Study of Acid Zone Delineation in Mataloko Geothermal Field Using Total Conductance Method

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Abstract. Mataloko geothermal field is located in Ngada Regency, East Nusa Tenggara, is one of geothermal field that has been built and operated by the State Electricity Company (PLN) with a capacity of 2,5 MW. Several manifestations in Mataloko are acidic, for example in Wae Luja Hot Stream with pH 2,92 and Wogoalo Hotpool 2 with pH 4. Gas composition in NCGs informs that H_2S gas content in MT-4 well is relatively greater compared to other wells. Geological logging data also shows that all wells in Mataloko contains acidic alunite minerals (pH <4) at a depth of 300-350 m. Such information indicates that the geothermal fluid in Mataloko is acidic. Mitigation of geothermal fluid acidity needs to be carried out because it can cause several problems in the future, such as causing corrosion in power plant infrastructure, production problems and environmental problems. The distribution of acidic fluid in Mataloko can be predicted using Total Conductance method with an electrical conductivity approach, so that when drilling is carried out, areas with acidic fluid content can be avoided. The results of this study show that the acid zone in the Mataloko geothermal field has a value of Total Conductance >±700 Mhos.

Keywords: *geothermal, acid fluid, mataloko, alunite mineral, total conductance, acid zone delineation.*

1. Introduction

Wae Luja Hot Stream in Mataloko geothermal field is located at the elevation of 1003m. Wae Luja river stream is heated by the manifestations, resulting in higher temperature with gas bubbles appear in the water. The temperature ranges from 72 to 91°C, with a pH of 2.9 to 3.0, TDS of 442 to 763 ppm, and EH of 292.6 to 352.0 mV. The boiling stream appears muddy, with moderate to thick H_2S odor. Then Wogoalo Hot Pool 2 is described as hot pool with the appearance of drying mud formation on the rim, moderate to high H_2S odor. The TDS reading is 387 ppm, with pH 4 and EH of 207 mV [1]. Chemical composition of dissolved gas phase (SCS) of MT-4 well generally shows a small concentration, but for concentration of NH_4^- and SO_4^{2-} is relatively larger compared to MT-2 and MT-3 wells. This condition can also be seen from the gas composition in NCGs, where the H_2S gas content in MT-4 well is relatively

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larger compared to other wells. This indicates that the MT-4 well fluid is acidic [2].

Previous study that have been done in Dieng informs three areas in Dieng geothermal field, Sileri, Sikidang-Merdada, Pakuwaja area have gravity and magnetotelluric (MT) anomalies show a conductance of >1.000 Mhos [3]. DNG-1 well (Sikidang) is an acid-chloride fluid. The fluid from the well shows a mixture of chloride and sulfate water at a certain depth. In addition, the fluid is likely formed by the oxidation process of H_2S in chloride water, condensation of volcanic gases into meteoric water and condensation of magmatic vapor at a certain depth. Isotope ratio value of ^{18}O in the DNG-2 and DNG-8 wells in Sikidang enriched ranges from 2-4% approaching andesitic water or magmatic water which indicates a mixture of meteoric water with magmatic water and can also indicate that the area has acidic fluid [4]. Acid alteration is characterized by jarosite, alunite, natroalunite, alunogen, pyrophyllite, zunyite, diaspores, sulfur, and kaolin (e.g. halloysite, kaolinite, etc.). Well C in Dieng geothermal field has acidic fluid as evidenced by the presence of zunyite and alunite at a depth of ~1600m [5].

Research on acidic fluids in the Mataloko geothermal field has never been done before. Mitigation of geothermal fluid acidity needs to be done because it can cause several problems in the future such as causing corrosion to power plant infrastructure, production problems and environmental problems. Based on the research literature on acidic fluid in Dieng geothermal field that has been explained previously in the paragraph above, it can be predicted that there are acidic fluids with indications of high Total Conductance value anomalies and the presence of acidic mineral alteration such as zunyite and alunite. Therefore, from this study, it is expected that the prediction of the existence of an acid zone can be done by delineating the acid zone by making an estimated map of the distribution area of acidic fluids using the Total Conductance method.

2. Material and Method

2.1 Study Area

2.1.1 Regional Structure

Based on satellite image interpretation (Figure 1), structural elements in the Bajawa area and its surroundings have north-south and north-south-southeast shear fault directions. However, most of the faults in the area approach the north-south direction. Therefore, the structure with the north-south-southeast direction consists of echelon lines formed by the north-south sinisterly shear. However, extensive and regional topographic analysis shows strong northeast-southwest trending lines and less clear and more localized north-south trending lines. This may indicate that the north-south trending rift zone accompanied by the east-southwest trending line/fault has the potential to form as a result of the northeast-southwest trending shear zone. Flores Island has 8 active volcanoes, with some of them closely correlated with caldera collapse events. The volcanoes are Anak Ranakah (part of the Poco Leok volcanic complex), Inerie, Inelika, Ebulobo, Iya, Kelimutu, Egon, and Lewotoi Volcano. The earliest volcanic eruptions occurred at Anak Ranakah (1987), Lewotobi (1992), and Inelika (2001) [1].

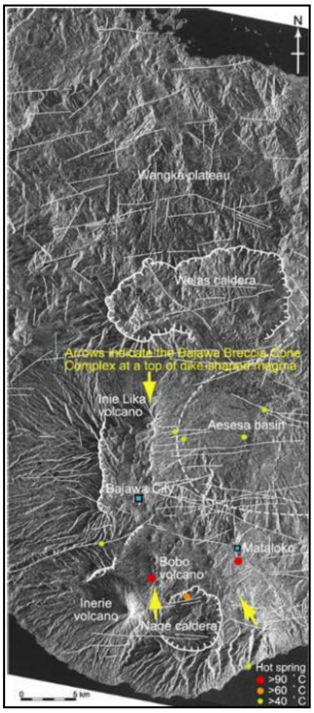

Figure 1JERS-1 SAR image of the Bajawa area (taken on 3 February 1996) including analysis results of lineaments, calderas, fracture zones, and other features (Muraoka et al., 2022)

2.1.2 Regional Stratigraphy

In the northern part of Bajawa, Tertiary rocks can be divided into three formations (Koesoemadinata et al., 1981) which were later refined by (Muraoka et al., 2002) into three groups according to the geological time scale, namely Miocene, Pliocene, and Quaternary. In the Miocene, the stratigraphy consists of the Nangapanda Formation (Np) with tonalite intrusion (Rt) as the bedrock.

Continued by the Pliocene episode which includes the Wangka Andesite (Wn) in the north and the Maumbawa basalt (Mb) in the south as well as products in the form of Welas Tuff (Wt), Waebela Basalt (Wa), Aesesa Formation (Ae), Matale Limestone (Mt), and Mere Basalt (Me). Quaternary rocks consist of Sasa Andesite (Ss), Aimere Scoria Flow Deposits (As), Siutoro Andesite (Si), Lahar Deposits (Lh), Bajawa Coal Cone Products (Mataloko Andesite (Mk), Bobo Andesite, and Inie Lika Andesite (Ik), Inieri Basalt (Ie), and Alluvium (Qa). The Mataloko Geothermal Working Area is covered by Mataloko Andesite (MT) and Alluvium (Qa) in the northern part. Mataloko Andesite (Mt) is part of the Bajawa Coal Cone Complex which was deposited during the Pleistocene [1].

2.2 Material

2.2.1 Primary Data

In this study, the primary data used were sourced from *Laporan Akhir Survei Geosains Tambahan Wilayah Kerja Panas Mataloko, PT. PLN Kantor Pusat* [1].

2.2.1.1 Water and Gas Geochemistry

Manifestation data used are mainly related to acidic properties (Table 1). Analysis is carried out by mapping the manifestation of water that has an acidic pH. Then testing is carried out in the laboratory to see the results of NCGs contained in the gas manifestation sample. While the available well data used are mainly related to acidic properties especially in well MT-4 (Table 2). Analysis is carried out by looking at the gas composition in NCGs, especially the H_2S gas content in exploration wells.

Table 1 Elemental analysis of thermal waters and meteoric waters at the Mataloko Geothermal Field (PT. PLN (Persero), 2020)

Name		Wae Luja Hot Stream	Wogoalo Hotpool 1	Wogoalo Hotpool 2	Matawae Warm Spring	Wogo Cold Spring 1	Wogo Cold Spring 2	Mata-wae Cold Spring	Reko River	Soge Cold Spring	Dada-wea Cold Spring
Elevation	(m)	1004	1038	1033	1057	1068	1073	1109	799	1301	1190
Temp	(ºC)	91	55.6	94.5	35.3	24.9	25.5	31.5	23.4	23.3	18.3
pH		2.92	5.8	4	6.35	6	6	6.5	8	6.52	7
Field TDS	(mg/kg)	763	195	387	192	98	196	144	10	120	90
Na		21	14	35	27	16	15	14	15	11	11
K		12	3	5	8	4	4	6	5	5	4
Ca		16	26	65	44	28	29	37	26	29	26
Mg		14	8.6	22	22	9.8	9.7	16	10	10	8.1
Cl		1	2	1	1	1	2	1	1	11	2
B		0.4	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
F		0.1	0.1	0.1	0.2	0.2	0.1	0.3	0.1	0.2	0.1
SO4		749	51	391	16	19	13	20	29	9	5
NH4		25	1	12	0.01	0.1	0.1	0.1	0.1	0.1	0.1
HCO2		1	113	1	330	143	175	230	143	130	158
SIO2		5	53	78	76	58	59	64	18	42	59
As		0.001	0.001	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Li		0.001	0.001	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Calc. TDS		934.52	271.82	610.32	524.42	279.22	307.02	388.52	247.32	247.32	273.42

Table 2 H_2S and NCGs chemical composition of well MT-4 (PT. PLN (Persero), 2020)

Year	Month	Well	H_2S (mol%)	Total NCGs (mol%)
2005	Jun-Jul	MT4	2.543	3.7
2006	Jul	MT4	2.732	3.66
2006	Jul	MT4	3.982	4.52
2006	Sep	MT4	2.925	4.1
2006	Oct-Nov	MT4	4.865	3.7
2006	Nov-Dec	MT4	3.306	2.72
2011	Nov	MT4	5.957	
2012	Feb-Mar	MT4	4.46	1.82
2012	Sep	MT4	8.06	1.7
2012	Nov	MT4	3.45	4.02
2013	Mar	MT4	13.26	2.21
2013	Aug-Sep	MT4		0.01
2013	Nov	MT4	0.816	0.59
2014	Apr	MT4	3.103	2.21
2014	Aug-Sep	MT4	21.56	2.04
2015	May	MT4	12.2	2.29
2015	Jul	MT4	0.487	0.13
2015	Sep-Oct	MT4		

2.2.1.2 Logging Geology

The geological logging data needed is primarily data that can show mineral alteration related to acidic properties (Figure 2). The analysis is carried out by looking at the depth at which acidic mineral deposition occurs in the Mataloko geothermal field rock formation.

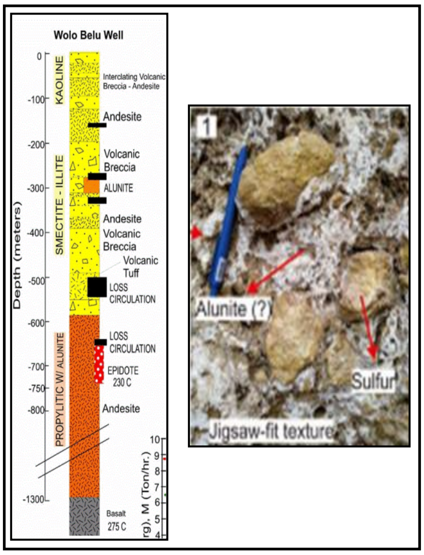

Figure 2 Logging geology and alunite mineral alteration in Mataloko Geothermal Field (PT. PLN (Persero), 2020)

2.2.1.3 Magnetotelluric

The geophysical data needed is mainly magnetotelluric data to calculate the Total Conductance value. The magnetotelluric data used uses the EDI file format (.EDI) and is obtained from *Laporan Akhir Survei Geosains Tambahan Wilayah Kerja Panas Mataloko, PT. PLN Kantor Pusat* [1].

2.3 Method

2.3.1 Research Methods

In general, this research was carried out in stages starting from preparation stage, data acquisition stage, data preprocessing and analysis stage and completion stage as in the flow chart below.

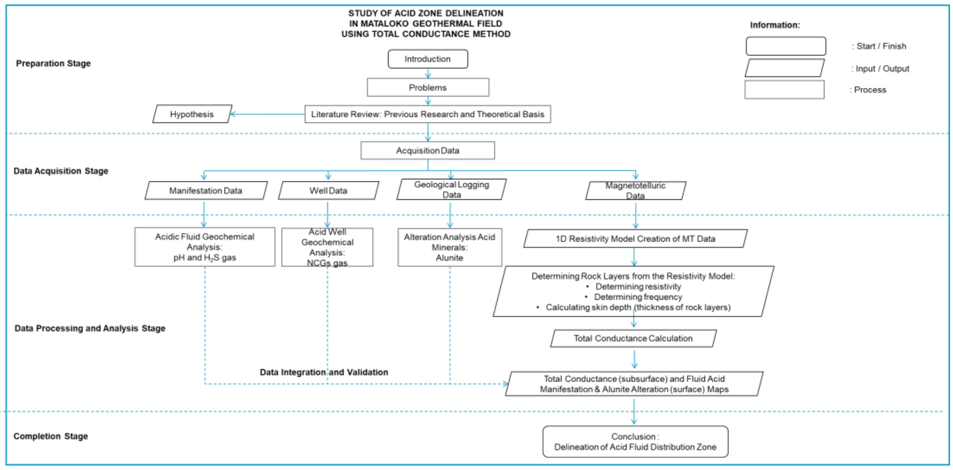

Figure 3 Research Method

2.3.2 Acid Fluid Geochemistry

Processes that occur in a geothermal system are closely related to the conditions and chemical equilibrium of the circulating fluid and the medium through which it flows. Therefore, the chemical composition of the fluid flowing to the surface on surface manifestations or in production wells carries information about geothermal resources in the reservoir. Chemical composition of the fluid can present the characteristics of the geothermal reservoir, including the type of fluid, the origin of the fluid, the estimated temperature in the reservoir, the boundaries of the reservoir, the gas content, and other things that hinder the use of geothermal resources, such as scaling and acid fluids [4].

2.3.2.1 Water Geochemistry

Ternary diagram Cl-SO_4-HCO_3 to determine the type of geothermal fluid and its characteristics. If the fluid is acid sulfate water, it is likely that the fluid was formed by the condensation process of geothermal gases near the surface and experienced oxygenation with surface water. These geothermal gases, including steam and other volatiles, are regionally isolated in deep fluids but separated from chloride water through a boiling process. This hot water has an acidic pH and very low chloride and bicarbonate content. Sulfuric acid water is located on the boundary of the area and is not far from the main upflow area. Classification of fluid types is made using the ternary diagram method, which compares several chemical parameters of water with different properties. Cl-SO_4-HCO_3 is a major anion in geothermal fluids. Cl-SO_4-HCO_3 diagram is used as a basic classification of water dominance types and to identify water samples that best represent reservoir conditions [4].

2.3.2.2 Gas Geochemistry

High hydrogen sulfide (H_2S) is often an indicator of acid in geothermal fields. H_2S is a gas that usually appears in geothermal systems, especially in reservoirs that have acidic fluid characteristics. H_2S is usually produced from volcanic and hydrothermal activities. High H_2S content in geothermal fluids can indicate the presence of an active heat source or interaction between hot water and sulfur-containing rocks. H_2S is often a characteristic of geothermal fields that have acidic fluid properties, especially in fields with high temperatures. When H_2S dissolves in water, it can form sulfuric acid (H_2SO_4) which increases the acidity of the fluid. This condition is often found in geothermal fields associated with active volcanic systems [4].

2.3.3 Alteration of Acid Minerals

The presence of alunite and jarosite is a strong indication of an acidic fluid zone in a geothermal system. Alunite and jarosite dissolution has an important influence on the pH of contacting waters. In materials that contain negligible neutralizing capacity, final pH values can be as low as 4. The most acidic pH values often coincide with the relationship between alunite and jarosite dissolution and precipitation of relatively crystalline hydroxides (gibbsite and crystalline $Fe(OH)_3$) [6]. Acid-SO_4 and acid SO_4-Cl waters both produce advanced argillic hydrothermal alteration characterized by the presence of alunite with a kandite at low temperatures and pyrophyllite and diaspore at higher temperatures [7].

2.3.4 Total Conductance

Electrical properties of rocks are the characteristics of rocks when an electric current is passed through them. Rocks in nature can be considered as an electrical medium like an electrical conductor wire. Electronic conduction occurs if rocks or minerals have many free electrons so that electric current is passed through the rocks or minerals by these free electrons. This electric current is also influenced by the nature or characteristics of each rock it passes through. One of the properties or characteristics of rocks is resistivity (resistance type) which indicates the ability of the material to inhibit electric current. The greater the resistivity value of a material, the more difficult it is for the material to conduct electric current, and vice versa [8].

Magnetotelluric method is a technique for imaging the electrical conductivity and structure of the Earth, from the near-surface down to the 410 km transition zone and beyond [9]. Diagrammatic three-layer apparent resistivity curves are used in geophysical exploration, particularly in magnetotelluric and electrical resistivity methods. The curves represent the apparent resistivity variations with depth, derived from a model consisting of three subsurface layers with different electrical resistivity values. If the resistivity is low, its indicates conductive materials [10].

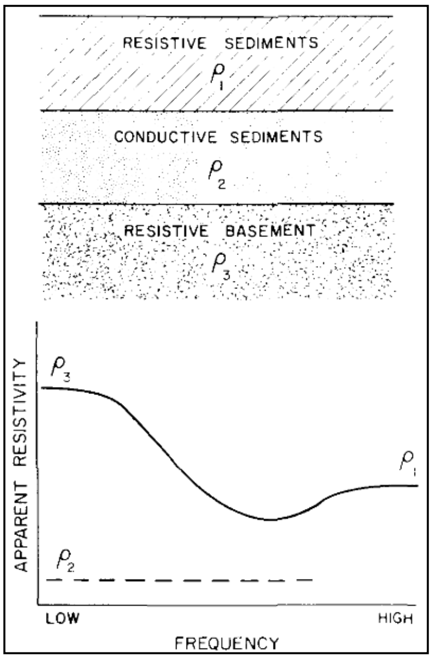

Figure 4 Digarammatic three-layer apparent resistivity curve for the model shown (Vozoff, 1972)

The concept of conductance helps to relate the thickness of a layer to its conductivity, and can be used to model resistivity. In the magnetotelluric method, the skin depth formula is used to calculate the penetration depth of the electromagnetic field into the earth, which is affected by the resistivity of the rock and the frequency of the applied field. In a uniform conducting medium, the length scale for electromagnetic induction is the skin depth, which is the distance over which the electromagnetic field decays by 1/e ≈ 0.37, in SI units can be [9]:

$$\delta = 503\sqrt{\rho T}$$

Where,

δ = skin depth (meter)

ρ = resistivity (Ωm)

T = period (second)

Total Conductance integrates both resistivity and thickness to quantify a layer's overall electrical conductivity. A thin layer with low resistivity or a thick layer with moderate resistivity can both yield high S, making it a valuable metric for distinguishing highly conductive layers [9]:

$$S = \frac{\delta}{\rho}$$

Where,

S = Total Conductance (Mhos)

3. Results and Discussion

3.1 Acid Fluid Geochemistry Analysis

3.1.1 Water Geochemistry Analysis

Based on the Table 1 and diagram on Figure 5, manifestations of Ratogesa Crater, namely Wae Luja Hot Stream and Wogoalo Hot Pool 2, are classified as acid sulfate water with pH 2,92 and 4. On a flat terrain system, the presence of acid-sulfate water points to the edge of the upflow zone [11]. Acid sulfate water is a product of the steam heating process, in which shallower aquifer is heated by steam ascending to the surface through the process of boiling [12]. Thus, having a very low content of Cl.

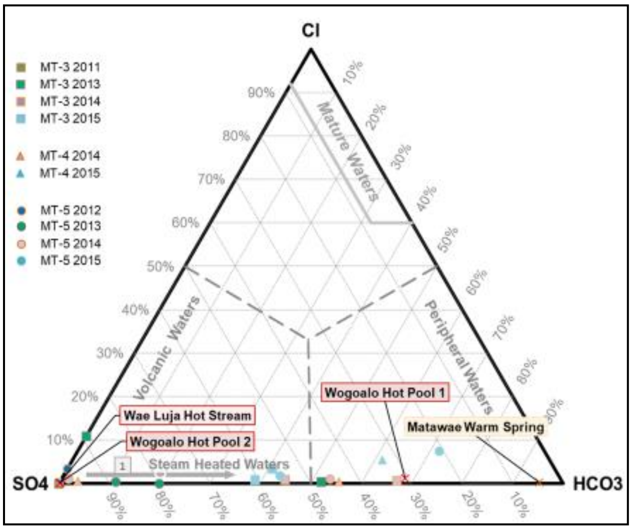

Figure 5 Cl-SO_4-HCO_3 ternary diagram of surface manifestations and SPW

3.1.2 Gas Geochemistry Analysis

Table 3 Comparison of gas samples from manifestations and well discharge from Dieng Complex and Patuha Geothermal Field (PT. (PLN) Persero, 2020)

Geothermal Field	Dieng Complex (Sikidang)		Patuha Complex (Kawah Putih)		Dieng Complex (HCE-7C)	
Reference	Van Bergen et al., 2000		Sriwana et al, 2000		JICA and WesJEC, 2016	
T (ºC)	95		97		181	
	mole% Stream	mole% NCG	mole% Stream	mole% NCG	mole% Stream	mole% NCG
H_2S	0.772	54.782	0.7	16.011	0.04	4.1
HCI	0.002	0.163	0.16	3.66		
HF	0.004	0.284				
Total NCG	1.409		4.372		0.975	

Based on comparisons between NCGs data from wells of Mataloko Geothermal field (Table 2) and Dieng complex & Patuha geothermal field (Table 3) with relatively similar conditions, the concentration percentages of H_2S in Mataloko are lower than Dieng and Patuha. Sulphur deposits and acidic manifestations also discovered in the surface of both geothermal fields. H_2S is interpreted to be sourced from complete scrubbing process of magmatic SO_2 from deep gases [1]. These conditions also encountered in Namora-I-Langit production area in Sarulla geothermal field.

Namora-I-Langit production area is reported to have dispersed zones of acidic production fluid. Not all production wells produce acidic production fluid, higher number of wells in northeastern part of the production area are reportedly neutral [13]. These patterns also occur in Dieng complex and Patuha geothermal fields, not all the production areas are discharging acidic fluid, despite having fluid samples which have magmatic fluid characteristics on its manifestations and wells [1].

3.2 Alteration of Acid Minerals Analysis

Analysis is carried out by looking at the depth at which acidic mineral deposition occurs in the Mataloko geothermal field rock formation. Based on Figure 2, Wolo Belu well contain acidic alunite minerals at a depth of 300 - 350m. The presence of alunite is an indication of an acidic fluid zone in a geothermal system.

3.3 Total Conductance

From magnetotelluric data with EDI file format (.EDI), data processing was carried out to create a 1D resistivity model (invariant) with WinGLink data processing application. After obtaining the 1D resistivity model (invariant) (Figure 6), such model should be matched with nomogram curve with the Grapher application. The curve point with the lowest resistivity value, which concludes that the layer is conductive [10], is drawn along the x-axis to determine the frequency and the y-axis to determine the resistivity (Figure 7). This process was repeated for 50 magnetotelluric points that had been directly measured in Mataloko geothermal field.

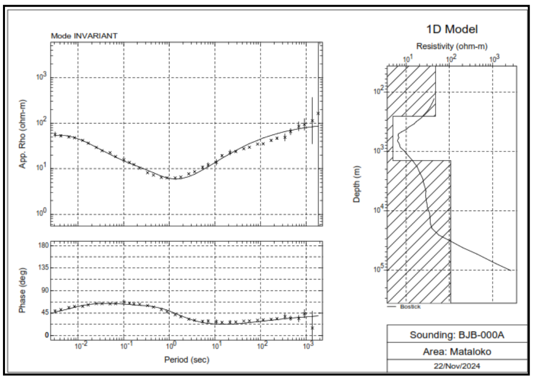

Figure 6 1D resistivity model (invariant) MTL 27

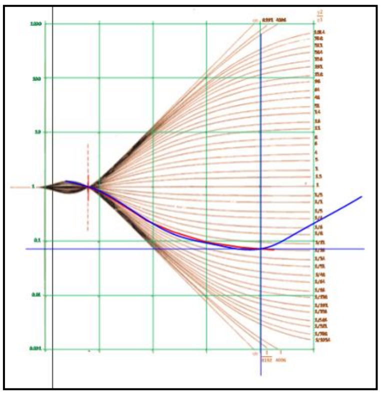

Figure 7 1D resistivity model (invariant) MTL 27 matching with nomogram curve

After obtaining frequency and resistivity parameters from the process above, the next process is to calculate skin depth to determine the thickness of conductive layer and continue with the calculation of Total Conductance. From the calculation results of 50 magnetotelluric points in Mataloko geothermal field, the skin depth and Total Conductance values were obtained as follows:

Table 4 Skin depth and Total Conductance values of Mataloko geothermal field

Code	X (mE)	Y (mS)	δ (m)	*S* (Mhos)	Code	X (mE)	Y (mS)	δ (m)	*S* (Mhos)
MTL 1	284402	9020977	1228	301	MTL 26	286664	9021752	495	454
MTL 2	284456	9021725	990	343	MTL 27	286701	9022523	840	733
MTL 3	284344	9022508	733	233	MTL 28	286527	9023293	820	333
MTL 4	284445	9023243	637	251	MTL 29	286569	9024066	1271	374
MTL 5	284502	9023913	442	354	MTL 30	286664	9024738	2137	195
MTL 6	284424	9024680	313	510	MTL 31	286649	9025498	833	328
MTL 7	284400	9025486	889	322	MTL 32	286651	9026243	826	222
MTL 8	284377	9026270	554	347	MTL 33	287394	9021034	1086	415
MTL 9	285132	9021050	969	184	MTL 34	287405	9021754	1595	377
MTL 10	288153	9026249	865	216	MTL 35	287420	9022571	726	464
MTL 11	285147	9022499	651	311	MTL 36	287421	9023242	1100	455
MTL 12	285138	9023280	725	216	MTL 37	287428	9023998	1006	406
MTL 13	288902	9021752	6153	425	MTL 38	288123	9024751	2315	259
MTL 14	285210	9024794	644	295	MTL 39	287406	9025582	525	428
MTL 15	285192	9025513	578	393	MTL 40	287383	9026299	1273	186
MTL 16	285136	9026273	664	267	MTL 41	288114	9020995	2223	588
MTL 17	285765	9020873	1427	289	MTL 42	288143	9021756	1793	372
MTL 18	285901	9021750	1056	214	MTL 43	288901	9022500	6001	297
MTL 19	285918	9022453	658	399	MTL 44	288164	9023252	3805	362
MTL 20	286064	9023310	617	444	MTL 45	288160	9024024	3241	337
MTL 21	285149	9024000	591	295	MTL 46	288897	9024730	2756	250
MTL 22	285873	9024778	818	337	MTL 47	288955	9025560	403	362
MTL 23	285941	9025561	510	319	MTL 48	288925	9026259	1615	267
MTL 24	285917	9026182	539	199	MTL 49	288871	9020977	7541	410
MTL 25	286612	9021017	888	587	MTL 50	288939	9023965	4310	335

Based on these calculations, the highest Total Conductance value is at MTL 27 with a value of 733 Mhos.

3.4 Acid Zone Delineation

Delineation of the acid zone is carried out by making a Total Conductance map (subsurface) and validated with the acid manifestation & well and alteration of acid minerals (alunite) (surface).

From Figure 8, it can be seen that the relatively high Total Conductance anomaly value with a value of ±700 Mhos is marked in red to yellow in around of MTL 27 point. This value correlates with the distribution map of acid manifestation &well and alteration of acid minerals (alunite) in Mataloko geothermal field.

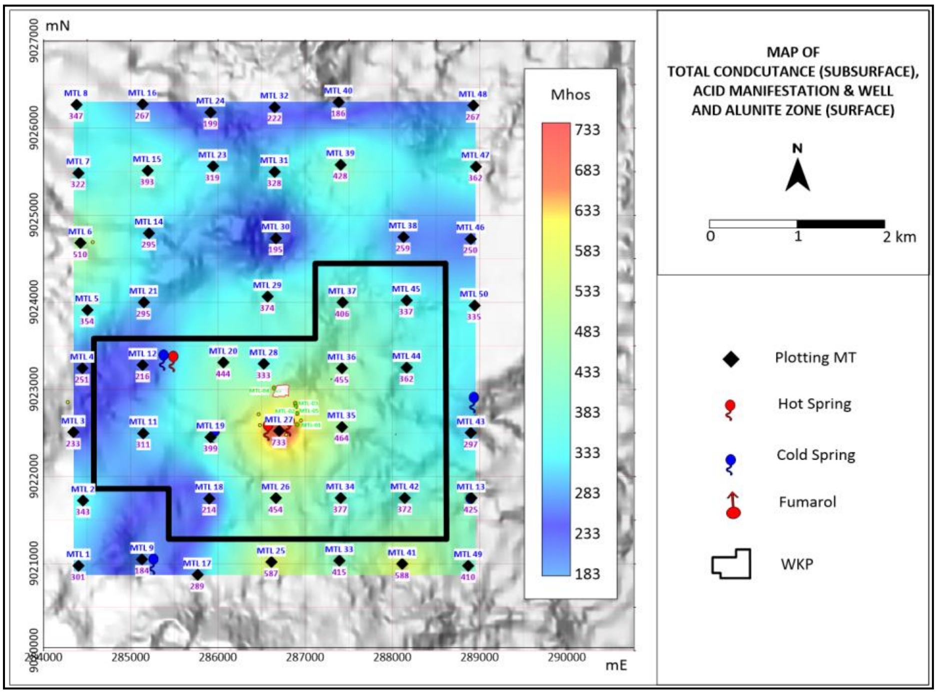

Figure 8 Map of Total Conductance (subsurface), acid manifestation & well and alteration of acid minerals (alunite) (surface)

From Figure 8, it can be seen that the relatively high Total Conductance anomaly value with a value of ±700 Mhos is marked in red to yellow in around of MTL 27 point. This value correlates with the distribution map of acid manifestation &well and alteration of acid minerals (alunite) in Mataloko geothermal field.

Then in Figure 9, the delineation of the acid zone is done by correlating Map of Total Conductance (subsurface), acid manifestation & well and alteration of acid minerals (alunite) (surface) (Figure 8) with the geological structure that develops in the Mataloko geothermal field (as a boundary). On the delineation map, the acid zone in Mataloko geotermal field is depicted in the purple area.

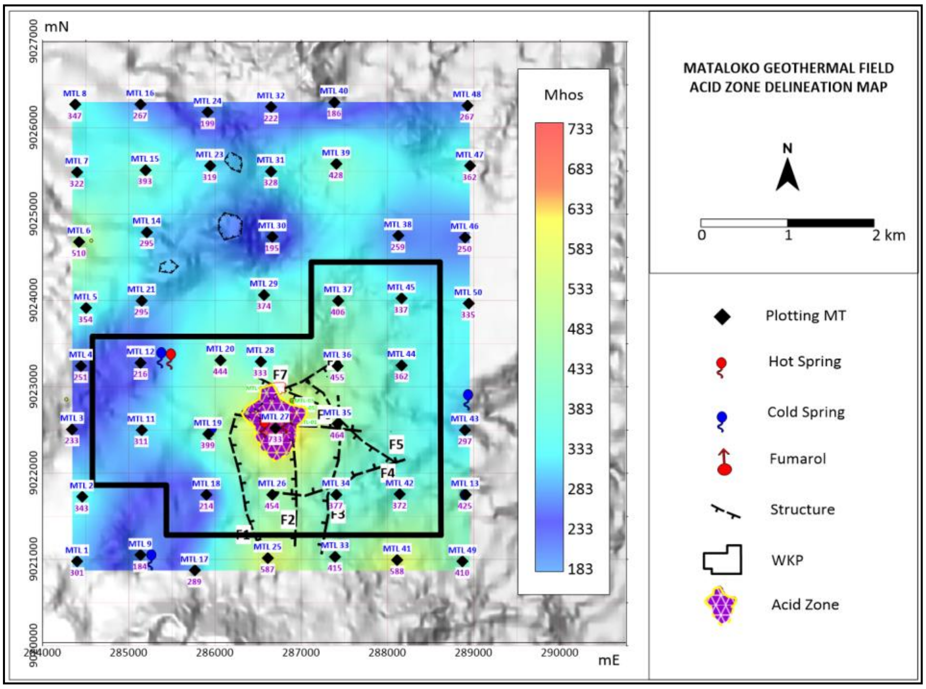

Figure 9 Mataloko geothermal field acid zone delineation map

4. Conclusion

Based on the above results, below are the concluding from this study:

1. Total Conductance method can be used for initial estimation of the distribution of acidic fluid in the Mataloko geothermal field. From the results of the calculation of the Total Conductance value, the acid zone in the Mataloko geothermal field has a value of >±700 Mhos.
2. Estimation of the distribution area of acidic fluids in the Mataloko geothermal field can be done by calculating the Total Conductance value which is validated with acidic manifestation & well and alunite as acidic alteration minerals. Also correlating with the geological structure that develops in the Mataloko geothermal field (as a boundary).

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