Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

The Resistivity Model of the Mindanao Geothermal Project, South Central Mindanao, Philippines

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Keywords: MT, resistivity, Mindanao

ABSTRACT

Latest MT data of the Mindanao Geothermal Production Field (MGPF) delineated a NW-trending MT anomaly characterizing the shallow electrical basement between the western flanks of Mt. Apo and eastern slopes of Mt. Zion. This is inferred to represent the extent of the high-temperature resource (>300^{o}C) at MGPF. The northeastern segment of the MT anomaly is located within the Sandawa Collapse, where several producing wells have been drilled. On the other hand, the southeastern extension of the anomaly is still untapped and covers the area beneath Mt Zion, Lake Macadac and the southern slopes of Mt. Apo.

The ~6 km^2 to the southeast outside of the Sandawa sector is estimated to have a potential to produce about 170 MWe increasing the exploitable resource at MGPF to ~460 Mwe total reserves.

The <30-Ω-m conductive zones located around the MT anomaly signify the most likely outer margins of the resource. The prominent low resistivity region mapped in the northwest depicts the major outflows towards Agco, Imba and Marbel thermal springs. The conductive zones south and west of Mt. Zion are interpreted to be indications of possible minor outflows to the southwest towards the Bulatukan hot springs. The Kapatagan anomaly, delineated by previous SRT and VES data southeast of Mt. Apo, appears to be a signature of another outflow path to the southeast. In contrast, the MT data affirm previous interpretation about Tico anomaly located north of the study area being a shallow manifestation of relict alteration.

1. INTRODUCTION

The Mindanao Geothermal Production Field (MGPF) is located within the Mt. Apo National Park in Central Mindanao, where Mt. Apo, the highest peak in the Philippines is located (Fig. 1).

Geoscientific exploration studies consisting of geochemical, geological and geophysical methods were conducted in Mt. Apo between March 1983 and October 1984. Geophysical investigations using Schlumberger resistivity traversing (SRT) and vertical electrical soundings (VES) have identified four low-resistivity anomalies within the Mt. Apo Volcanic complex (Delfin et al., 1984): Marbel, Kapatagan, Bulatukan and Tico anomalies (Fig. 2 and Fig. 3). The better correlation of structures and thermal features in Marbel anomaly compared to the other anomalies led to exploratory drilling of APO-1D and APO-2D in 1987 and 1988, respectively. The provisional and arbitrary geothermal boundary was then approximated using SRT apparent iso-resistivity at AB/2 = 500 m and the bottom layer geoelectrical structure obtained from VES (Fig 3). After almost ten years of exploitation, a development program is being planned within the 701 hectares of geothermal reservation to tap the full potential of the geothermal resource, after recent well data show a bigger exploitable reservoir capacity than previously estimated.

2. MT SURVEY

Magnetotelluric method measures the fluctuations of the natural electromagnetic field at the Earth's surface. Data acquisition comprises simultaneous measurements of varying magnetic field and induced electric field. The relationship between these two orthogonal components gives impedance that can be expressed in terms of two important parameters viz., apparent resistivity and phase. The analysis of phase and resistivity at different frequencies yields information over a range of depth levels and provide a model for the subsurface geoelectric structure.

To assist in the re-assessment and resource management for Mindanao Geothermal Production Field (MGPF), a magnetotelluric (MT) survey, was conducted in the area. The main objective of the survey was to model the resistivity structure and delineate the extent of the geothermal resource particularly outside the southeastern section of the geothermal reservation which is vague in the previous resistivity surveys.

Resistivity data were acquired during two field seasons between December 2004 and February 2006 utilizing 2 sets of Phoenix MTU-5A 2000 acquisition system. The first survey was carried out between January 2004 and June 2005 with 114 sounding stations covering an area ~60 km^2 centered at 701 geothermal reservation (Fig 1). Additional 32 stations were occupied from October 2005 to February 2006 covering two areas, the area NW of "701" and the southern flanks of Mt. Zion and Mt. Apo.

Robust processing was carried-out using Phoenix SSMT2000 software. This included initial data editing, removing of data outliers at each frequency range and the conversion to EDI standard format. Impedance tensor rotation (principal axis) and 1-D/2-D modeling were calculated using the WinGLINK software.

3. RESULTS

Isoresistivity maps at different elevations were derived using 1-D Occam inversion of all TE mode curves (Fig 4). These were constructed to show vertical variations of true resistivity at four different elevations between 500 m and –1000 m.

A moderately high resistive body (>50 Ω-m) was mapped at an elevation of 500 m beneath Pad-C and Pad-H within the Sandawa collapse (Fig 4A). At deeper levels (0, -500 and –1000 m), the NW-trending shallow electrical basement, also referred to as the MT anomaly, expands farther south beneath Mt. Zion, Lake Macadac and the southern slopes of Mt. Apo (Figs 4B, 4C and 4D).

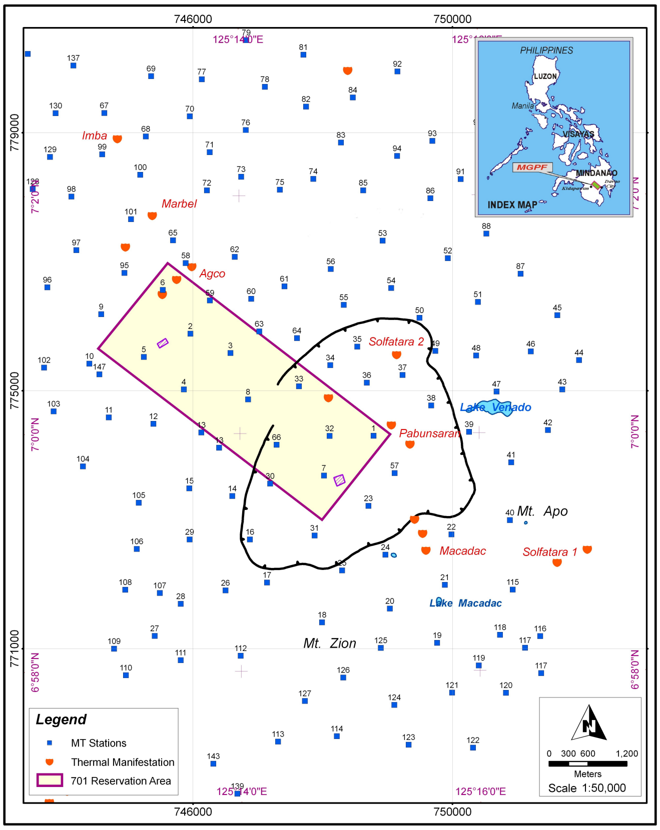


Figure 1: Location map of MGPF and MT stations

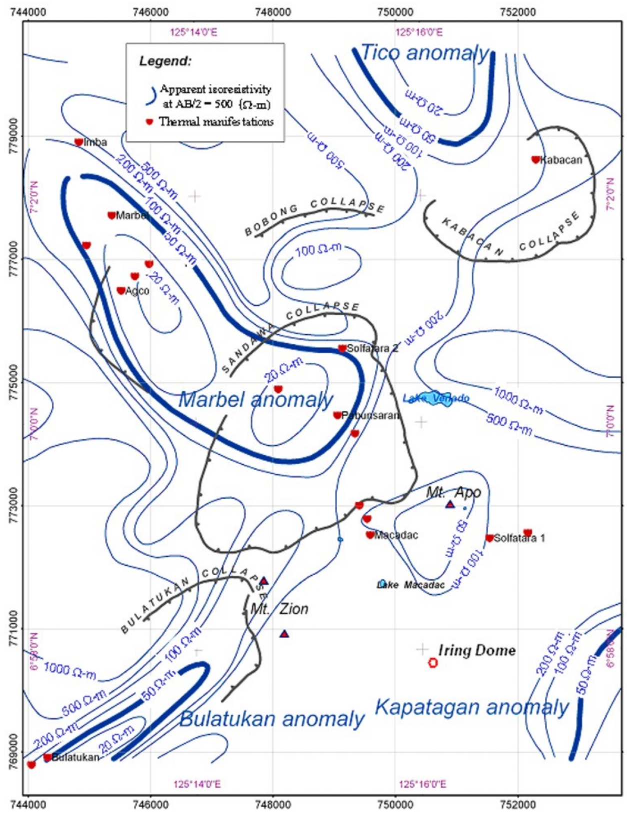


Figure 2: Apparent isoresistivity map at AB/2=500 m based on SRT (Delfin et al., 1984)

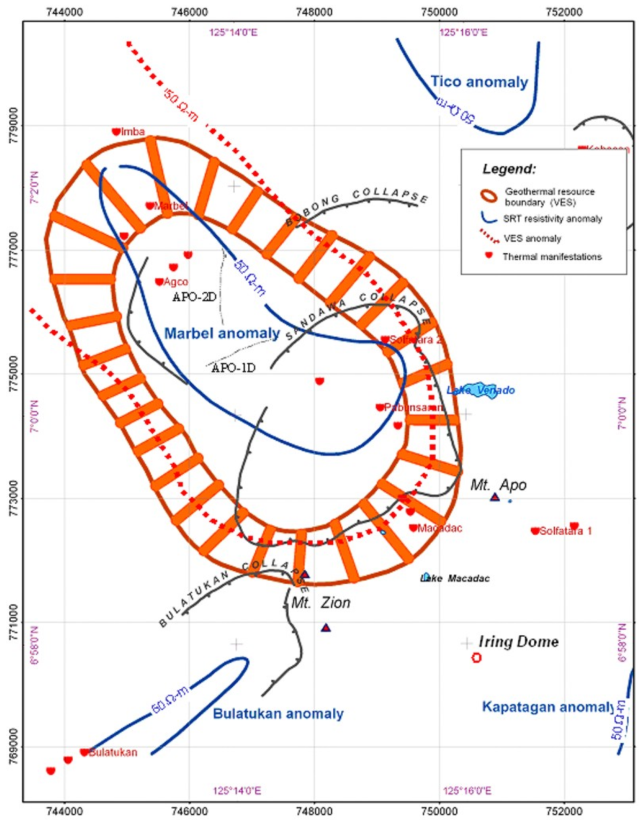


Figure 3: Provisional geothermal resource boundary derived from VES and SRT data (Delfin et al., 1984)

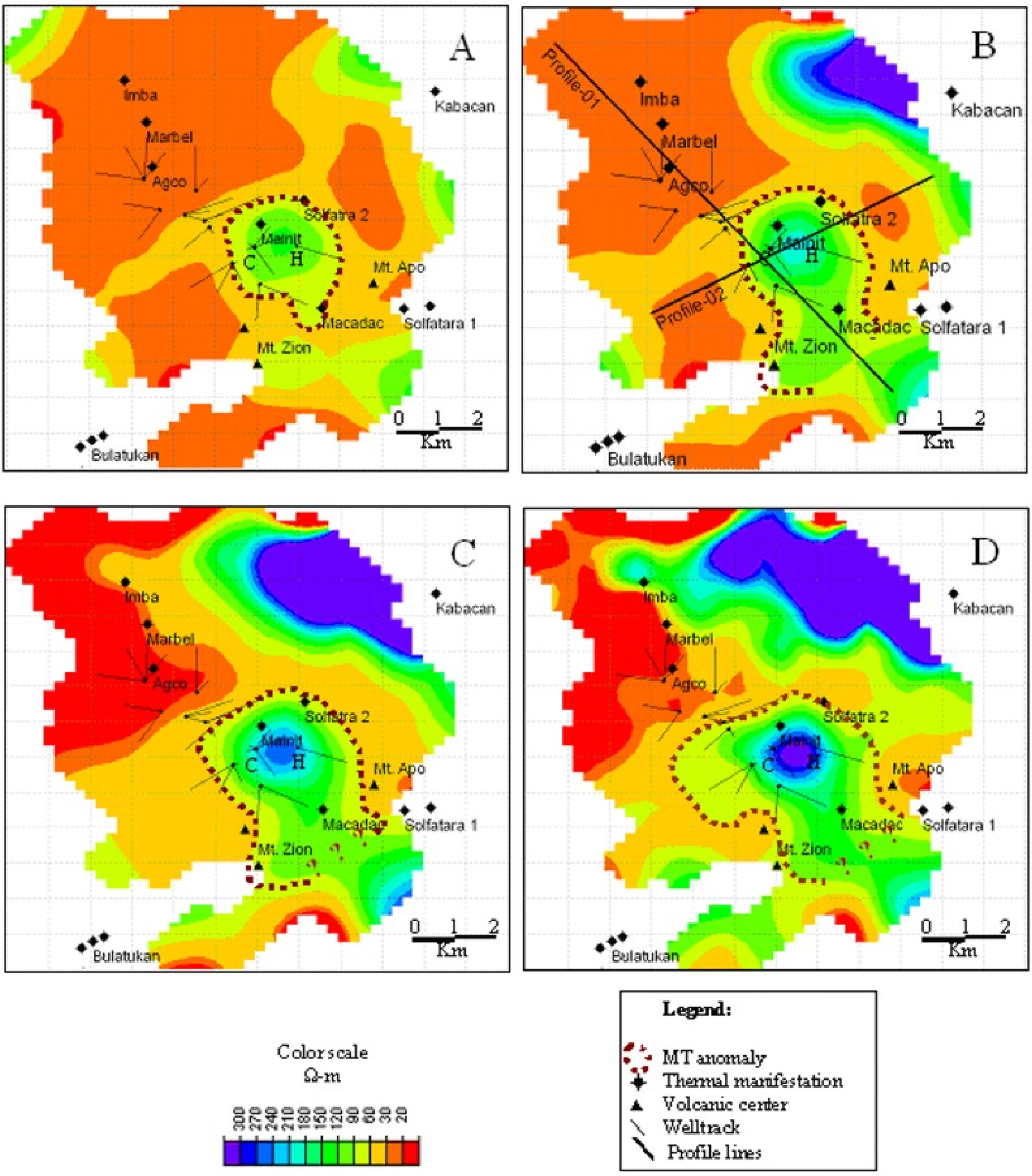


Figure 4: Isoresistivity map at different elevations A) 500 m, B) sea level C) -500 m and D) -1000 m

The anomaly is surrounded by four <30 Ω-m conductive zones (Fig 4A and Fig 4B), the most prominent of which was delineated along the NW sector towards Agco, Marbel and Imba thermal springs. Two conductive zones west and south of Mt. Zion lie close to the Bulatukan thermal springs. A relatively small but similarly conductive area was plotted north of Mt. Apo.

At -500 m elev. (Fig 4C), a conspicuous NW-trending resistivity gradient separates the MT anomaly from the highly resistive >300 Ω-m northeastern block located near the Kabacan thermal spring. Two profile lines derived from 2-D modeling (Fig. 5), illustrate the geoelectrical structure within Mt. Apo geothermal system.

Profile 01 cuts across the thermal springs of Agco from the NW to Lake Macadac in the SE. The conductive layer in this profile is thickest in the NW beneath Agco (>2000 m) and thins out to ~1000 m towards the SE overlying the resistive basement, which is referred to as the MT anomaly. The shallowest portion of the resistive layer is found beneath the area between Pad H and Lake Macadac at eleveof about 500 m, RSL.

Profile 02, which runs perpendicular to P01, is capped by a ~200 m-thick highly resistive surface layer. At the center of the profile is the MT anomaly, which is shallowest beneath Pads C and H. Both ends of this profile exhibits ~2000 m-thick conductive second layer.

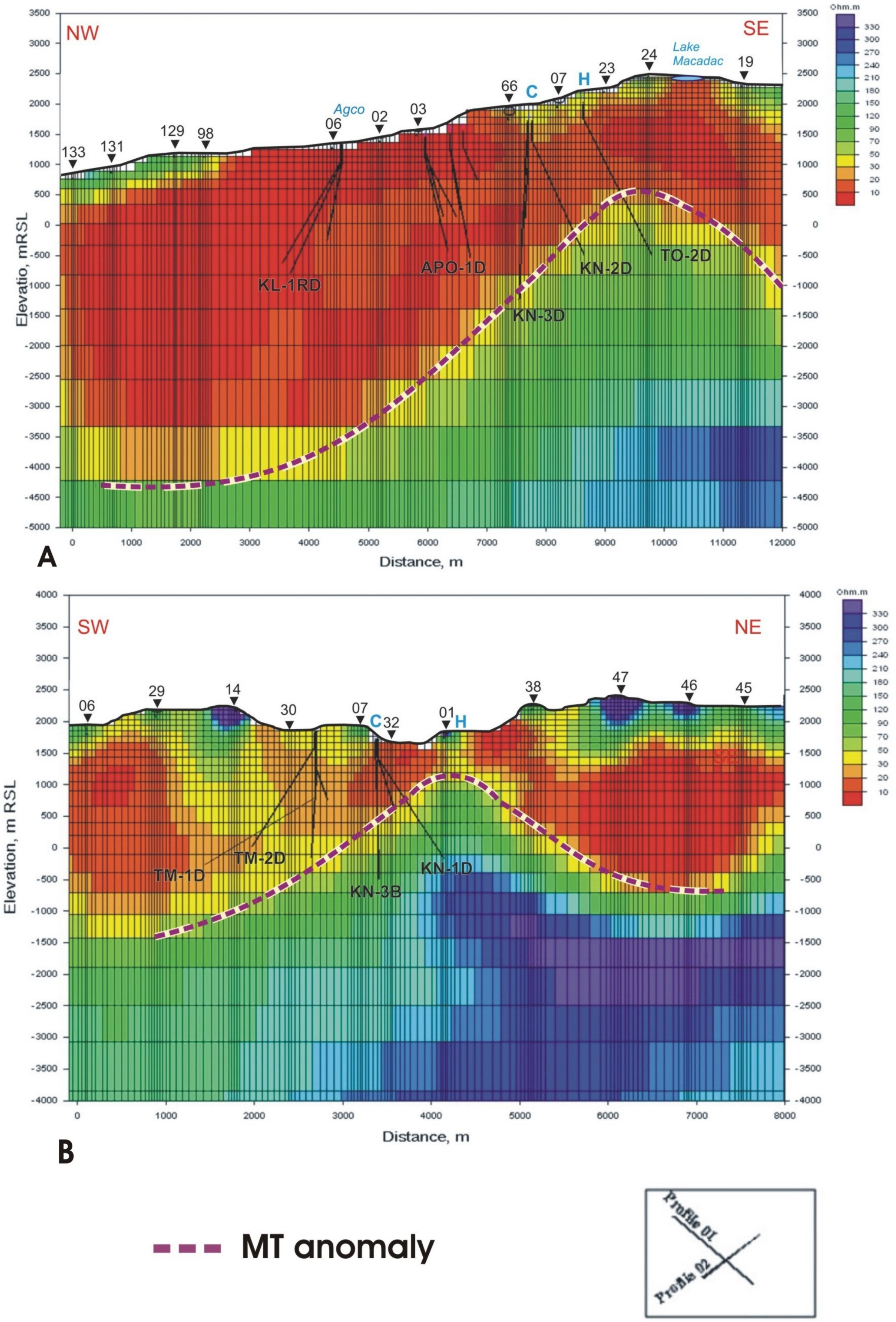


Figure 5: 2-D resistivity models along A) P01 and B) P02

4. CORRELATION OF MT DATA AND SUBSURFACE INFORMATION

The subsurface stratigraphy of M1GP is shown in Figure 6 (Gonzales et al., 1994). The youngest unit is the Apo Volcanics (AV), which is subdivided into a younger (yAV) and an older (oAV) member. The yAV is confined mainly to the Mt. Apo peak while the oAV is composed of the dissected and eroded lower flanks. Petrographically, the oAV is subdivided into an upper (oAVu) and a lower (oAVl) sequence. Their contact is marked by a hematized claystone, which is 15 m thick in Kullay, and interpreted to be a paleosol. The oAVu is generally composed of hornblende andesite, dacite and minor pyroxene basaltic andesite lavas, tuff breccias and minor hyaloclastites.

Drilling in M1GP encountered three (3) more rock formations namely: Sabpangon Sedimentary Formation (SSF), the Contact Metamorphic Zone (CMZ) and the Sandawa Intrusive (SI).

The SSF is composed of carbonaceous sandstone, siltstone and rare limestone intercalated with hyaloclastites and intersected only in well AP-2D.

The CMZ was intersected by at least four (4) wells, namely KN-1D, KN-2D, KN-3D and SK-6D. The CMZ is completely altered to a hornfelsic mosaic of biotite + actinolite + quartz.

SI refers to the younger intrusives composed of relatively fresh, coarse-grained biotite-hornblende quartz monzodiorite possibly cut by andesitic and dacitic dikes. The configuration of the SI is thought to have an irregular outline mirrored by the CMZ, the latter making the "chilled zone" caused by the intrusion of the SI. Apparently, the SI, which is confined within the Sandawa Collapse, is younger than the oAVl.

Figure 7 shows the comparison of the resistivity model (Profile 01 in Fig 5) with measured temperatures, lithology and occurrences of clay alteration minerals based from well data. The modeled MT anomaly coincides with the same area of elevated temperatures (>260°C) and shallow intersection of the Sandawa Intrusive and Contact Metamorphic Zone. The steep resistivity gradient below station 66 coincides with the abrupt drop in measured temperatures and the absence of CMZ.

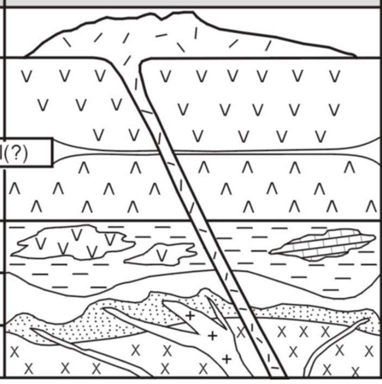
FORMATION			STRATIGRAPHIC COLUMN	DESCRIPTION	Max. Thick (m)
Apo Volca-nics (AV)	Young (yAV)			Summit domes and lakes; found as microdiorite dikes in APO-1D and APO-2D	5
	Old (oAV)	Upper (oAVu)		Hornblende andesite, dacite and minor pyroxene basaltic andesite lavas, tuff breccias and minor hyaloclastites	
		Paleosol(?)		Hematized claystone	15 (Kullay)
		Lower (oAVl)		Basaltic andesite to basalt and minor pyroxene andesite lavas, tuff braccias and hyaloclastites	
Sabpangon Sedimentary Formation (SSF)				Carbonaceous sandstone, siltstone and rare limestone intercalated with hyaloclastites	610; only in Apo-2D
Contact Metamorphic Zone (CMZ)				Completely metamoprphosed volcanics(?) with honfelsic texture	
Sandawa Intrusive (SI)				Relatively fresh biotite hornblende quartz monzodiorite; cut by andesitic/dacitic dikes (?)	

Figure 6: Stratigraphic column at MGPF

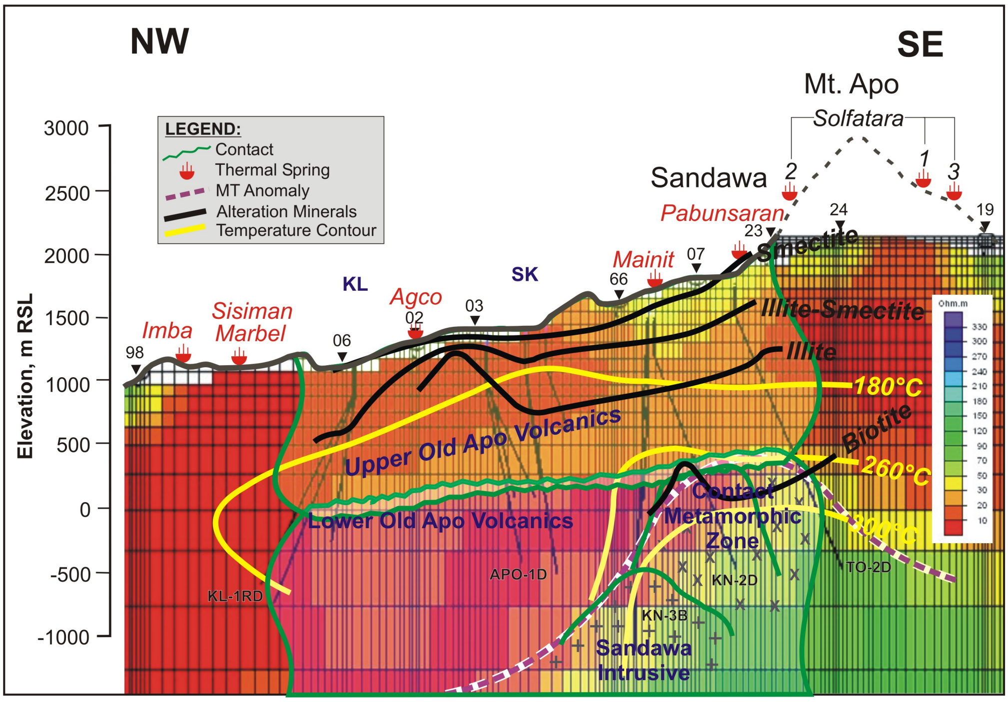


Figure 7: Correlation of resistivity structure with well data

The thickest <30 Ω-m conductive zone to the northwest is consistent with the major outflow region where temperature reversal is measured in well KL-1RD.

5.0 MT MODEL OF THE MINDANAO GEOTHERMAL SYSTEM

The NW-trending MT anomaly defined by the >50 Ω-m shallow resistive basement at sea level most likely approximates the extent of the high temperature region of Mindanao hydrothermal system (Fig 8). The northern half of the anomaly coincides with the zone of elevated temperatures exceeding 300^{0}C and shallow intersection of the Contact Metamorphic Zone and Sandawa Intrusives. The southern end of the anomaly is delineated beneath Mt. Zion and Lake Macadac. This includes the southern flanks of the peak and is inferred to be a mirror image of the northern half high temperature contour. This untapped southern region covers an area of ~6 km^2.

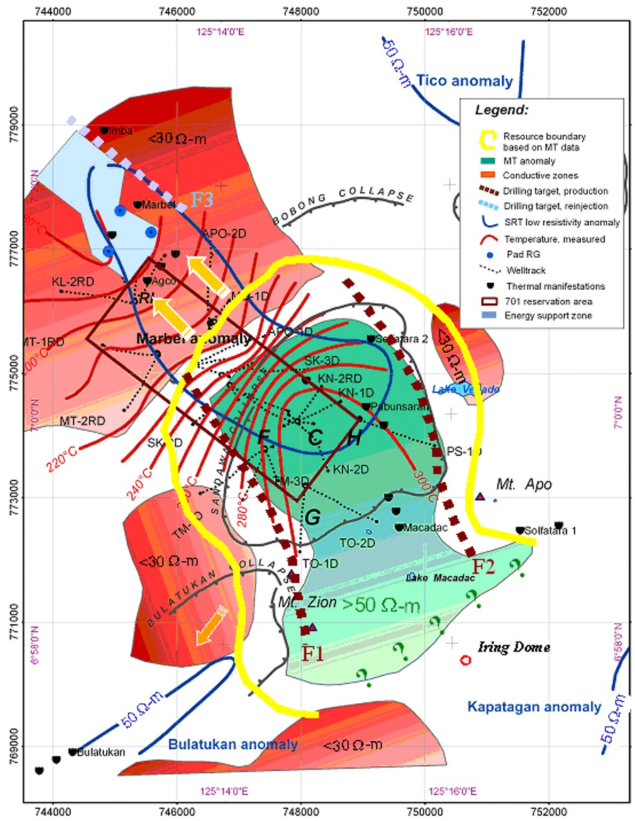


Figure 8: Resistivity model of MGPF

Based on the estimated 29 MWe per km^2 power density within the Sandawa sector (Esberto, 2006), the newly delineated resource area outside of the Sandawa sector has a potential of an additional ~170 MWe. This increases the possible total exploitable resource estimate at MGPF to ~460 MWe.

The <30-Ω-m conductive zones located around the MT anomaly signify the most likely outer margins of the resource. The widespread low resistivity region mapped in the NW characterizes the major outflows towards Agco, Imba and Marbel thermal springs. The conductive zones south and west of Mt. Zion are indications of possible minor outflows to the SW towards the Bulatukan hot springs. The Kapatagan anomaly, delineated by SRT and VES southeast of Mt. Apo, appears to be a signature of another outflow path to the southeast.

The Tico anomaly, identified by SRT and VES as near-surface anomaly was interpreted as surface manifestation typical of relict alteration (Delfin et al., 1989). This interpretation is supported by MT data which show that the area is underlain by highly resistive formation even at shallow depths and overlain by low resistivity material with probable thickness of <100 m. The underlying highly resistive formation is probably associated with massive volcanic or basement rocks that are natural good insulators.

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