BEYOND BOUNDARIES: EXPLORING INTERPRETATIONS FROM CORRELATION OF RESISTIVITY WITH VARIOUS RESERVOIR DATA IN MT. APO GEOTHERMAL AREA

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ABSTRACT

Magnetotelluric (MT) method is one of the most used resistivity methods in geothermal industry. Due to its extensive investigation depth, it is commonly used for defining the reservoir boundaries.

In 2017, an MT survey was conducted in Mt. Apo geothermal field (MGPF) with the aim of updating its resistivity model. A total of 170 MT soundings were subjected to 1D and 2D inversion modeling. The 1D approach presented a conservative interpretation at reliable depths while 2D inversion provided reservoir characterization at further depths using statistical methods.

The typical resistivity signature exhibited by volcanic-hosted geothermal areas in the Philippines shows a three layered resistivity structure composed of a continuous updoming low resistivity layer (<10Ωm) in between higher resistivity layers with the intermediate layer commonly associated with the reservoir's clay cap. The recent Mt. Apo survey revealed an atypical feature not previously identified. It is characterized as a NE-trending moderately resistive anomaly that appears to cut through the supposedly continuous conductive layer of the reservoir. The anomaly appears in both 1D and 2D inversion models.

This paper discusses the various interpretations of this resistivity anomaly as correlated with local structural geology, regional tectonics and well data revealing spatial association with acid zones and structural trends and potentially indicating an unidentified regional structure.

1. INTRODUCTION

The Mt. Apo geothermal area is located in South Central Mindanao as illustrated in the regional map of **Figure 3**. The geothermal development block lies on the northwest flank of the Philippines' highest peak, Mt. Apo, and produces a total output of 100 MW with power plants Mindanao 1 and Mindanao 2 producing 52MW and 54MW respectively.

1.1 Geology

Mt. Apo is part of a triangular field of Pliocene-Quaternary volcanoes in Central Mindanao which also includes volcanoes Makaturing and Hibok-hibok as illustrated in **Figure 3.** General surface geology of Mt. Apo is composed of multi-episodes of andesitic to basaltic lava flows, with scattered distribution of pyroclastic materials which are collectively called the Apo Volcanics (AV) which is further subdivided into a younger (yAV) and an older (oAV) member. Subsurface geology reveals more lithological formations such as the sediments of the Sabpangon Sedimentary Formation (SSF), the completely metamorphosed volcanics with hornfelsic texture of the Contact Metamorphic Zone (CMZ), which surrounds the massive, coarse-grained pluton known as the Sandawa Intrusive (SI). The relationships of these lithologic units are illustrated in **Figure 1.**

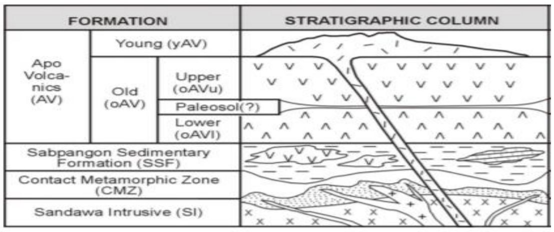

Figure 1: Stratigraphic Column of Mt. Apo (Los Baños et. al., 2010)

The structural geology of the Mt. Apo geothermal area is dominantly influenced by the nearby regional structure that is the Cotabato Fault, sometimes referred to as the Mindanao Fault as illustrated in **Figure 2**. The Cotabato fault is characterized as an active left lateral strike-slip fault that trends NW-SE and delineated from the provinces of Zamboanga del Norte to South Cotabato. Its influence resulted to the formation of NW trending faults identified to be the major channel of thermal manifestations throughout the area. Meanwhile, NNE to almost N-S trending structures with longer strike lengths, are observed to be predominant within the Sandawa sector located inside the Sandawa Collapse. Furthermore, remote sensing studies detected the presence of almost N-S trending lineaments traversing the central region of Mindanao from the north in Zamboanga Del Norte down to Digos, Davao del Sur. (Pioquinto, 2014).

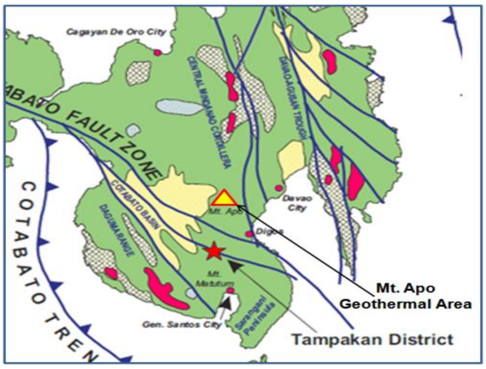

Figure 2: Geological and Structural Map of Mindanao Island (Middleton et. al., 2004 modified after Domasig et. al., 1998)

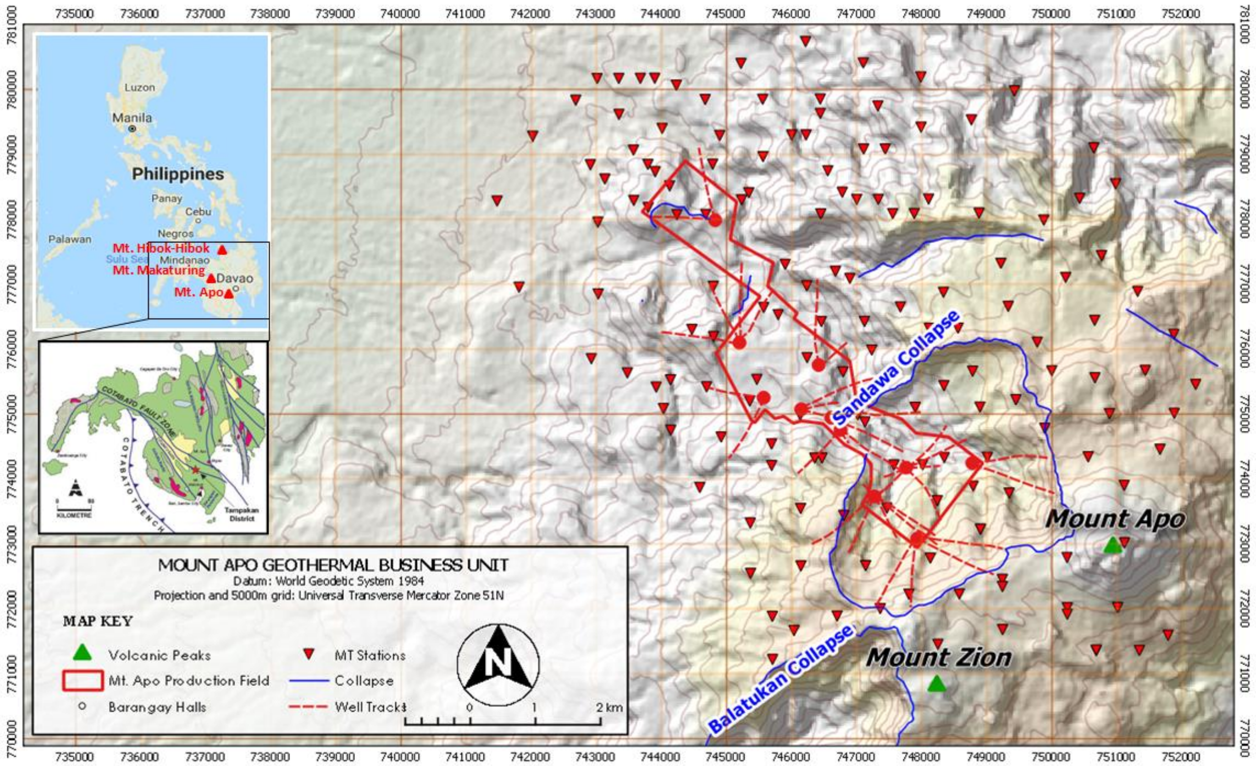

Figure 3: Mt. Apo Geothermal Production Field is located in the northwestern flank of Mt. Apo. A total of 170 MT station data were used for the 2017 resistivity study.

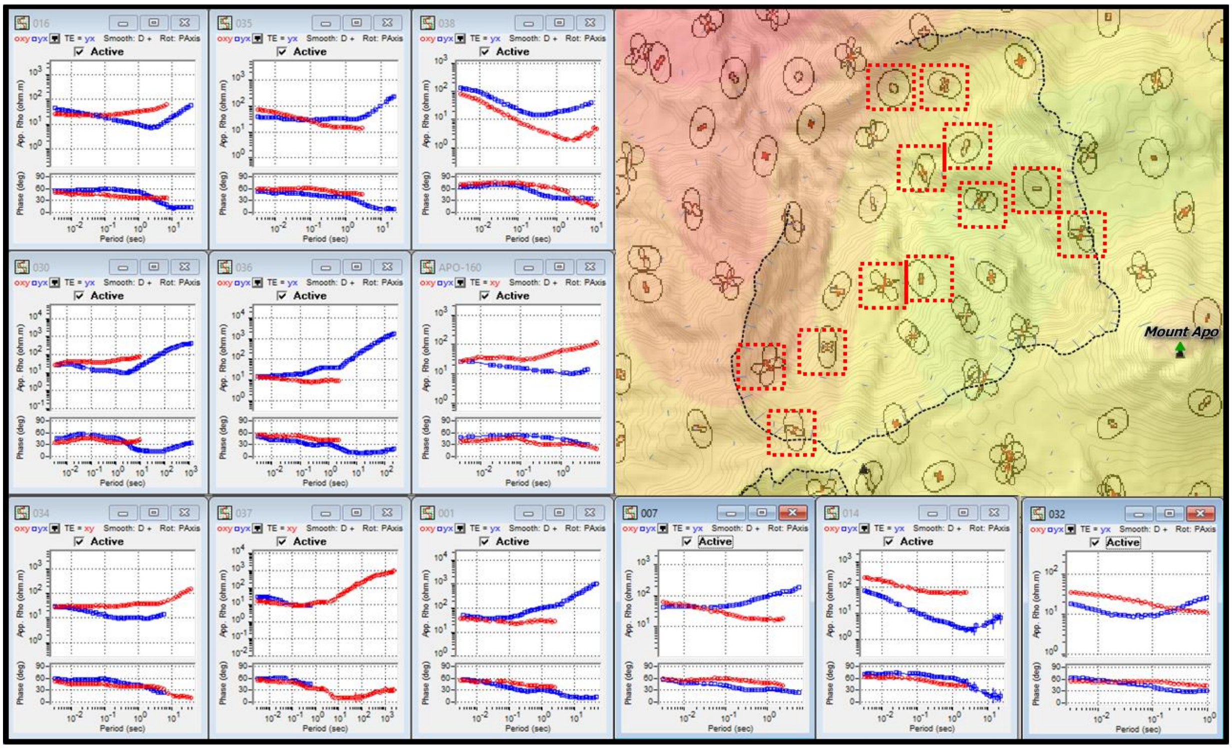

Figure 4: Splitting of TE and TM curves observed in stations associated with the resistivity anomaly within Sandawa Collapse. Polar Diagrams show most stations within the Sandawa Collapse have mostly 2D and 3D dimensionality.

The interplay of regional tectonics is believed to have a major role in the trends of the structures in the Mt. Apo geothermal field. The structural framework in the region can already be observed from the two predominant structural trends observed. It is interpreted that the left-lateral Cotabato Fault influenced the formation of NW-SE trending faults in the area while the northeasterly subduction along the Cotabato Trench produced an apparent compressional component resulting to the formation of almost N-S, NNE to NE trending extensional fractures and Riedel shears. It is also possible that the direction of breach of the Sandawa Collapse is structurally influenced as sector collapse of volcanoes traversed by basement faults in a strike-slip setting are common with substrate tectonics and magma intrusion playing a major role in flank eruptions, lateral collapse and erosion (Lagmay et al., 2000), (Tibaldi et al., 2008).

1.2 Geophysics

Various geophysical surveys have already been conducted in the area including an SRT and VES surveys in 1984 which identified and characterized four shallow resistivity anomalies in and surrounding the geothermal area. These anomalies are the Marbel, Kapatagan, Bulatukan and Tico anomalies. Of these four, the Marbel anomaly stands out as the anomaly with strong association with the thermal features in the area evidently controlled by the major NW-trending structure. It is characterized as an elongate NW-trending anomaly with steep resistivity contrasts in the NE and SW margins. The anomalies identified by the SRT and VES surveys are illustrated in **Figure 5.** The results of these surveys became the strong basis for the delineation of the development block of the MGPF.

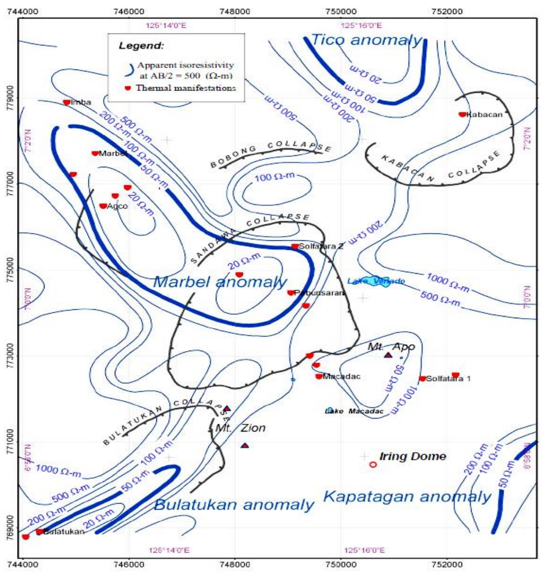

Figure 5: SRT and VES surveys identified four low resistivity anomalies: Marbel, Tico, Bulatukan and Kapatagan anomalies (Los Baños et. al., 2010)

The MT Survey in 2004 was the first deep penetrating resistivity survey conducted in the Mt. Apo installing a total of 129 stations. Results of this survey outlined a NW-trending MT anomaly characterized as a highly resistive body (>100 Ωm) within the Sandawa collapse, the MT anomaly appears to extend farther south at greater depths. This anomaly is inferred to represent the extent of the high temperature resource (>300°C) at Mt. Apo. The northeastern segment of the MT anomaly is located within the Sandawa Collapse, where several producing wells have been drilled. (Rigor et al.,2006)

The conductive zones located around the MT anomaly signify the most likely outer margins of the resource. The prominent low resistivity region mapped in the NW depicts the major outflow while those in the south and southwest of Apo are interpreted to be indications of possible minor outflows. Results of the 2006 MT Survey are illustrated in **Figure 6.**

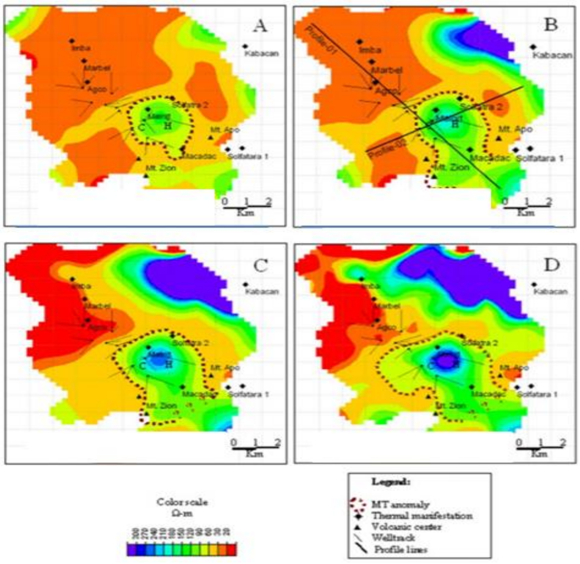

Figure 6: 2006 MT survey results identified a high resistivity anomaly within the Sandawa Collapse inferred to represent the high temperature resource (Los Baños et. al., 2010)

Another MT survey was conducted in 2017 with the aim of updating its resistivity model. With additional 41 stations, the study made use of a total of 170 MT soundings that were subjected to 1D and 2D inversion modeling. The recent survey revealed an atypical feature not previously identified, characterized as a moderately resistive zone (20Ωm - 60Ωm) that cuts through the conductive layer (<20Ωm) as observed in both 1D and 2D inversion models.

2. METHODOLOGY

Magnetotelluric (MT) method is one of the most used resistivity methods in geothermal industry. MT measures the fluctuations of the natural electromagnetic field at the Earth's surface with simultaneous measurements of varying magnetic field and induced electric field. Due to its extensive investigation depth, it is commonly used for defining the geothermal reservoir boundaries.

Data modeling was entirely done using the WinGLinkTM Integrated Geophysical Processing software. With the use of the program, resistivity profiles and iso-resistivity plan maps were produced.

Because of the limitations of 2D in profile orientation and uncertainty viewing, 1D inversion modeling was also carried out. One of the main advantages of the 1D approach is that it can limit the model to reliable depths, however the truncated data will appear blank in the models thus anomalous zones and other resistivity features at depth may be omitted. 2D inversion on the other hand uses statistical methods for corrections in static shift which restricts human error and modeler biases. 2D data are rotated towards the average geoelectric strike of the study area.

The resistivity anomaly identified and characterized in the 2017 MT study was correlated with various datasets available in Mt. Apo Geothermal Area with the aim of interpreting and possibly further characterizing it and its potential implications. With the use of GIS platforms such as QGIS, spatial correlations of the MT results were carried out to come up with different interpretations of the anomaly. These datasets include well data, local structural data and regional structural data.

3. DISCUSSION

The typical resistivity signature exhibited by volcanic-hosted geothermal areas in the Philippines shows a three layered resistivity structure composed of a continuous updoming low resistivity layer (<10Ωm) in between higher resistivity layers with the intermediate layer commonly associated with the reservoir's clay cap. However, 2017 MT results showed an atypical feature in the Mt. Apo resistivity model in the form of a NE-trending moderately resistive (20Ωm-60Ωm) anomaly that appears to cut through the conductive layer of the reservoir located beneath Sandawa Collapse. This anomaly appears in both 1D and 2D inversion models.

Further investigation on the previous MT study in Mt. Apo revealed that this feature can already be recognized in the resistivity profiles of Rigor et al. in the 2006 MT study but it was not acknowledged, characterized nor discussed in the report.

Station raw data shows that most stations associated with the anomaly shows strong splitting of TE and TM curves as shown in **Figure 4.** Polar diagrams of these stations show that most have a dimensionality of 2D or 3D.

The resistivity contrast with the conductive layer, the splitting of TE and TM curves, and the dimensionality suggested by polar diagrams may be indicative of a subsurface 3D structure, that is possibly a fault (Daud et. al., 2015). Daud explained that 'A fault structure can be indicated by resistivity contrast produced by conductive fluid filling the fracture zone or produced by different formation with different resistivity. The resistivity contrast causes MT curve splitting and impedance polarization.'

To interpret the anomaly and explore potential implications, correlation with well data, local structural geology, and regional tectonics was carried out.

3.1 Correlation with Well Data

The moderately resistive anomaly appears to cut through the conductive layer. Due to this behavior, it was initially inferred that the anomaly may possibly be a reflection of an actual discontinuity in the reservoir's clay cap. However, well alteration data disagree.

In **Figure 8**, Well A is intersected along resistivity profile NW05. Profile NW05 traverses the Sandawa collapse and supposedly encounters the resistivity anomaly. Well A is expected to encounter the anomaly, however well lithology shows presence of clay minerals Illite and Smectite right in the zone where it is expected to come across the anomaly. This is also observed in other profiles such as Profiles NW04 and NW03 as illustrated in **Figure 9.**

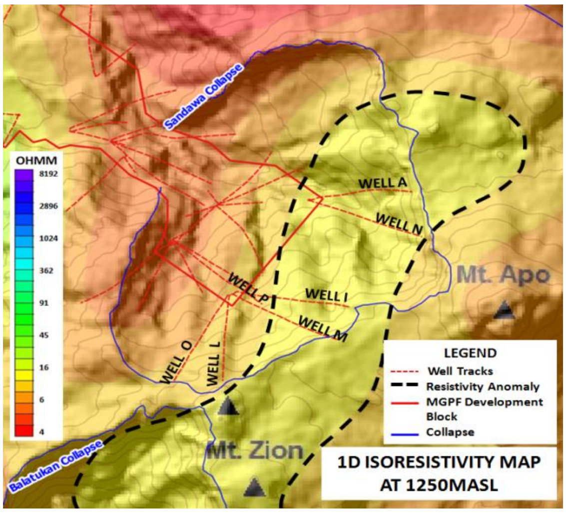

Figure 7: 1D Isoresistivity Map at 1250MASL shows geographical overlap of the resistivity anomaly with known acidic wells A, L, M, N and P.

Iso-resistivity map at 1250masl, as shown in **Figure 7,** demonstrates the intersection of these profiles with the anomaly in map view. At this elevation the anomaly appears as a NE-trending elongate feature, isolated by a linear 20Ωm resistivity contour with sharp resistivity contrasts in the NW and SE. Following Daud's explanation, these characteristics possibly indicates a three-dimensional structure beneath the Sandawa collapse.

In the same figure, it also appears that the inferred structure has geographical overlap with the end points of known acidic wells in the Sandawa sector such as Wells A, L, M, N and P. It is postulated that the structure may possibly hold control over the distribution of the acid within the Sandawa sector. The implication of this hypothesis is the possibility that the acidic zone may possibly be mapped out if the postulated structure indeed holds control over the distribution of the acid.

A relationship between the potential structure and the extent of acidity is suggested which concurs with Daud's explanation of a 'conductive fluid filling a fracture zone' as an explanation for the resistivity contrast associated with faults. This suggested relationship should be further correlated with petrography and geochemistry for verification.

3.2 Correlation with Local Structures

Exploring further the hypothesized structure, the resistivity anomaly is correlated with local structural data. In 2016 an update on the structural model of Mt. Apo Geothermal area was conducted by Latayan et. al. and new NE-SW faults with a strike direction ranging from 40° to 70° were identified in the Sandawa sector as illustrated in **Figure 10.** These faults and fracture patterns are described to be particularly distinct in the Sandawa and Marbel-Matingao sectors and are inferred as antithetic faults (Latayan et. al., 2016). Coincidentally, the elongated appearance of the anomaly at 1250masl **(Figure 7)** trends NE with an estimated strike range of 30°-45° NE.

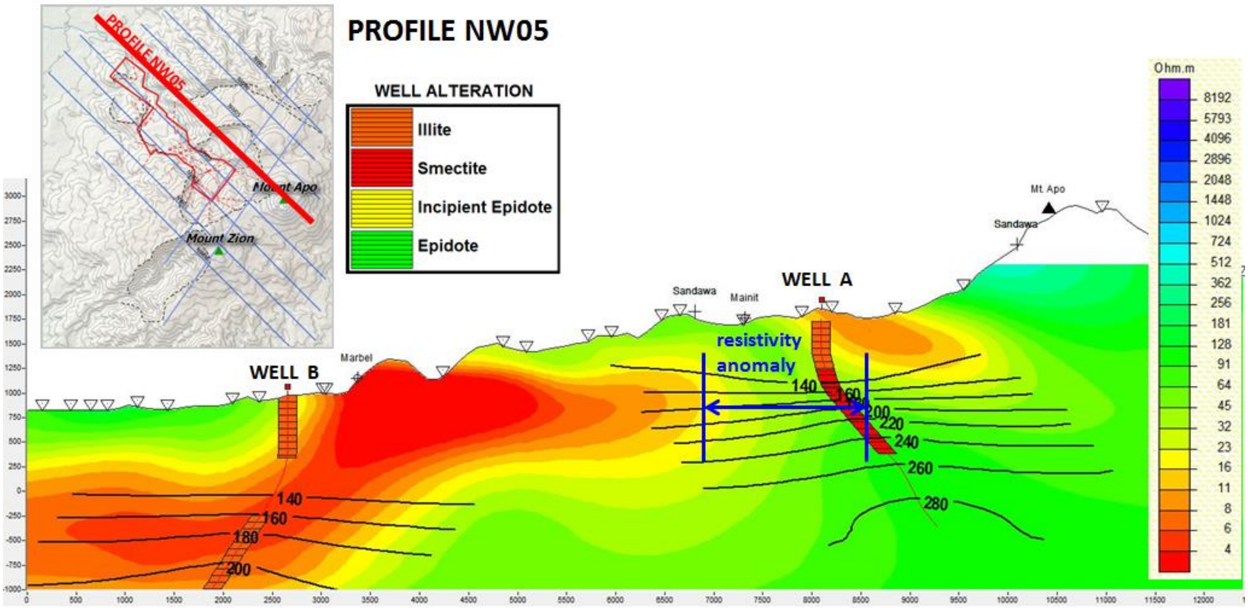

Figure 8: Resistivity Profile NW05 and Well A are expected to intersect with the resistivity anomaly. Well A's lithologic data shows presence of minerals Illite and Smectite which are clay minerals associated with the geothermal clay cap.

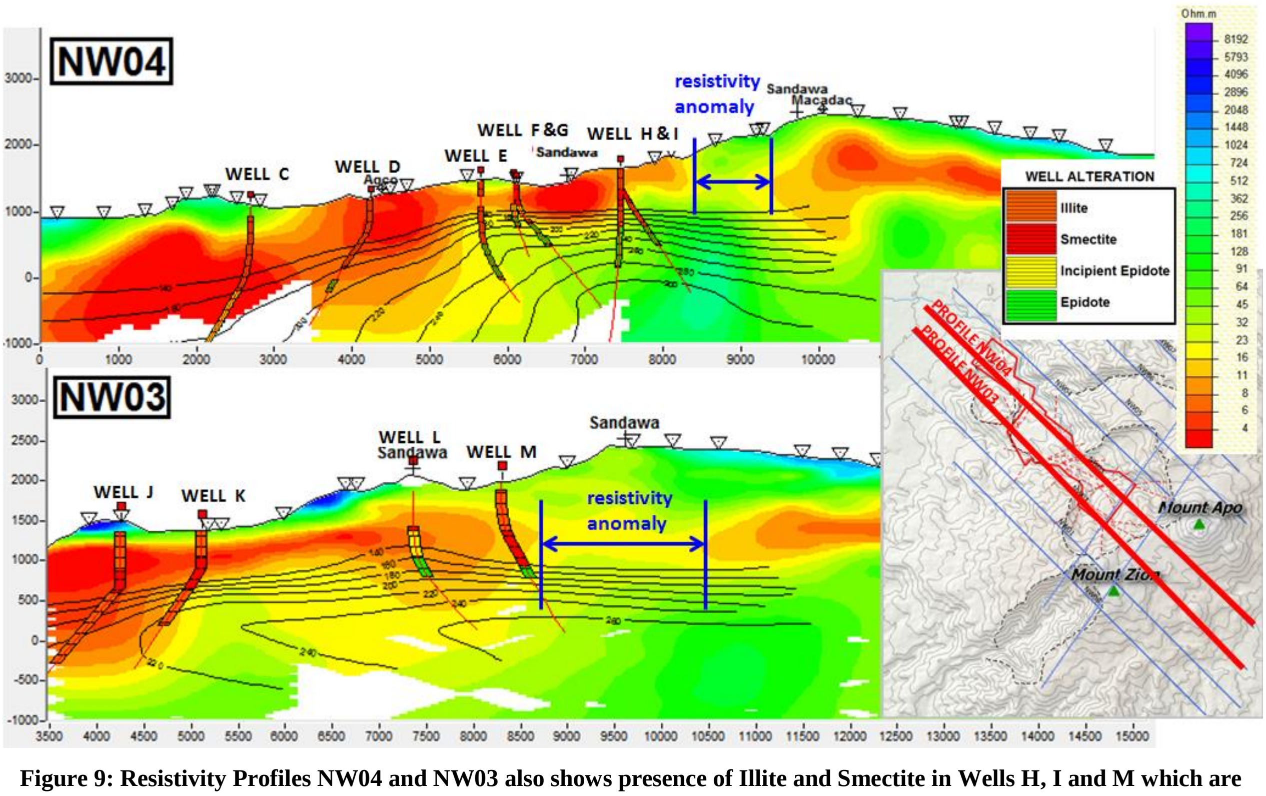

Figure 9: Resistivity Profiles NW04 and NW03 also shows presence of Illite and Smectite in Wells H, I and M which are wells that are expected to encounter the resistivity anomaly.

The recent structural study associates NE-trending faults to be antithetic to regional stresses. Antithetic faults are defined as minor, secondary faults, usually one of a set, whose sense of displacement is opposite to its associated major and synthetic faults. Antithetic-synthetic fault sets are typical in areas of normal faulting. The most prominent regional structure near Mt. Apo geothermal area is the Cotabato Fault (CF), also referred to as the Mindanao Fault in other literature.

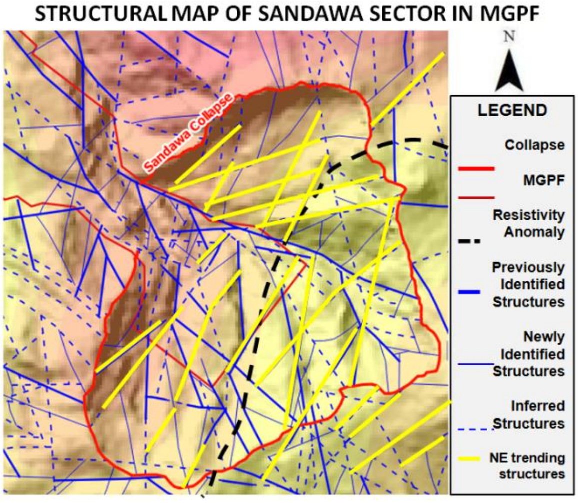

Figure 10: Results of the 2016 Structural Mapping in Mt. Apo Geothermal area. In yellow are the newly identified NE trending structures described as antithetic faults

3.3 Correlation with Regional Structures

In regional perspective, the Mt. Apo Geothermal Area has several similarities with the Tampakan District of South Cotabato. Located along the southern Central Mindanao Cordillera with Mt. Apo just 100km to its north and Mt. Matutum 15km to its south, Tampakan District also lies within the tectonic regime of the Cotabato Fault Zone (CFZ). Mt. Apo is located north of CFZ while Tampakan is located at the south as illustrated in **Figure 2.**

Structural Geology of this mineral district identifies major WNW-trending structures with prominent orthogonal NNE-trending dilational structures showing major control of the high-sulfidation epithermal mineralization and alteration zones of the area. The Tampakan copper-gold deposit lies at the intersection of WNW- and NNE-trending structures and the higher-grade zone of copper mineralisation has been defined and identified to extend in a NNE orientation over a distance of approximately 1.2 km coincidentally coinciding with NNE-trending Pula Bato Fault as shown in **Figure 11**. (Middleton et. al., 2004).

The NE-trending structures in the Sandawa sector are possibly correlatable to the NNE-trending dilational faults of Tampakan District. This would agree with Latayan et. al.'s characterization of the NE structures within Sandawa Collapse as antithetic faults. It also concurs with Tibaldi's interpretation of NNE and NE structures in central Mindanao as extensional fractures and riedel shears that resulted from the subduction of the Cotabato Trench. Correlation of these similar trends and common characteristics hypothesizes the existence of a previously unknown NE/NNE-trending regional structure extending from Mt. Apo in the northeast to the Tampakan District in the southwest.

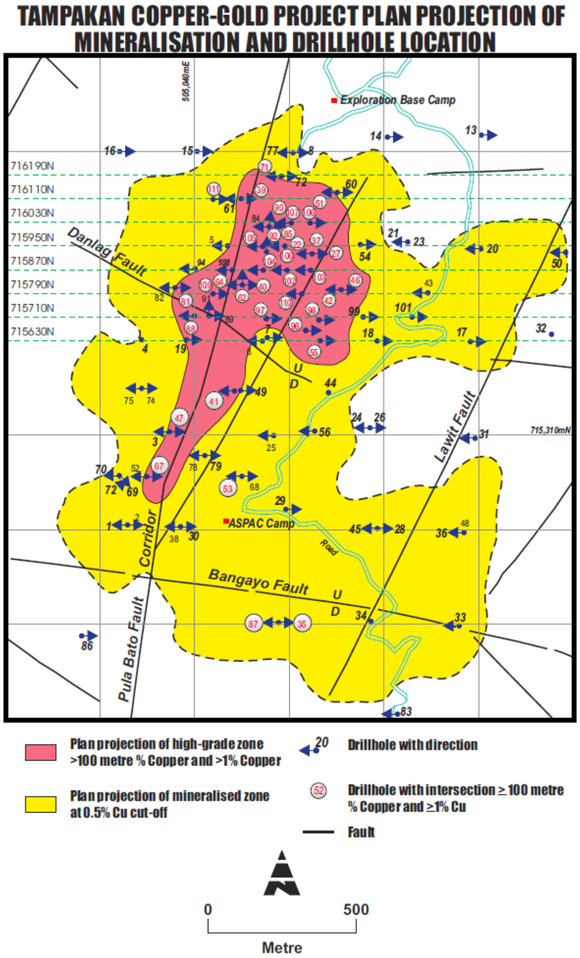

Figure 11: Mineralisation map of Tampakan District (Modified after Middlteon et. al., 2004)

4. CONCLUSION

Results of the recent MT survey in the Mt. Apo Geothermal Area discovered an atypical NE-trending feature within the Sandawa Collapse. The feature is manifested in 2D and 1D models as a NE-trending moderately resistive (20Ωm - 60Ωm) anomaly with sharp resistivity contrasts in the NW and SE appears to cut through the supposedly continuous resistive layer (10Ωm). Daud et. al. theorizes that these characteristics are possible indicators of a subsurface three-dimensional structure or a conductive fluid filling a fracture zone.

To further investigate the anomaly and its potential implications, correlation of the resistivity anomaly with various datasets was carried out and resulted to various possible interpretations.

Well data correlation disproved the possibility of a discontinuous claycap and showed geographical overlap with the end points of known acidic wells suggesting a possible relationship between the anomaly and the distribution of acidic fluids in the area implying the possibility that a structure holds control over the extent of acidity.

Correlation with new structures showed newly identified structures and fracture patterns that trend similarly with the anomaly which concurs with the possible interpretation of a fault. Regional perspective on structural geology leads to correlation of the the Mt. Apo Geothermal Area with the nearby Tampakan Mineral District. It is postulated that that NE trending anomaly in Mt. Apo is correlatable with the NNE-trending structures of Tampakan which are characterized as dilational fractures showinng major control in the distribution of mineralisation, agreeing with the interpretation of Latayan et.al. of the NE-trending structures as antithetic faults and Tibaldi et. al.'s characterization of NNE and NE structures in central Mindanao as extensional fractures

The use of magnetotelluric data for the characterization of known regional structures has been done before such as the San Andreas Fault. However, it is uncommonly used to identify relatively unknown subsurface structures. In correlation with various data sets, this paper explored the possibility of a) identifying and characterizing unknown local structure, b) correlating a resistivity anomaly with the possible distribution of an acid zone, c) identifying a regional structure by correlating regional structural trends. It is in the agreement of the different and independent datasets that reduces the uncertainty of these interpretations.

Further investigation and research is recommended to verify the interpretations discussed in this paper. A kinematic study is suggested to verify and characterize the inferred structure and further correlation with petrography, geochemistry, and reservoir data is also suggested.

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