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Resistivity Model Based on 2D Inversion of Magnetotelluric Sounding Data in Bacon-Manito, Southern Luzon, Philippines

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ABSTRACT

Two-dimensional (2D) inverse modeling of Magnetotellurics (MT) data gathered during several field campaigns in Bacon-Manito (Bac-Man) revealed three anomalies referred to as Palayan Bayan, Tikolob and Malobago. The combined interpretation of Schlumberger resistivity traversing (SRT) and vertical electrical sounding (VES) data, gravity data, geologic data, well alteration and stable temperature data has led us to conclude that each anomaly is associated with a geothermal system. The emergence of the E-W resistivity trend was noted to be aligned with the local gravity high and the good correlation of this resistivity trend with the major fault system in Bac-Man was also noted. The Palayan Bayan anomaly is associated with the current Palayan Bayan production field. The Tikolob anomaly is interpreted to be a possible geothermal system in the western sector of the Bacon-Manito field separate from Palayan Bayan system. The geothermal system associated with Malobago anomaly is believed to be relict due to the exposed conductive zone in the area as observed in the MT model and relict alteration minerals present on the surface. An elongated, less prominent anomaly branching from both Tikolob and Palayan Bayan may represent the shared outflow between the Tikolob and Palayan Bayan systems.

1. INTRODUCTION

Bac-Man geothermal reservation is located within the provinces of Albay and Sorsogon in the Bicol Peninsula (Figure 1). The area of Bac-Man is overlain by Pliocene to Recent andesitic and basaltic volcanoes collectively known as the Pocdol Volcanics. Pocdol is part of the 200 km NW-SE trending volcanic chain in the Bicol region that includes Mts. Labo, Isarog, Iriga, Malinao and Mayon to the northwest and Mt. Bulusan to the southeast (Panem and Alincastre, 1985). The NW-SE Bicol volcanic chain corresponds locally to the Pocdol Belt which influences the volcanism while the major structural control is the Bac-Man Fault Zone, which is an extension of San Vicente Linao Fault (Braganza, 2011; Escanlar, et.al. 2013). Geoscientific exploration surveys as early as 1970's were conducted in Bac-Man which led to the drilling of a total of fifty-nine (59) production and reinjection wells in the area.

A relatively deep penetrating resistivity imaging technique referred to as magnetotellurics (MT) was conducted in Bac-Man during several seasons to provide added information in the assessment of Bac-Man and aid in the management decisions. This method involves measurement of the total electromagnetic field time variations at the Earth's surface.

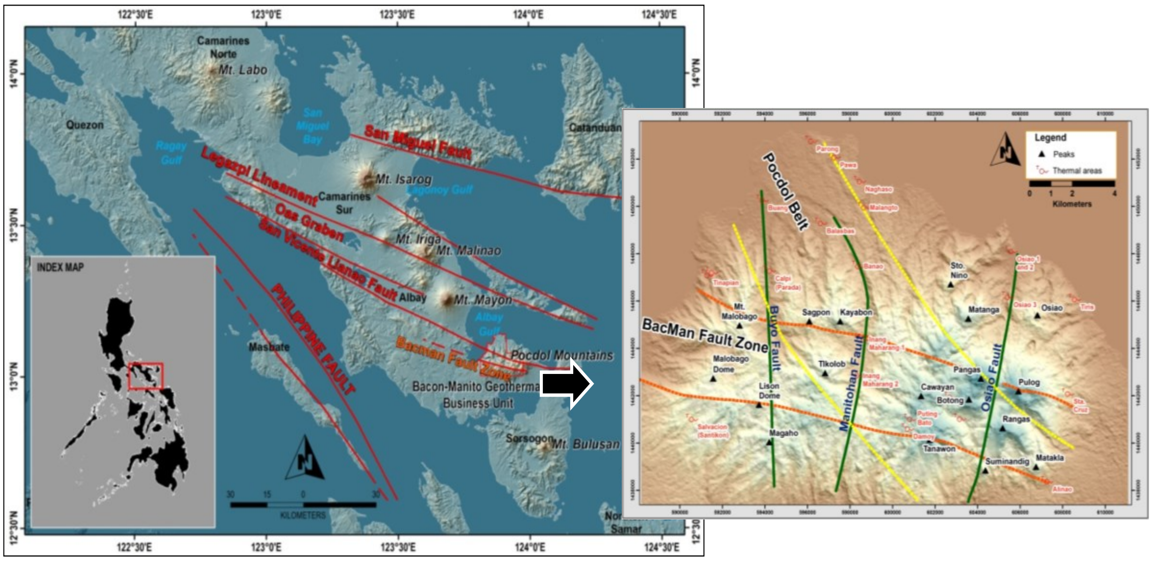

Figure 1: Location map of Bac-Man showing regional structures.

Hydrogeophysical conceptual models generated using MT data from earlier campaigns (Los Baños, et. al., 2011; Apuada and Rigor, 2000) had drawn interest in the western sector of Bac-Man in the area of Kayabon, Tikolob, Sagpon and Malobago, referred to as West Bac-Man. This report will provide an updated hydrogeophysical model of Bac-Man based on the recalculated MT models, which now incorporate the new data collected from the very recent 2011 and 2012 survey campaigns. The 2011 and 2012 surveys were specifically conducted to further assess the probable existence of geothermal resource/s as indicated by the presence of volcanic centers, thermal areas and packets of low resistivity anomaly previously mapped by Schlumberger surveys in the western sector of Bac-Man.

The MT surveys were carried out in several campaigns: 1999 at 99 sites, 2001 at 34 sites, in between 2008 and 2010 at 107 stations. Measurements at 166 sites were conducted in 2011 followed by 121 stations in 2012 covering the area in the north of the current production field and west of Manitohan River referred to as West Bac-Man. A total of 527 stations were occupied covering a total area of 188 km^2 (Figure 2). The 1999 to 2001 surveys were conducted to cover the Palayan Bayan area and the area north of Kayabon and Sagpon. In 2008 and 2010, these two areas were revisited and some stations from the 1999 to 2001 surveys were reoccupied. The 2011 survey, on the other hand, was programmed to cover the area north of Palayan Bayan and at the same time conduct denser sampling in the western sector of BacMan. The 2012 survey was programmed to cover the remaining southwestern portion of BacMan.

2. DATA ACQUISITION AND PROCESSING

MT data were recorded for an average of 40 hours for each station. The Phoenix V5 MT System™ was used during the first two MT surveys in 1999 and 2001 and the Phoenix Geophysics System 2000™ was utilized in the subsequent surveys. Raw time series data collected from 527 MT stations distributed over an area of 188 km^2 were robust processed using SSMT2000 software (Phoenix Geophysics, 2005) for all available frequency bands. The remote reference method (Gamble, et al., 1979), which involved deploying additional sensors at a distance from the measurement site, was used to address noise effects in most of the MT measurements collected in Bac-Man. The remote site was selected such that noise is not correlated with the noise from the measurement site and also ensuring that the incoming magnetic signal is still coherent. Cross-power editing was done using MTEditor to mask nosier segments of the MT curves. These edited data were imported in WinGLink as standard EDI files. The D+ function (Beamish and Travassos, 1992) was fitted to each curve to check if the data were geophysically plausible. 2D MT inversion was employed in generating the final models and was used as basis for developing the hydrogeophysical model of Bac-Man. Of the 527 stations, only 271 stations were used in the final model on the basis of data quality. The remaining data from 256 stations were discarded due to very high noise contamination. Most of these rejected data were from first measurements of the stations. A few repeat measurement attempts were successful and data were seen to improve by extending the recording period. The contamination was attributed to local noise sources, weak MT signal during the acquisition and constant raining in the area.

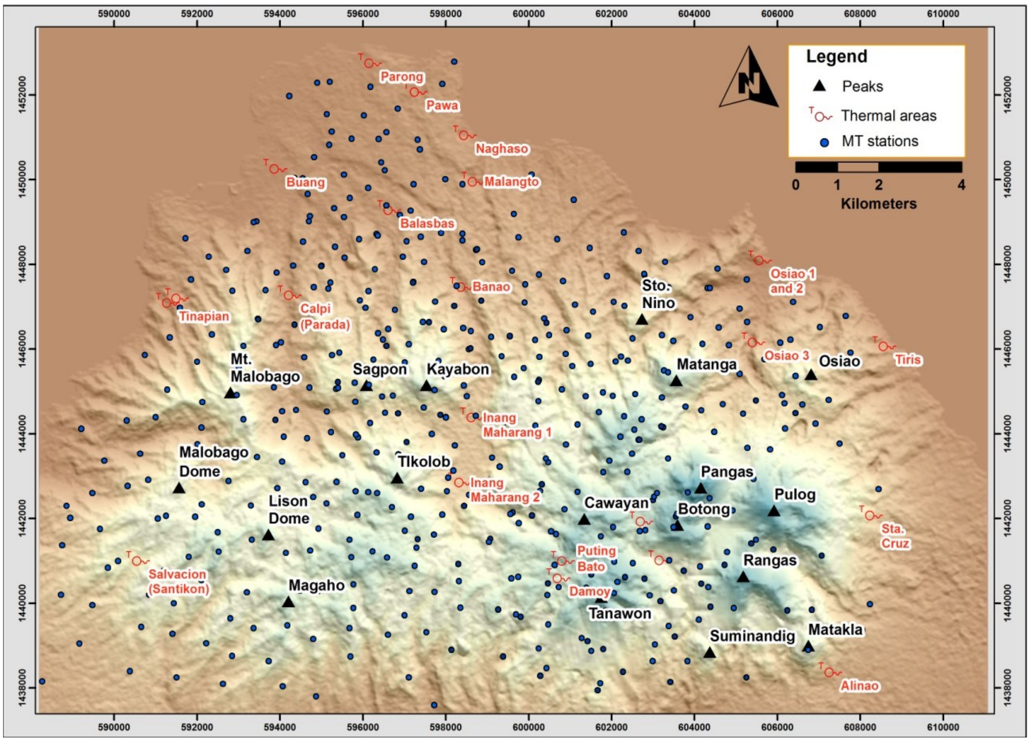

Figure 2: Location map of Bac-Man MT stations. A total of 527 MT stations were occupied in a total area of 188 km^2.

3. DISCUSSION OF RESULTS

3.1 Resistivity Profiles

Two SW-NE profiles, one running across Tikolob (Figure 3A) and the second one cutting the main production field (Figure 3B) were compared side-by-side. The distinct doming feature in Tikolob, which is also observed in Palayan Bayan, may indicate a possible geothermal system. The low resistivity zone, which noticeably thickens to the north, may be the clay cap of the system with possible upflow beneath Tikolob. The low resistivity signature in the west may have been due to the presence of clay alteration minerals such as smectite, smectite-illite and illite, which were also observed in the wells in Palayan Bayan. Fluids are inferred to outflow towards the north where several thermal manifestations are located.

A profile running west to east along the length of Bac-Man Fault Zone transecting Malobago and Tikolob in the west and Cawayan and Botong in the east (Figure 4) shows the three distinct resistivity layers as observed from the SW-NE profiles. A high resistivity surface cover (in green) can be noted with an eroded portion observed in Malobago. This layer overlies a single, continuous zone of low resistivity. The third high resistivity layer underlying the conductive layer forms three domes beneath Malobago, Tikolob and Cawayan. The high-low-high resistivity trend observed in Bac-Man is typical of a geothermal system where the shallowest portion of the third layer may be considered as the hottest central portion of the resource.

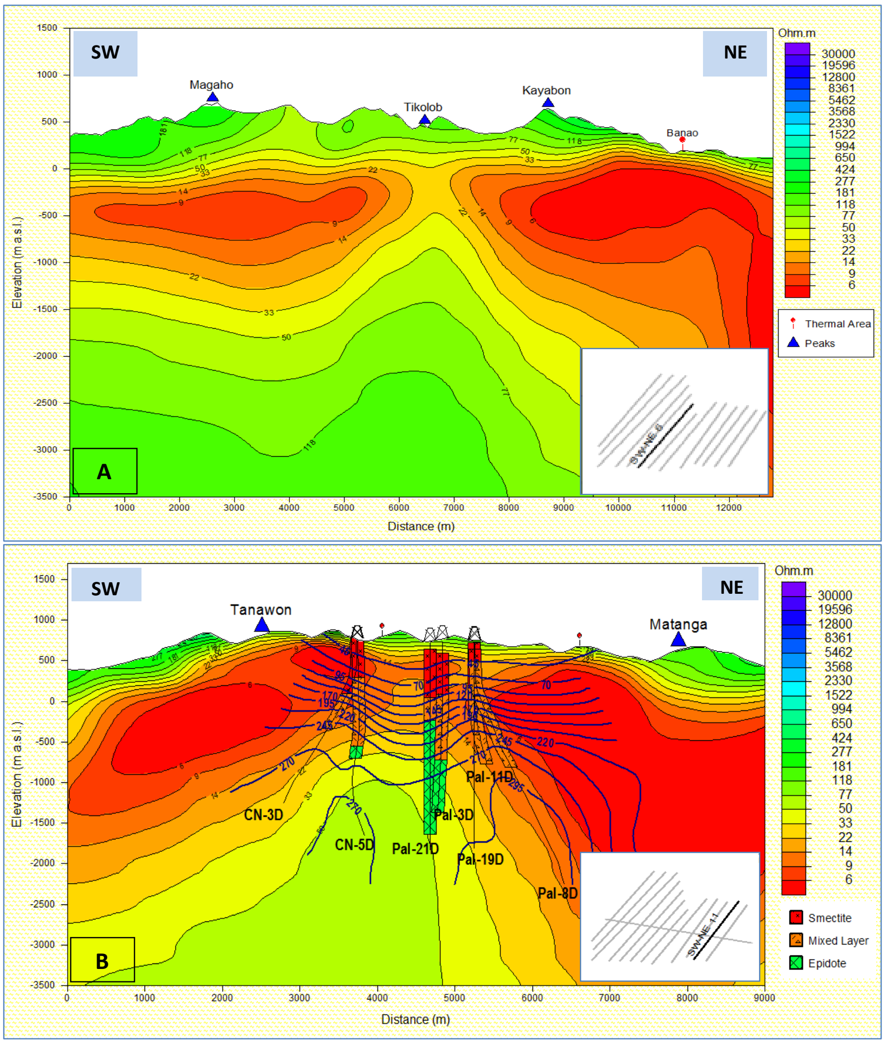

Figure 3: Bac-Man 2D MT profiles. (A) West Bac-Man profile transecting Mts. Magaho, Tikolob and Kayabon. (B) Palayan Bayan profile cutting across the production field. Cawayan wells (CN-3D and 5D) and Palayan Bayan wells (Pal-21D, 3D, 11D, 19D and 8D) are correlated with well alteration data and stable temperature data in solid blue contours.

The occurrence of conductive clay minerals and resistive high temperature alteration products in the wells in Palayan Bayan was observed to fit the MT model. The smectite, the mixed layer of illite-smectite and the illite zones generally correspond to <30 Ω-m layer. The zone of high temperature mineral geothermometers such as epidote, actinolite and biotite correlated with the > 30 Ω-m zone of the MT model. The occurrence of high temperature minerals intersected at shallow depths coincides with the shallowest modeled high resistivity zone of the Palayan Bayan MT anomaly. The shallow Cawayan Intrusive Complex (not shown) was also encountered in the general subsurface area where the Palayan Bayan MT anomaly was modeled.

3.2 Isoresistivity Maps

MT was able to replicate the results and confirms the previous interpretations based on shallower resistivity methods. Isoresistivity maps at a constant depth of 200 m and 500 were generated and were compared with SRT and VES data (Figures 5A and 5B). A good match can be noted between the DC resistivity data and MT data. Regions of low resistivity (< 30 Ω-m) coincided with the anomalies previously mapped using SRT (Layugan, 1986) method. Likewise, the high resistivity blocks earlier mapped using VES (Layugan, 1986) were also imaged using the MT method (Figure 5B). The low resistivity zone to the north was inferred as possible outflow path of fluids.

The striking coincidence of the region of mapped high gravity and the MT anomalies can be observed from Figure 5C. The areas of high resistivity observed at -1100 m elevation are well within the zone of high gravity anomaly where the dense rocks interpreted as intrusive rocks are located (Los Baños and Olivar, 1997).

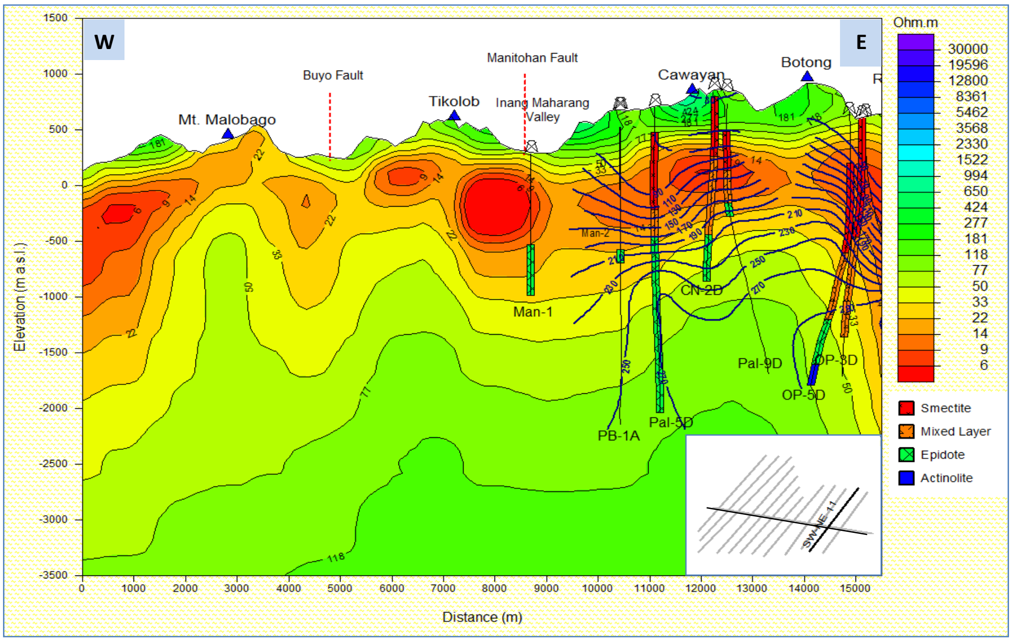

Figure 4: 2D MT model along a west to east profile parallel to the strike of Bac-Man Fault Zone showing three distinct updoming features; 1) beneath Mt. Malobago, 2) below Tikolob and 3) beneath Cawayan and Botong located within the producing field where temperature and alteration data correlate well with the Palayan Bayan MT anomaly/updome feature.

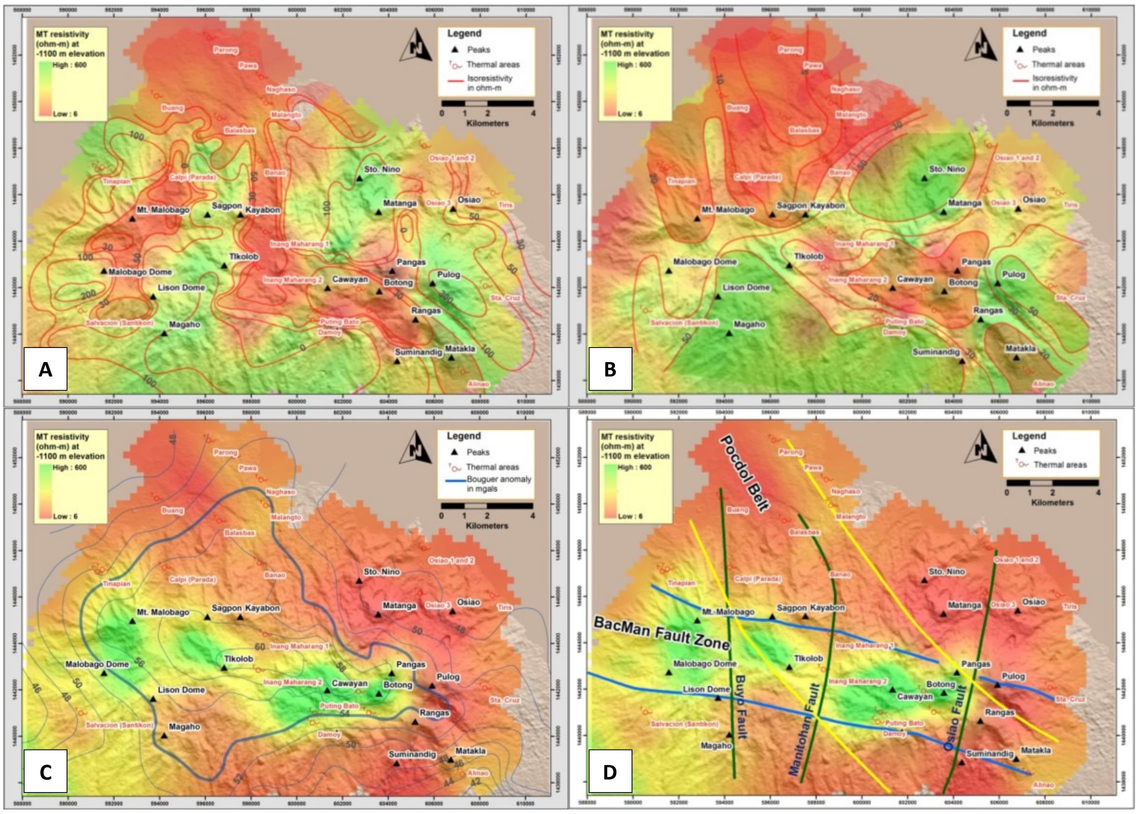

Figure 5: (A) MT isoresistivity at 200 m depth (color shadings) vs. isoresistivity contours based on SRT and VES at AB/2 = 500 m. (B) MT isoresistivity at 400 m depth (color shadings) with isoresistivity overlay based from third/bottom layer of VES data. (C) MT isoresistivity at -1100 m elevation (color shadings) with gravity overlay. (D) MT isoresistivity at -1100 m elevation (color shadings) with major geologic features.

The zones of high gravity and high resistivity MT anomalies (Figure 5C) coincided with the delineated Bac-Man Fault Zone. It can be noted that the MT anomalies generally fall inside the intersection of major fault zones and structures (Figure 5D). These intersections seem to create localized ‘compartments’ where these MT anomalies form. The Palayan Bayan anomaly falls inside the convergence of Pocdol Belt and Bac-Man Fault Zone. This is bounded to the west by Manitohan Fault and to the east by Osiao Fault. The Tikolob anomaly, on the other hand, is marked by Manitohan Fault to the east and Buyo Fault to the west. The Malobago anomaly sits on the far western portion of the Bac-Man Fault Zone and is separated from Tikolob anomaly by the Buyo Fault. The placement of these anomalies underscores the significance of the structures in the formation of geothermal systems.

3.3 3D Visualization

A volumetric pixel or voxel (Figure 6) was derived from the 2D horizontal elevation slices at 200 m interval from sea level down to -3500 m to provide 3D perspective of the resistivity structure of Bac-Man. The 2D horizontal grids were preprocessed in GRASSGIS to generate a voxel. The MT voxel was inputted into ParaviewGeo for viewing in 3D. A 25 ohm-m isovolume was extracted from the voxel to highlight the anomalies identified from the resistivity profiles and plan maps. The MT model was rendered with Digital Elevation Model (DEM) and well trajectories in different ways: A) DEM B) Cutaway view of DEM and the conductive layer revealing the 25 ohm-m isovolume. C) Cutaway view of DEM, conductive layer and the 25 ohm-m isovolume. D) DEM and conductive layer removed from view. The MT anomalies were modeled as domes of high resistivity observed beneath Palayan Bayan, Tikolob and Malobago with Palayan Bayan being the largest of the three anomalies.

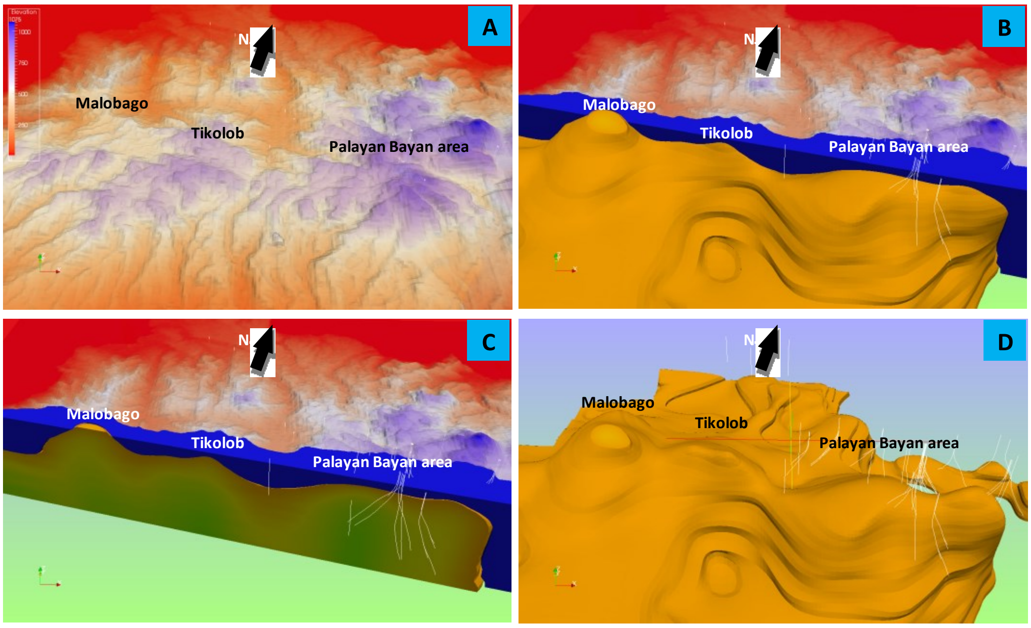

Figure 6: 3D visualization of MT data. (A) DEM (B) Cutaway view of DEM and the conductive layer revealing the 25 ohm-m isovolume. (C) Cutaway view of DEM, conductive layer and the 25 ohm-m isovolume. (D) DEM and conductive layer removed from view.

4. BAC-MAN HYDROGEOPHYSICAL MODEL

The Bac-Man hydrogeophysical model is characterized by an active hydrothermal convective cell as represented by the Palayan Bayan production field and a possible geothermal system beneath Tikolob. Heat is provided by the dense intrusive rocks in the location of mapped gravity-high. Fluids upflow beneath Tikolob and Palayan Bayan production area (Figures 7A and 7B). The shallowest portion of the possible reservoir in Tikolob is at 700 m from the surface. The trace of the outflowing fluids is marked with white dashed line (Figure 7A). This is inferred to be a shared outflow between Tikolob and Palayan Bayan reservoirs. This 20 ohm-m zone stemming from both Palayan Bayan and Tikolob anomalies indicate a relatively high temperature outflow. Fluids leak to the surface and in the process alter the near-surface rocks. This may be manifested as the northern portion of the L-shaped anomaly mapped by SRT method (Figure 5A). It is worth mentioning that the possible hydrothermal system associated with Malobago anomaly may already be relict. The age of Malobago is believed to be dating back to Late Miocene or ~5.33 Ma (Tebar, 1988). The exposed low resistivity layer and the smectite alteration minerals mapped on the surface in this area suggest erosion. Additional sampling was conducted to verify the age of Malobago and this will be re-evaluated as soon as age dating analysis is completed.

5. CONCLUSION

Results from the MT method have aided us in characterizing the known Palayan Bayan geothermal system. The result from the MT survey has corroborated the findings of the previous geoscientific studies in Bac-Man. The MT model agrees and correlates well with the shallower VES and SRT methods. The low resistivity anomalies mapped by these methods were also modeled in MT. These shallow anomalies were interpreted to be near-surface expressions of fluid convection in the subsurface. This study confirmed the existence of the known Palayan Bayan reservoir. It also established the existence of a possible separate geothermal system in West Bac-Man located beneath the area of Tikolob and a likely relict system beneath Malobago as illustrated in Figure 7.

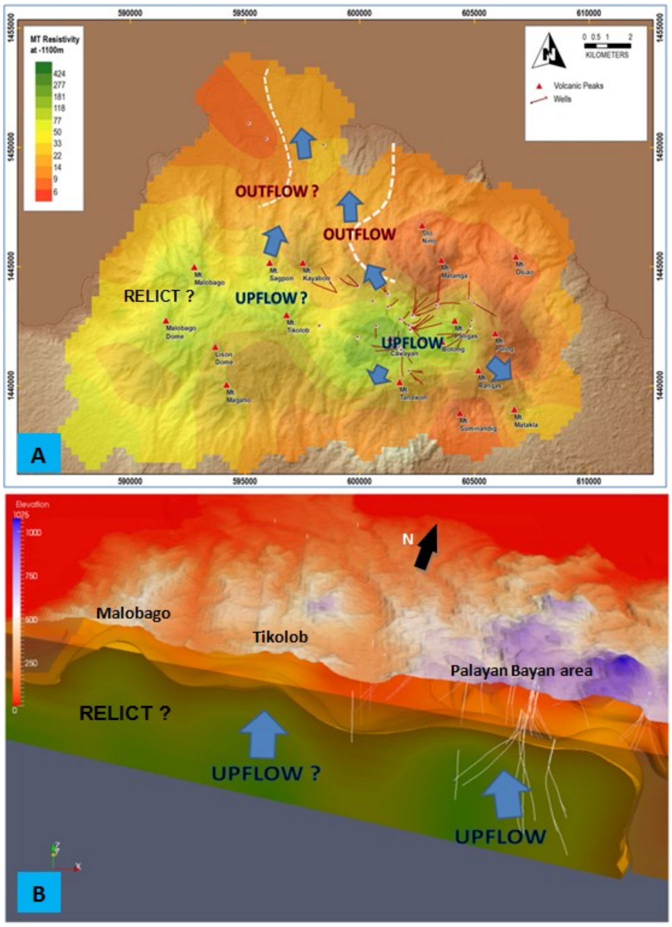

Figure 7: Proposed Bac-Man hydrogeophysical model. The Palayan Bayan system corresponding to the production field is imaged from MT resistivity and is characterized by a high-low-high resistivity trend an updome feature. A likely active system is also imaged with possible upflow beneath Mt. Tikolob. The trace of a likely relict system beneath Malobago, which is characterized by an exposed conductive layer is imaged using MT resistivity. Resistivity pattern suggest mixing of outflow from Palayan Bayan and Tikolob systems.

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