandstone grains may also be in grain-to-grain contact or with interstitial detrital chloritized biotite.

2. 3 Rangas Sedimentary Formation

Clastic rocks composed mostly of quartz-rich sandstones were intersected in the deeper levels of RS-1D and RS-3D below the GSF at ~2700m. In RS-1D, this lithologic unit is characterized by fine to very-coarse grained, clast-supported quartz sandstone. The matrix may have interstitial secondary biotite or commonly altered/metamorphosed to extremely finely sugary pyroxene with surficial leucoxene. Micritic limestone occurs as rare fine laminations.

In RS-3D, graded, fine to coarse-grained quartz-rich calcareous sandstone is composed of detrital, angular quartz and plagioclase, with abundant fossil foraminifera enclosed in a hematite/ smectite-rich matrix or calcite. Towards the well bottom, the sandstone layers are fossiliferous and quartz clasts become dominant.

These quartz-rich sandstones were first observed in RS-1D and initially interpreted to represent the deeper-open marine facies of the GSF. However, micropaleontological analysis of the quartz sandstones in RS-3D revealed nannoplankton contents diagnostic of Late Miocene, which is distinct from the Late Miocene-Early Pliocene age of the GSF based on planktonic foraminifera. In contrast, the foraminiferal assemblage in the quartzose sandstones gave an indeterminate age. A separate name, Rangas Sedimentary Formation, is thus proposed for this older unit. Furthermore, its quartz-rich framework composition, specifically the sutured inter-crystalline boundaries within the polycrystalline detrital quartz, more likely indicates a plutono-metamorphic provenance. The Late Miocene sedimentation possibly reflects a tectonic episode which saw the upliftment and un-roofing of a plutono-metamorphic terrain. This contrasts with the dominantly volcanic (andesitic-basaltic) framework composition of the clastics in the overlying GSF which evinced a sedimentation history influenced by an andesitic to basaltic arc volcanism.

2. 4 Cawayan Intrusive Complex

Cawayan Intrusive Comples (CIC) was intersected by wells RS-1D and RS-2D, being more prevalent in RS-1D below 2,000 m, in contrast to its very limited occurrence in RS-2D. The contact with surrounding country rock is characterized by intense alteration to high temperature minerals such as actinolite and secondary biotite, together with a metamorphic aureole consisting of hornfels of variable mineralogy such as clinopyroxene, hornblende, tremolite, quartz, garnet, and calcite.

In RS-1D, the dikes occur intermittently and are mainly microdiorite and occasional andesite-dacite porphyries. The accessory minerals of biotite hornblende, clinopyroxene, and quartz occur in variable amounts at various depths. The zone of intrusion and its attendant contact metamorphic aureole is ~ 300 m thick. The occurrence of the CIC coincides with the stratigraphic boundary of the GSF and RSF in RS-1D. Together with the intersected faults, these geological structures provided favorable permeable pathways for the multiple dike intrusions and circulation of hydrothermal fluids. These dikes are possibly related to magmatic activities of Mt. Rangas which is proximal to the RS-1D well track.

In RS-2D, ~20 m-thick intensely sheared hypabyssal diorite composed dominantly of feldspars and minor quartz is associated with hornfels composed of actinolite, garnet, biotite and quartz. This dike appears to be grading into a microdiorite towards its deeper intercept where it is composed of mostly feldspars with subordinate quartz and actinolite. The contact metamorphic hornfels are corroded by anhydrite, calcite and/or pyrite. An older intrusive event is considered for this dike since the surrounding andesite tuff breccia is not associated with high temperature alteration minerals such as secondary biotite and/or actinolite. The associated contact metamorphic hornfels also exhibited a retrograded character.

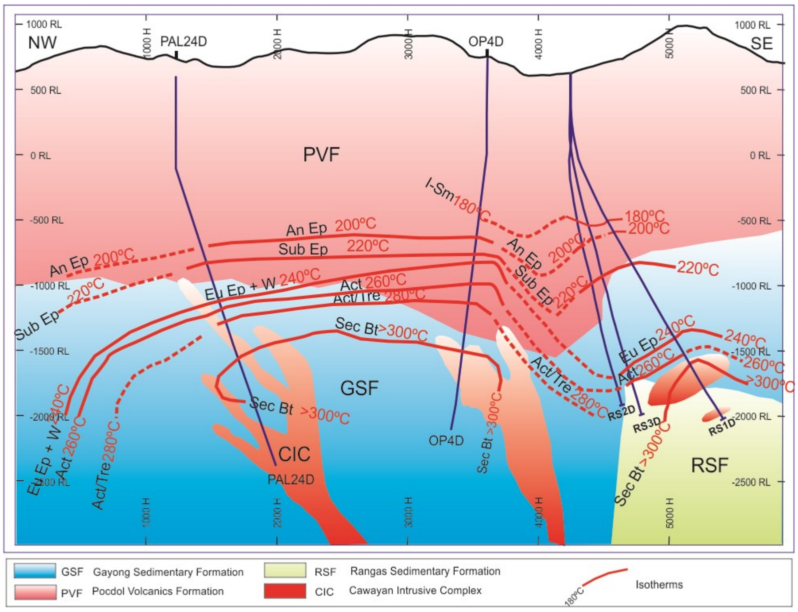

Figure 3. Stratigraphic and Hydrothermal Alteration Correlation along Section BB' (NW-SE) in Palayang Bayan-Botong-Rangas, Bacman Geothermal Field

2. HYDROTHERMAL ALTERATION AND GEOTHERMOMETRY

Hydrothermal alteration minerals are commonly used in Bacman as key geothermometers and shown in Table 1 and were likewise used in predicting subsurface temperatures for the Rangas 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

Table 1. Key Mineral Geothermometers in Bacman (Ramos and Santos, 2012)

Hydrothermal alteration, mostly of neutral-pH assemblages, varies from weak to intense in the three Rangas wells, generally increasing in intensity at deeper levels especially in RS-1D. In this first well, weak alteration to mostly low temperature clays smectite + vermiculite with associated calcite and chlorite are common in the upper 900 m. These minerals co-exist with low temperature silica opal and tridymite in the shallower levels above 500 m. Alteration becomes moderate near the midsection with the appearance of illite-smectite. Intense alteration affected the host rocks starting at about 1,500 m. High temperature minerals such as euhedral epidote, actinolite and secondary biotite displayed a prograding trend towards deeper levels especially at the sections where the CIC intruded both the GSF and RSF. The predicted maximum temperature during drilling based on the mineral geothermometry secondary biotite was >300°C which was consistent with the measured reservoir temperature of ~330°C (Figures 2 and 3).

In RS-2D, the upper sections are likewise altered to low-temperature clays smectite + vermiculite + chlorite and their corresponding inter-layered phases. Illite-smectite was first noted at ~500 m and illite at ~1300 m which are shallower relative to RS-1D. The occurrence of subhedral epidote in the midsection of the well (1, 600-2,000 m) suggests that this is the hottest section with an estimated temperature of ~ 220-240°C. This depth is coincident with the hypabyssal diorite which was considered an old CIC dike. However, the recurrence of both illite and incipient epidote at the deeper sections indicates that the estimated maximum temperature to be expected at the well bottom is about 200-220°C. This relatively low temperature condition may be attributed to suspected cooler water incursion as evidenced by the presence of pervasive earthy hematite. The passage of these cooler fluids may be correlated with the northwest-southeast trending faults intersected by RS-2D near its well bottom.

The third well RS-3D exhibits the same pattern for low temperature clays smectite + vermiculite with associated calcite in the upper ~1,300 m of the well. The first appearance of illite-smectite in weak amounts at ~1,300 m together with finely crystalline quartz in the breccias matrix indicate an estimated temperature of ~180°C. At deeper levels below ~2,000 m, prograding assemblage of subhedral epidote + illite with associated quartz, chlorite, illite-smectite and anhydrite suggests estimated temperatures of ~220- 240°C. The well may have attained a maximum temperature of ~250°C with the occurrence of actinolite at ~2,500 m till well bottom. This alteration mineral geothermometry is consistent with measured reservoir temperatures of 260°C (Figures 2 and 3).

Figures 2 and 3 show the correlation of key hydrothermal alteration minerals in the three (3) Rangas wells. The mineral geothermometry contours show that RS-1D was drilled through the hottest part of the Rangas sector where high temperatures ranging from ~250°C to > 300°C are indicated by mineral geothermometers euhedral epidote, actinolite and secondary biotite. These minerals occur at relatively shallower levels in RS-1D relative to RS-2D and RS-3D. The temperatures take a slight dip to the northeast where RS-3D encountered an estimated maximum temperature of ~250°C with the persistence of actinolite till well bottom. Cooler conditions exist towards the south-southwest where RS-2D attained a maximum temperature of ~240°C at midsection and a probable temperature reversal to ~200°C at well bottom.

3. CONCEPTUAL HYDROGEOLOGICAL MODEL

The current hydrogeological model of the Bacman geothermal field shows hot neutral-pH fluids upflowing northeast of Rangas mainly beneath Mt. Pangas in the vicinity of the Palayang Bayan-Botong sectors. Secondary biotite and actinolite alteration and vein mineralogy defined high temperature isothermal contour exceeding 300 °C in the Palayang Bayan upflow zone where multiple intrusions were intersected by numerous wells (Figure 4). These upflowing fluids take a preferential outflow direction to the northwest in Inang Maharang and a possible minor one to the southeast towards Rangas along permeable structures (Ramos and Santos, 2012).

Recent drilling in Rangas revealed the presence of high temperature conditions of at least 300 °C in the vicinity of RS-1D (Figure 2). The alteration isothermal contours across Palayang Bayan-Botong-Rangas (Figure 3) show that the high temperature secondary biotite contour is centered and relatively extensive in the Palayang Bayan-Botong main upflow zone. In comparison, this same isothermal contour has a localized and deeper occurrence in Rangas suggesting the possible existence of a small convective cell beneath this sector. The apparent "temperature depression" between Palayang Bayan-Botong and Rangas sectors as shown by the isothermal contour trends (Figure 3) likely mark the boundary of this convective cell. The heat source of this "mini-convection" may be associated with the roots of a volcanic feature such as Rangas dome. A similar scenario possibly exists in the other sectors of Bacman in Cawayan and Tanawon where prominent volcanic edifices are likewise remarkable. These "mini-systems" are being masked by the fluids from the more extensive and larger system in the Palayang Bayan-Botong main upflow zone. The continuous flow of these hot-neutral pH fluids towards the southeasterly direction are being chanelled by major northwest-southeast and north-south-trending permeable structures (Figure 4). Towards the northeast, RS-3D still encountered hot fluids but at lower temperatures relative to RS-1D indicating diminishing thermal conditions in this part of Rangas. On the other hand, the probable temperature reversal at the deeper levels of RS-2D, as a result of cooler water incursion through other permeable faults (Figure 4), indicate that the south-southwest quadrant of Rangas possibly demarcate the southern boundaries of the Bacman geothermal resource.

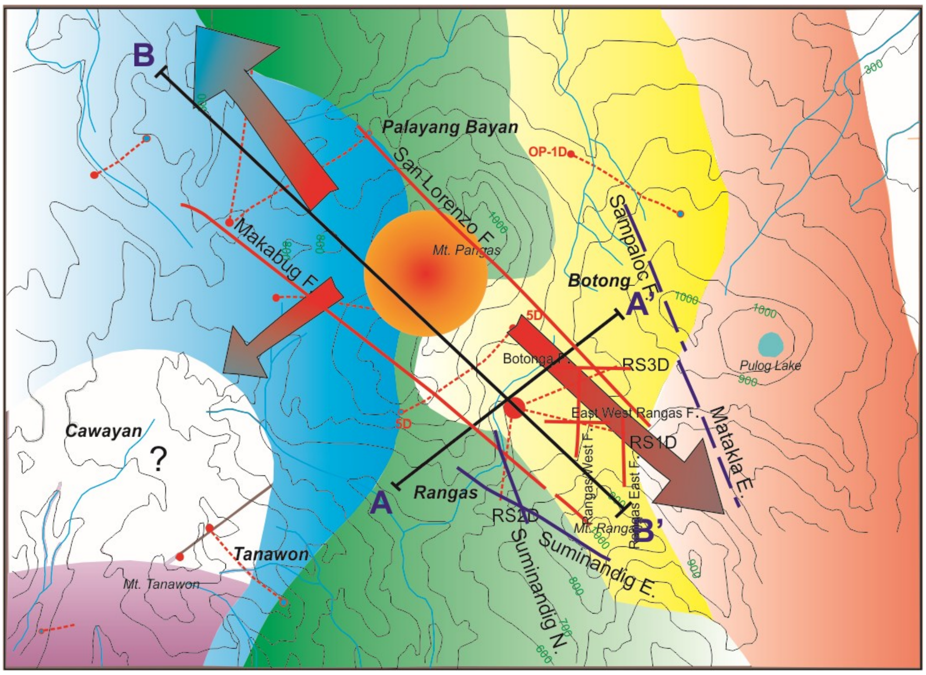

Figure 4. Conceptual Hydrogeological Model of Rangas Sector, Bacman

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