Magnetotellurics (MT) Resistivity Signature of a Geothermal Prospect with Au-Cu Mineralization in Surigao del Norte, Philippines

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ABSTRACT

Magnetotelluric (MT) soundings were conducted in the Mainit geothermal prospect in Surigao del Norte, Philippines. This area is located in a highly mineralized district of Surigao del Norte, Philippines with abundant deposits of Au and Cu. The survey was concentrated within and around the Quaternary volcanic domes of Paco-Maniayao Volcanic Complex (PMVC). Based on the generated models, surface high resistivity values of 100-700 ohm-m were mapped within the central region of PMVC covering a maximum thickness of around 500 m. This can be associated with the younger units of the Paco-Maniayao Volcanics. The thick low resistivity layers with values of ≤15 ohm-m in the western portion of the model reflect the sedimentary deposits such as sandstone, siltstone and, more generally, clays belonging to the Tugunan Formation. Extensive outcrop of Tugunan sedimentary rocks are found as patches in the central lowlands and along the slopes of Malimono Mountains in the west and northwest of PMVC. Modeled sections show that this low resistivity layer extends to a thickness of greater than 3000 m in the west and tapers off towards the east. The increased resistivity to the east of PMVC with values of more than 40 ohm-m is related to the intrusive rocks of the older Mabuhay Volcanics. These intrusive bodies have outcrops following a NNW-SSE trend and are associated with mineral occurrences such as porphyry Au-Cu deposits found in the central region i.e. Boyongan and Bayugo mineral districts and other areas northeast of PMVC. The intrusive body is believed to be a remnant of a waning and old geothermal environment which also led to epithermal mineralization in the area.

1. INTRODUCTION

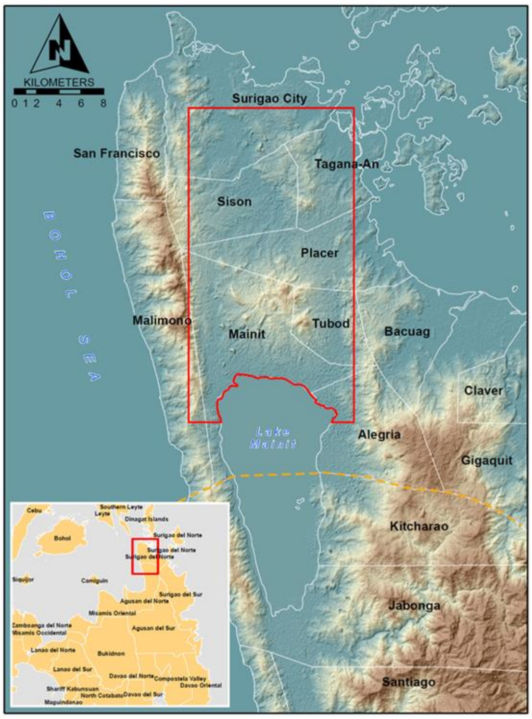

Figure 1: Location map of the Mainit geothermal prospect area.

The Mainit Geothermal Prospect is situated in northern Mindanao, southern Philippines and within the Province of Surigao Del Norte. It covers the southern part of Surigao City and the municipalities of Mainit, Alegria, Tubod, Placer, Sison and Tagana-an. Immediately south of the prospect area is Mainit Lake. Two other nearby water bodies are Bohol Sea to the west and part of the Pacific Ocean to the east. The prospect area is highlighted in red in the map below.

† Deceased August 03, 2014

Two identified Fault systems bound the prospect area. To the west is part of the Philippine Fault Zone or locally called as Mayag Anao-aon Fault. To the east is the Surigao Valley Fault. The Mainit Prospect area forms the central lowland or graben structure brought about by the simultaneous movements along these Faults. It has been identified with Paco-Maniayao volcanic cover of late Pleistocene age which is the youngest rock unit (Omac and Fermin, 2012). Within this graben is the identified Paco-Maniayao Volcanic Complex (PMVC) wherein secondary surface structure related to the formation of the volcanic centers, domes and hills were mapped. These structures, aside from the broken concentric features associated to the rim of the ancient (outer) and young (inner) caldera of the region, form a nearly NS-EW trend (Omac and Fermin, 2012).

The stratigraphic sequence of rock units in the prospect area is summarized in Table 1.

Table 1: Major formational units in Mainit geothermal prospect (after Omac and Fermin, 2012).

Formational Unit	Components	Period/ Age
Paco-Maniayao Volcanics	Andesite lava flow, tuff and pyroclastics	Late Pleistocene
Tugunan Formation with formation of the Ipil Andesite	Calcareous mudstone, shale, siltstone, sandstone and conglomerate	Late Pliocene to Early Pleistocene
Mabuhay Volcanics with intrusion of the Boyongan-Bayugo porphyry stocks and Ipil Andesite	Hornblende andesite, pyroclastics, lava flows with epiclastic rocks	Late Miocene to Early Pliocene
Motherlode Turbidite Formation with overlying Timamana Limestone	Calcareous mudstone, siltstone, sandstone and minor conglomerate	Early Miocene to Middle Miocene
Bacuag Formation	Coralline limestone, calcareous shale and intercalated basalt flows	Late Oligocene to Early Miocene
Sohoton Formation	Metamorphosed conglomerate and sandstone, marbles and shists, meta andesites, metadiabase and metamarls	Late Cretaceous
Ultramafic Basement	Serpentenized harzburgite, dunite and peroxinite	Early Cretaceous

Large portion of the graben structure is generally covered by Paco-Maniayao Volcanics and surrounded by recent alluvial deposits. Magnetotelluric survey was done on this late expression of volcanism called as Paco Maniayao Volcanic Complex (PMVC). The cluster of deposits of these volcanic units between the two major faults in the prospect area is highlighted Figure 2.

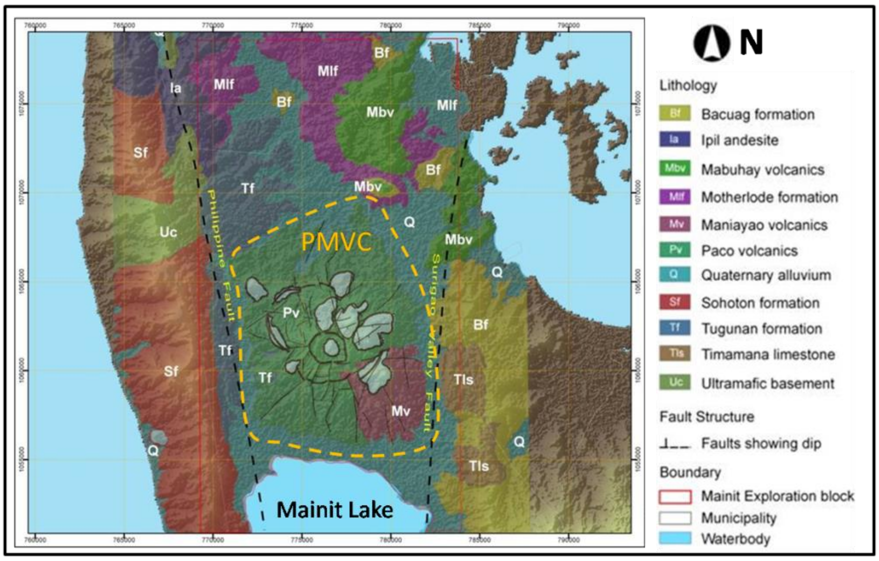

Figure 2: Geologic and structural map of the Mainit geothermal prospect highlighting the Paco-Maniayao Volcanic Complex (after Omac and Fermin, 2012).

2. MAGNETOTELLURIC (MT) METHOD

The magnetotelluric (MT) method is a passive electromagnetic technique which involves measuring fluctuations in the natural electric field and magnetic field in orthogonal directions at the surface of the Earth as a means of determining the conductivity structure of the earth at depths ranging from a few tens of meters to several hundreds of kilometers (Simpson and Karsten, 2005).

The Earth's electromagnetic field at low frequencies of <1 Hz is generated by ionospheric and magnetospheric currents caused by solar wind interacting with the Earth's magnetic field. Electromagnetic field at higher frequencies of >1 Hz is due to the thunderstorms near the equator which are distributed as guided waves between the Earth and the ionosphere. Both these electromagnetic fields are the sources of MT signals being measured. An induced electric field by a time-varying magnetic field generates an electric current in the ground. By measuring variations in magnetic and electric fields in the surface of the ground, subsurface resistivity information can be obtained (Hersir and Arnason, 2009).

2.1 Data Acquisition and Processing

A total of 96 MT stations were occupied within PMVC. MT data acquired for a single station range from around 20-40 hours using a 5-channel set-up with E_X, E_Y, H_X, H_Y and H_Z components (E and H stand for electric and magnetic fields respectively while the subscripts signify orthogonal directions with x and y along the horizontal and z along the normal axes). A fixed 4-channel MT station with E_X, E_Y, H_X and H_Y components called remote station located approximately 30 km south of the survey area was continuously and simultaneously made to record as stations were occupied in the prospect area.

Robust processing of the transformed MT time series data of E_X, E_Y, H_X and H_Y channels from the roving stations was implemented using coherency and resistivity variance parameters. This was done to reduce the effect of outlying measurements in the time series. Likewise, the magnetic data from the remote station was used to reduce the downward bias of the computed MT apparent resistivity of the roving stations produced by incoherent noise in the local magnetic field using the remote referencing method (Gamble et al., 1979). MT measurements and processing were done using Phoenix MT equipment and software.

2.2 MT Data Modeling

2.2.1 Geo-electric Strike Determination

Under the assumption of a 2D earth, subsurface resistivity generally varies along one of the horizontal and vertical directions relative to the ground. Variations along the horizontal direction is determined by what is called as geo-electric strike. In determining the orientation of this strike in the area, tipper vectors relating the horizontal to the vertical magnetic field variations from MT data were used. This relationship is represented by equation 1.

$$H_z = [T_x \quad T_y]\begin{bmatrix}H_x\\ H_y\end{bmatrix} \tag{1}$$

where H_x, H_y and H_z are magnetic field along the horizontal ground (x and y-axes) and perpendicular to the ground (z-axis) while T_x and T_y are tipper elements along the horizontal axes at any given frequency.

A horizontal contrast in conductivity across a geo-electric strike drives current to flow along this resistivity gradient. This induces a vertically-oriented magnetic field as dictated by the induction vectors. By Parkinson convention, these vectors point to a conductive region. A major geo-electric strike can be deduced when the orientation of these vectors becomes more consistently aligned at certain depth or frequency range.

This tipper strike direction will dictate the rotation of the MT impedance, **Z**, tensor given by equation 2 such that the off-diagonal elements are utilized in the consequent 2D inversion. This makes Z_{xy} parallel to the strike direction which is called the transverse electric (TE) impedance element and Z_{yx} perpendicular to this strike direction which is called as transverse magnetic (TM) impedance element. The diagonal elements of the **Z** tensor are ignored in the inversion.

$$\boldsymbol{Z} = \begin{bmatrix}Z_{xx} & Z_{xy}\\ Z_{yx} & Z_{yy}\end{bmatrix} \tag{2}$$

where Z_{ij} is the impedance element along arbitrary axes (i-axis points along the electric field line while j-axis points along the magnetic field line) at a certain frequency.

The real component of the induction vectors from the tipper information of MT data generated using the WinGLink software showed a consistent alignment roughly pointing to the west at depth associated with frequencies of 0.01 Hz and 0.1 Hz. The trend of the vectors' direction is inferred to be related to the Philippine Fault Zone which extends to the western region of the prospect area. This identified strike roughly points along the north-south axis. Thus, MT impedance tensor of all the stations in PMVC are rotated at zero degree.

2.2.2 2D MT Inversion

Sections generated for 2D inversion run parallel with the east-west axis. MT data points of up to 0.01 Hz using both TE and TM modes were inverted. Section inversion was implemented on WinGLink software using Randy Mackie's 2D inversion code with static shift included as one of the inversion parameters. All models prior to inversion were set to a homogenous resistivity of 100 ohm-m with topography considered as cut by the section lines.

2.3 Results and Interpretation

2.3.1 Previous Geophysical Findings

The shallow lateral resistivity of the prospect area was modeled using data from the Schlumberger vertical electrical soundings (VES). The model showed high resistivity values of around 100-400 ohm-m located underneath at least four domes in the area of PMVC. At lower elevation of around 100 m, low resistivity values of <10 ohm-m were seen encircling the base of the volcanoes. With the shallow data soundings obtained, it was interpreted that the area has a simplified 2-layer model: 1) a highly resistive surface layer corresponding to Quaternary Volcanic Flows, and 2) a conductive layer represented by Tertiary Sedimentary rocks (Catane et al., 1989).

There was no distinct contrast found between the outflow of geothermal fluids as manifested by the thermal springs and the resistivity of the sedimentary layer. The apparent shapes of the low resistivity layers at probed depths show no noticeable pattern associated with thermal upflow and outflow phenomena.

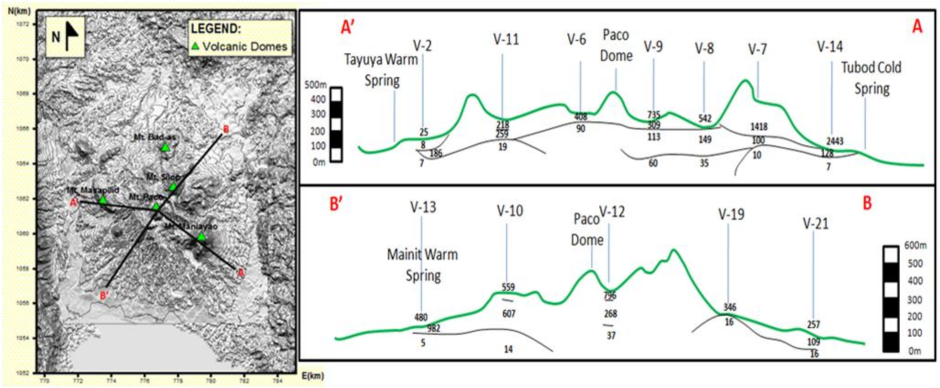

Figure 3: Resistivity cross sections from the Schlumberger vertical electrical soundings (VES) along two intersecting profile lines within PMVC (modified from Catane et al., 1989). Subsurface resistivity values are in ohm-m.

2.3.2 MT Model Findings

Based on the representative sections shown in Figure 4, high surface resistivity values of about 100-700 ohm-m were mapped. These could be associated with the young flows originating from the Paco-Maniayao Volcanics which is generally andesitic in composition (Omac and Fermin, 2012). This volcanic cover is highly prominent and thick in the central part of PMVC as seen in sections EW-5, EW-7 and EW-10 (Figure 4). And the presence of andesite porphyry cover within the Boyongan and Bayugo mineral districts (Oliveros, 2011) as intersected by EW-10 profile supports the association of high resistivity with andesites. The thick and low resistivity layer with values of ≤15 ohm-m in the western portion of all the representative sections largely reflect the sedimentary deposits such as sandstone, siltstone and, more generally, clays belonging to the Tugunan Formation. The models show that the low resistivity layer extends to a depth greater than three kilometers in the west and tapers off towards the east. Extensive outcrops of the Tugunan sedimentary rocks are found along the eastern slopes of Malimono Mountains in the west (Figure 2) and occasional patches in the central lowlands. An increase in resistivity values of >40 ohm-m which are believed to be intrusive rocks of the older Mabuhay Volcanics is observed beneath the thinner conductive layer in the eastern part of the sections. These intrusive bodies have outcrops generally located on the eastern side of PMVC (Rohrlach, 2005). EW-13 in Figure 4 confirms the surfacing of this intrusive body as shown by a continuously high resistive layer from bottom to top in the eastern half of the section. They are associated with mineral occurrences such as porphyry copper-gold deposits found in Boyongan and Bayugo mineral districts (Rohrlach, 2005). Also, a high lateral resistivity gradient was observed in majority of the sections. This was inferred to be caused by some faulting mechanism which will be discussed later.

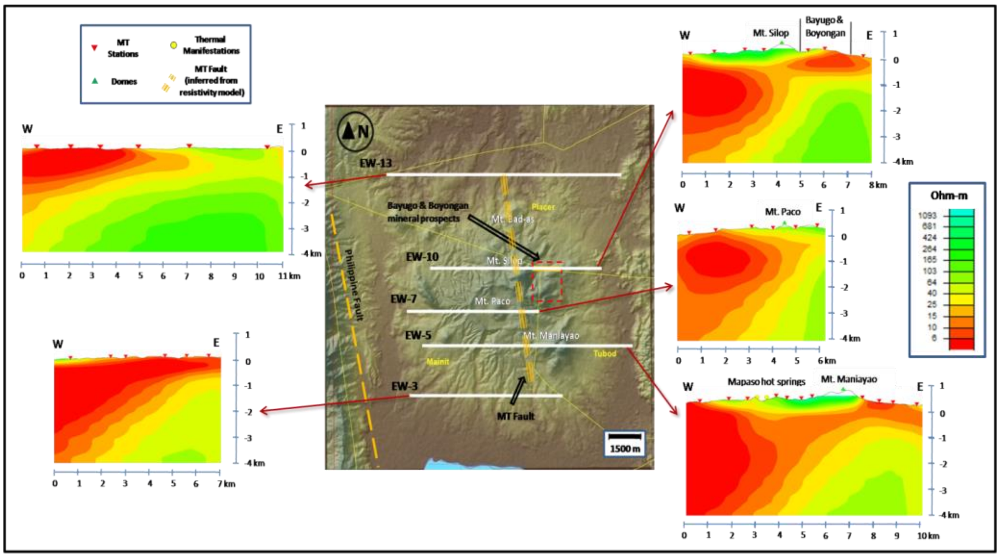

Figure 4: Major 2D resistivity sections of the Mainit Geothermal Prospect showing the inferred MT fault.

The 2D resistivity model along the EW-10 cross section in Figure 5 illustrates the correlation between the major resistivity zones with different rocks belonging to the Paco-Maniayao Volcanics, Tugunan Formation and Intrusives. Drill hole data of up to 690 m depth from Bayugo mining prospect indicate some components of the shallow low resistivity layers of the inversion model as seen in Figure 5B. The remnants of the low-temperature illite-smectite correlate with other alteration and porphyry minerals including diorite (Oliveros, 2011) are seen within the bounds of the identified low resistivity layer. From this, we also infer that part of the identified low resistivity layer from the sections may be contributed by low-temperature alteration minerals of a geothermal system. The high resistivity values starting from 15 ohm-m above the altered zone can be related to andesite.

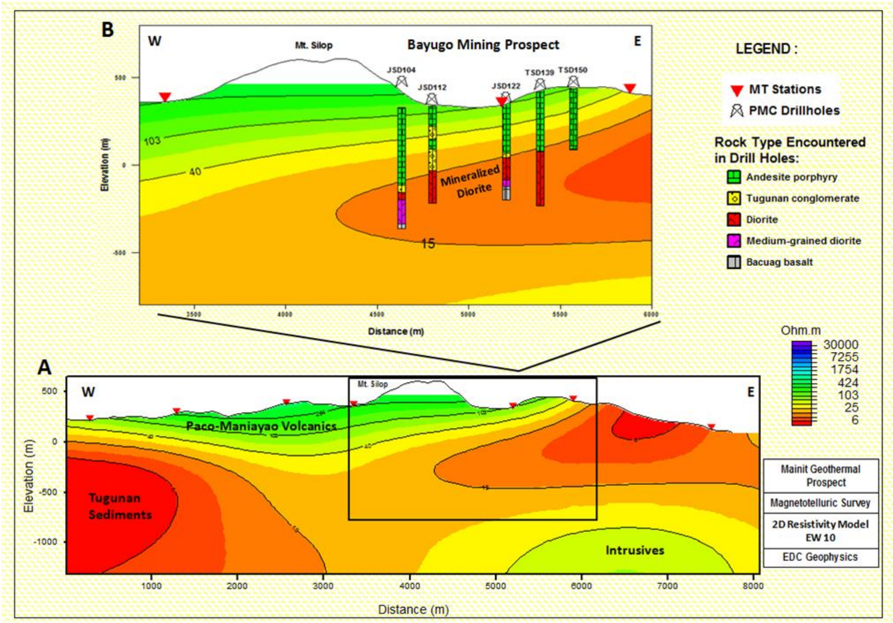

Figure 5: A) 2D resistivity model along EW-10 cross-section showing the major resistivity zones as interpreted and correlated with the different rocks found in the area such as Paco-Maniayao Volcanics, Tugunan Sediments and Intrusives. B) Enlarged view of a part of EW-10 cross-section (area inside box in A) showing five drill holes of Philex Mining Corporation's (PMC) Bayugo mining prospect. Low resistivity layer of ≤ 15 ohm-m is generally attributed to the mineralized diorite body which includes illite-smectite.

Figure 6 shows a representative isoresistivity map (1000 m below sea level) which was generated from the all the inverted 2D sections. Here, the increasing resistivity from 40 ohm-m which was associated with intrusive rocks is seen to form a single unit trending along a north-south direction in the east while the decreasing resistivity from 15 ohm-m generally associated with the sedimentary unit segregates the western side. The young volcanic cover with a thickness of up to 500 m is not present at this elevation.

Based on Figures 4 & 6, a lateral contrast between the high resistivity to the east and low resistivity to the west is distinguishable. From this observation, a major discontinuity which we call MT Fault may be inferred that divides the low resistivity layer of the Tugunan sedimentary and the high resistivity layer of Intrusive rocks. The inferred MT Fault forms a north-northwest to south-southeast orientation. This postulation can be supported by the following:

1) The presence of the north-south striking surface faults identified within the PMVC by Omac and Fermin in their geologic mapping in 2012 approximately coincides with the orientation of the inferred MT Fault,
2) The inferred MT Fault is closely parallel to the strike of the Philippine Fault transecting the area,
3) The north-northwest alignment of the young Volcanic Domes of the PMVC like Mt. Bad-as, Mt. Silop, Mt. Paco and Mt. Maniayao and the thermal springs at Trinidad and Tungao is consistent with the inferred MT Fault. These volcanic and thermal features are manifested along the inferred fault; and
4) The north-northwest to south-southeast structural control of the copper and gold deposits in the Mainit mineral district (Rorhlach, 2005) also jibes with the strike of the inferred MT Fault.

As identified above, this structure including the Philippine Fault may have played a major role in the origin of the old volcanic system related to the copper-gold mineralization as well as of the younger volcanism which is now manifested by the Volcanic Domes/Paco-Maniayao Volcanics.

Looking closely at the location and surface temperatures of the known thermal springs in the area as seen in Figure 6, we see that the thermal springs at Mapaso with temperatures of around 35-40^{o}C (Abecia, 2010) are found within the low resistivity/sedimentary zone. In addition, despite their proximity to the young Volcanic Domes these thermal springs have low surface temperatures. On the other hand, the hotter springs at Placer and Alegria with >40-53^{o}C in temperature (Abecia, 2010) are found near the high resistivity/intrusive block. Based on the resistivity model, it is more likely to happen that the heat source would come from the pre-defined high resistivity region than from the low resistivity block. Correspondingly, the receding heat from this intrusive body may warm up the thermal springs. But a structural control possibly heats up the relatively warmer Tayuya spring of around 44 ^{o}C (Abecia, 2010) in the west. The intrusive body is believed to be a remnant of a waning and old geothermal system which led to shallow epithermal mineralization in the area. (Rohrlach, 2005). This can be cited as a low-temperature geothermal system.

Although, the emerging heat from the young Paco-Maniayao volcanism may trivially contribute to the identified system since its resistivity expression is not well distinguished from the models.

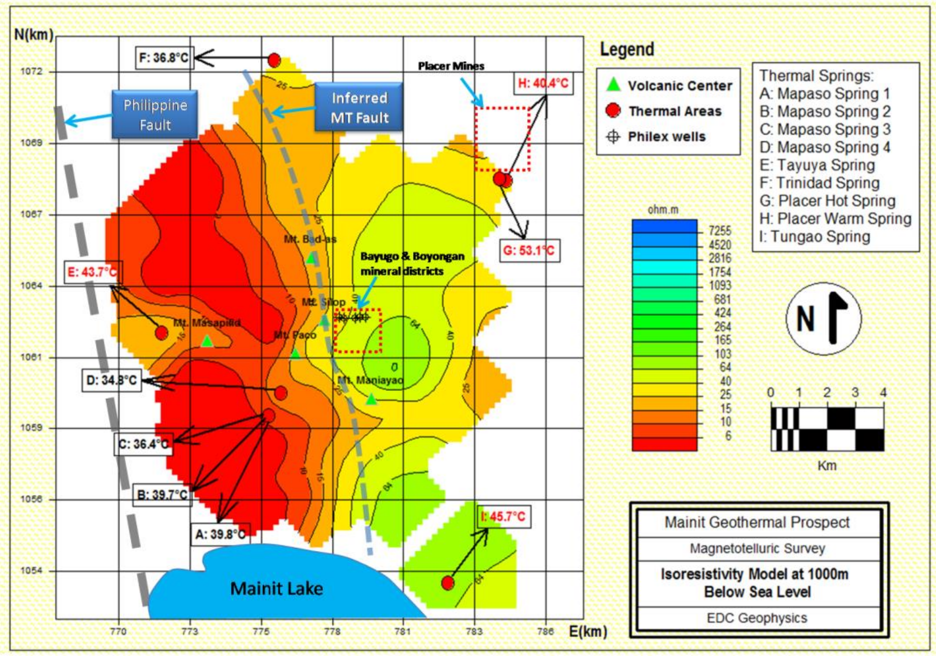

Figure 6: Isoresistivity map at 1000m below sea level showing the location of the Volcanic Domes, the Philippine Fault, the inferred MT fault which was interpreted from the MT resistivity gradient, thermal springs and their surface temperatures. Mining districts in Bayugo, Boyongan and Placer are also included.

3. CONCLUSION

High resistivity layer on the surface of PMVC is associated with the Young Paco-Maniayao Volcanics. The low resistivity layer of <15 ohm-meter is interpreted to be generally composed of the Tugunan Sedimentary Formation which is seen to be outcropping in the west and northwest of PMVC. Part of this low resistivity block may be contributed by presence of low temperature alteration minerals like illite-smectite as found in Bayugo mineral district. A bottom high resistivity layer is postulated to be the Intrusive Unit from the Mabuhay Volcanics surfacing in the northeast of PMVC. This layer is believed to have an important role in the mineralization process as manifested by the mineral deposits in Boyongan and Bayugo and other areas northeast of PMVC.

A major structure named MT Fault was inferred. This NNW-SSE fault direction is inferred based on a high lateral contrast of resistivity values from west to east bordered by the alignment of Mt. Bad-as, Mt. Silop and Mt. Maniayao as seen in the isoresistivity map starting at 1000 m below sea level. This structure including the Philippine Fault may have played a major role in the origin of the old volcanic system related to the copper-gold mineralization and to the younger volcanism which is now manifested by the Volcanic Domes/Paco-Maniayao Volcanics. The identified intrusive unit from the older volcanic system is possibly a remnant of an old and waning geothermal system as evident from the reported presence of low intensity hydrothermal alterations in Boyongan and Bayugo areas.

REFERENCES

Árnason, K. and Hersir, G. P.: Resistivity Methods- MT. Iceland Geosurvey (2009).

Abecia, V.M.: Geochemical Assessment of Mainit Geothermal Prospect, Surigao Del Norte, Philippines, Energy Development Corporation (2010).

Catane, J.P.L., Herras, E.B., and Maneja, F.C.: Geoelectric Investigations in the Surigao Geothermal prospect, Philippine National Oil Corporation Internal Report (1989).

Omac, X.L. and Fermin, M.D : Preliminary Geological Assessment of the Mainit Geothermal Prospect, Energy Development Corporation (2012).

Oliveros, N.C.: Technical Report on the Boyongan-Bayugo Deposit in Surigao Del Norte, Mindanao, Philippines, Philex Mining Corporation, Technical Report of Exploration Results and Mineral Resources (2011).

Gamble, T.D., Goubau W.M., and Clarke, J.: Magnetotellurics with a remote magnetic reference, *Geophysics*, **44**, (1979), 53-68.

Rohrlach, B.D.: Independent Geological Report on the Surigao Property Group Northern Mindanao, Philippines, MRL Gold Philippines, Inc. and Panoro Minerals Ltd (2005).

Simpson, F. and Karsten, B.: Practical Magnetotellurics, Cambridge University Press, Cambridge, UK, (2005), 254 pp.