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MISE-Á-LA-MASSE AND GRAVITY DATA SURVEYS AT THE KAMOJANG GEOTHERMAL FIELD

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ABSTRACT

Numerous geophysical surveys have been performed at the Kamojang geothermal field. In spite of these surveys, the success rate of production well drilling is only near 60%. To more precisely define areas of permeability within the reservoir and the drilling success rate Mise-á-la-masse and gravity surveys are performed. These surveys, combined with previous geophysical results, have identified a possible productive region in an area previously believed to have low permeability.

1. INTRODUCTION

The purpose of this paper is to present an integrated geophysical interpretation, with geological constraints, of the Mise-á-la-masse method. The geophysical work is carried out in order to develop a realistic geothermal system model of the ultimate potential and the reservoir boundaries. Although the prospect area was already localized by the Schlumberger mapping method and a shallow temperature survey, almost 40% of the wells do not produce commercial amounts of steam. To overcome this problem ongoing research is conducted, to improve drilling success and to give better matches between the field performance and the modeling results.

Electrical resistivity is related to the lithology, porosity, temperature and fluid content of rocks. The Mise-á-la-masse survey is a quick method to map the electrical resistivity distribution within the geothermal area. The processed data is interpreted to delineate and locate the promising geothermal area in the Kamojang geothermal field.

Gravity prospecting is one of the geophysical methods for obtaining a gross model of the structure of a geothermal system. This method has also been applied in monitoring subsidence and estimating mass recharge, which is reduced by fluid withdrawal in the reservoir during long-term exploitation.

The Kamojang geothermal field is located in the western part of Java Island Indonesia, about 42 km SSE of the west Java province capital city Bandung. The field is geographically situated between 07° 11' 02"– 07° 06' 08" South latitude and 107 ° 44' 36"– 107° 49' 30" East longitude or at UTM (Universal Transverse Mercator) zone 48 between 803,000–812,000 East and 9,205,000–9,214,000 North. Topographic elevations range from 1,400-1,800 m above sea level (a.s.l.). The Kamojang field can be reached from two district cities, Garut and Majalaya. Intensive geological, geochemical, and geophysical investigations started in the Kamojang geothermal field in 1972. This project was a collaboration between the Indonesia and the New Zealand governments as part of the bilateral aid project, namely the Colombo Plan. In 1973, the drilling of exploratory and production wells was done for a 5 MW capacity pilot power plant. The first stage 30 MW turbine was completed in February 1983. Subsequently the second and third steps were completed in September 1987, for generating 2 x 55 MW or a total of 140 MW.

The objective of the Mise-á-la-masse field survey, carried out in October-November 1996, was to confirm the extension of the geothermal field prospect from 14 km^2 by the direct current Schlumberger resistivity method in 1972 to 21 km^2 by the CSAMT (Controlled Source Audio Magnetotelluric) method in 1988 (Figure 1). The MAM field survey was done by the Indonesia Oil and Gas State Owned Company (Pertamina). The Exploration Geophysics Laboratory, Faculty of Engineering, Kyushu University and the ITB-Community Services was responsible for the field survey lay out design plan, data acquisition quality control and data interpretation.

2. WELL DATA

The main production zone is confined to the lower section of the Gandapura complex within the depths ranging from 700 to 1,200 meters. In 1926, five wells were drilled ranging between 18.5-130 m in depth. Well 3 is still discharging with a temperature of 130°C and 12,400 kg/hr. steam. Pertamina has drilled 66 wells with bottom hole temperatures ranging from 115-245°C. The pressure and temperature logs indicate a typical vapor dominated convecting geothermal system. The pressure and temperature increase linearly down to the top of the steam zone. At greater depths they increase slowly. However, there are some wells that are not consistent with this vapor dominated type such as KMJ-9 (at 724 m a.s.l.) and KMJ-10 (at 715 m a.s.l.). Some of the well data information from the Kamojang geothermal field are already published in international geothermal journal/seminar proceedings and most of the well data information are available in a Pertamina internal report (Pertamina, 1995).

The geometry of the Kamojang reservoir is the result of the complex interactions of active volcano-tectonic processes,

older stratigraphy, and structure. Generally the caprock is 500-600 m thick but seems to be only 200-300 m thick toward the northern and eastern parts. This caprock consists of prophylitic altered volcanic rock. In the Kamojang geothermal field the resistivity is more sensitive to reservoir permeability than the temperature or rock alteration type. The productive geothermal reservoir, which usually has high porosity, high permeability, high temperature, and adequate size with sufficient fluid, is located between 600-2,000 m in depth. The reservoir consists of strongly altered andesitic rocks and some volcanic pyroclastics. Permeability is produced by structural events such as faults, joints and fractures or by stratigraphic characteristic such as intergranular porosity in lapilli.

3. GEOPHYSICAL METHODS

3.1 Mise-á-la-masse

The Mise-á-la-masse field data acquisition consists of two fixed current electrodes C_1 and C_2, which are located about 5 to 6 km apart and are assumed not to influence each other. The fixed potential electrode, P_2, is located about 3 to 4 km distances away in the opposite direction of the current electrode C_2. The potential electrode P_1 is distributed around the charged well C_1 as shown in Figure 2. Design of the Mise-á-la-masse field survey is based on maximum coverage from the current electrode at the production well within the study area. The KMJ-48 directional well and the KMJ-63 vertical well were selected for the charged current electrode C_1, because they were not yet connected to the geothermal production pipeline. Both wells are good steam producers at 89.7 ton/hour and 76.1 ton/hour respectively. The C_2 and the P_2 are almost 5 km and 3 km away from the well respectively and are used together at the same location for both wells. Based on the Mise-á-la-masse survey results in 1996, the further Mise-á-la-masse study in 1998 was carried out to identify the geothermal prospect distribution to the north and north-east by using KMJ-47 as a charged current. An advanced application of this MAM method in fluid flow monitoring of the Enhanced Oil Recovery processes has been developed by Ushijima et.al., (1997).

The equipment used in this survey has the capability of charging up to 2 Ampere current using 1.5 K.Volt of direct current voltage. The surveyed area is measured along the radial lines for almost 20 km total length for each charged well. The electric potential P_1 on the ground surface was measured at 100 m intervals along the survey lines. Observation points at 100 m intervals were determined by the topographic survey team prior to the potential measurement by the Mise-á-la-masse team. The potential electrodes, P_1 and P_2, are immersed with a saturated copper sulfate solution in the porous pots, to eliminate the polarization effect during the Mise-á-la-masse potential measurement. The current electrode C_2 is a 1.5 m long copper rod 3 cm in diameter, buried and covered with bentonite to keep good earth contact.

3.1.1 Resistivity Inversion

Mizunaga and Ushijima (1991) have given a thorough description of the 3-D resistivity numerical computation. The subsurface illustration of the line source and the block model are given in Figure 3. The calculation of average apparent resistivity within each block is

$$\log r_m = \frac{1}{M}\sum_{i=1}^{M} \log r_{ai} \qquad (1)$$

where r_m = average apparent resistivity within each block (Ωm), r_{ai} = inversion apparent resistivity (Ωm), M = value is the slope of the apparent resistivity curve on a log-log plot which is approximated using numerical differentiation method.

The Jacobian of the homogenous model is expressed as

$$\frac{?\partial f}{?\partial r} = r^{-2}\iiint_{Vol} \nabla f \nabla f \, ©d\Omega \qquad (2)$$

where f = electrical potential, r = resistivity. The potentials due to the current source and potential electrode are

$$f = \frac{rI_\ell}{2\pi}\frac{1}{|r_c|} = \frac{rI_\ell}{2\pi}\frac{1}{\sqrt{(x-x_c)^2+(y-y_c)^2+(z-z_c)^2}} \qquad (3)$$

$$f' = \frac{r}{2\pi}\frac{1}{|r_p|} = \frac{r}{2\pi}\frac{1}{\sqrt{(x-x_p)^2+(y-y_p)^2+z^2}} \qquad (4)$$

The inversion procedure of the numerical model for the 3-D Mise-á-la-masse inversion based on the least square deconvolution of the apparent resistivity is

$$(J^T J + \lambda C^T C)\Delta p = J^T \Delta g \qquad (5)$$

where J = Jacobian matrix of partial derivatives, λ = damping factor, g = differences between measured and calculated apparent resistivity values, p = correction to the model parameter, C = smoothness constraint. In this computation, the inversion involves the calculation of the apparent resistivity value from the model and from the Jacobian matrix of partial derivatives and then solves the linear equation.

3.2 Gravity

The gravity data acquisition in the west part of Kamojang was carried out in 1997 by Lemigas (R & D Gas and Oil Technology of Indonesia). The project was initiated by Pertamina to support the geoelectrical mapping. Observation points are distributed randomly and along existing access roads.

The gravity data processing involves data reductions such as corrections for drift, tides, ellipsoid earth gravity reference, free air, bouguer, and terrain. The Bouguer anomaly map is derived from the calculation of Complete Bouguer Anomaly

$$CBA = g_{obs} - (g\varphi - FAC + BC - TC)\ \text{mgal} \qquad (6)$$

where Ellipsoid earth gravity reference (IUGG, 1979), $g\varphi = 978.03185(1 + 0.005278895 \sin^2\varphi + 0.000023462 \sin^4\varphi)$ mgal; where gφ = theoretical gravity as a function φ/latitude of the gravity observation point; Free Air Correction (FAC) = - 0.3086 h mgal; Bouguer Correction (BC) = 0.04187 h mgal;

where h = elevation of gravity station (m). Terrain Correction (TC) mgal; consists of inner zones (A,B,C,D) and outer zones (E,F,G,H,I,J). Gravity anomalies typically arise from relatively small density difference between different rock formations and quantitative interpretation is very sensitive to these values. The quantitative gravity data interpretation is carried out by the 2-D gravity modeling by the Talwani method.

4. PROCESSING RESULTS

4.1 Mise-á-la-masse

Theoretically the potential value will always have a circle shape and decrease gradually away from the current source C_1. The data processing consists of plotting the observed field data of V/I in mV/A, the theoretical V/I in mV/A, the apparent resistivity r_a in Ωm, and the difference values of the observed and the theoretical between the potential ΔV/I and the apparent resistivity Δr_a. From the resulting maps, we can interpret a general distribution of the low resistivity area and the discontinuity of the contour pattern, which correlates with the producing geothermal area and structural features. The apparent resistivity (r_a) and the potential differences (ΔV/I) show the low resistivity area of less than 8 Ωm covering almost all of the radially measurement points. The exceptions lie along lines A15-18, B11-18, E12-13, H11-14, L19-20, M12-13 and M17-18, S21-26, T19-20, U19-20. The extension of the main prospective anomaly around the KMJ-63 well is bigger than the KMJ-48 well (Figure 4).

4.1.1 Resistivity Inversion Results of the Mise-á-la-masse Method

The inversion results of the MAM data using the charged current of KMJ-48 and KMJ-63 is represented by the block of 500x500 m size in x and y axis with 4 layers in z axis at depth of 300 m, 900 m, 1,500 m and 2,300 m, respectively (Figure 5). The low resistivity is located SSE of KMJ-63 and SSW of KMJ-48. The low resistivity block moves from south to north starting near to the KMJ-48 at depth of 1,500 m. The inversion results can be completed much faster than the forward interpretation. The minimization of the error between observed and calculated data was automatically done by iteration. The low resistivity area is wider at the 1,500 m level, but the extension does not continue to the SSW direction from KMJ-63. This can result from multiple causes such as the presence of the Ciharus lake, a uniformly tight volcanic formation, or an absence of structures within this area.

4.2 Gravity

The gravity data are mostly from the in western area between 800,000-808,000 East and 9,205,000-9,215,000 North (Figure 6). The Bouguer gravity map with density of 2.5 gr./cc, consists of regional and residual anomalies trending SW-NE in southern area. In north area the orientation is more SE-NW. Interpretation of the WSW-ENE gravity profile is shown on Figure 7, where the Bouguer anomaly increases toward the ENE. The geological model for the WSW-ENE gravity profile was controlled by the CHR-1 vertical well at an elevation 1,483 m with a total depth of 1,804 m.

Bouguer gravity anomalies consist of those due to shallower mass inhomogeneities superimposed on an undisturbed regional field. A regional gravity field is typically a long wavelength anomaly caused by deep seated mass inhomogeneties.

Such a field can slightly distort the observed anomalies and must be subtracted from the observed values to obtain residual anomalies of shorter wavelength which are caused by mass inhomogeneities in the upper few kilometers of the crust.

The Bouguer anomalies indicate that the gradient of the regional field must be small in the NS direction

5. DISCUSSION

Sudarman et.al., (1996) and Sumintadireja et.al., (1997 and 1998) discussed of the application of various geophysical methods in geothermal resource exploration. However, geothermal exploration is very complex with high uncertainty of steam production from development wells, even if the location is already surveyed by various geological and geophysical methods. Based on the experience in Kamojang, where only 60% of the wells produced commercial steam, we have to improve the drilling success ratio by doing integrated studies. At Kamojang, the MAM survey has optimum detection coverage for a 1.6 km radius from the charged casing well.

The geothermal reservoir boundaries and depth can be identified or inferred by correlating the observed resistivity anomaly from various geophysical methods. The MAM result gives higher resolution compared to the previous Schlumberger mapping.

The caldera shape in WNW part of the study area is clearly identified by the MAM survey. The gravity survey also supports the MAM data in west area. The prospect boundary in west area is not clearly identified, but the reservoir can be predicted in the altered auto brecciated andesite rocks. In the Kamojang geothermal field the resistivity change is more sensitive to the reservoir permeability than the temperature or rock alteration type. Electrical conductivity is mainly a function of the total ionic mobility of the ions in solution whereas the pH is a function of the hydrogen ion concentration. The higher chloride springs are generally sub-alkaline, are hotter and have a greater discharge.

Based on the experience of the power plant operational in Kamojang, an hydrothermal system will decrease its permeability with time by pressure solution or by deposition of minerals from the water as they cool and loose CO_2. Therefore the permeability maintenance must be carried out by periodically fracturing or by re-injection under the direction of the Mise-á-la-masse and gravity data

interpretation result. Re-injection of the geothermal water is necessary to recharge the reservoir in order to maintain power plant output and to prevent chemical pollution. The main reservoir area is represented by the low/negative potential different (ΔV/I) value, therefore the location of re-injection well is suggested in the limit of the main reservoir.

We have to reevaluate the area which already considered as a low permeability zone, in other words there is a promising area located within the previously stated as low permeability zone, such as the area between line of L8-17, line of K13-18 and line of Q4-12.

6. CONCLUDING REMARKS

The geophysical investigation of mapping and VES Schlumberger, CSAMT, MAM, gravity survey has already been completed at Kamojang. However, all the survey results give slightly different results in delineating the reservoir. The combination of several geophysical methods is the best way for defining the reservoir boundaries (Figure 1).

The MAM method can be performed following the completion of the first exploratory well. The MAM method is a quick mapping method and can be use for locating fracture/fault zones, conductive areas and reservoir extensions. Gravity data gives subsurface information, which can be combined with other geophysical data.

Interpretation of the Mise-á-la-masse results at the Kamojang geothermal field need detailed elaboration of other geophysical and geological data. The Mise-á-la-masse results define the reservoir boundaries. These results indicate a need to reevaluate a potential production area located in a low permeability zone.

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Ushijima K., Mizunaga H., Tanaka T., and Masuda K., 1997, Fluid flow monitoring of EOR process by electrical prospecting, SEG Expanded Abstract, vol., pp.651-653.

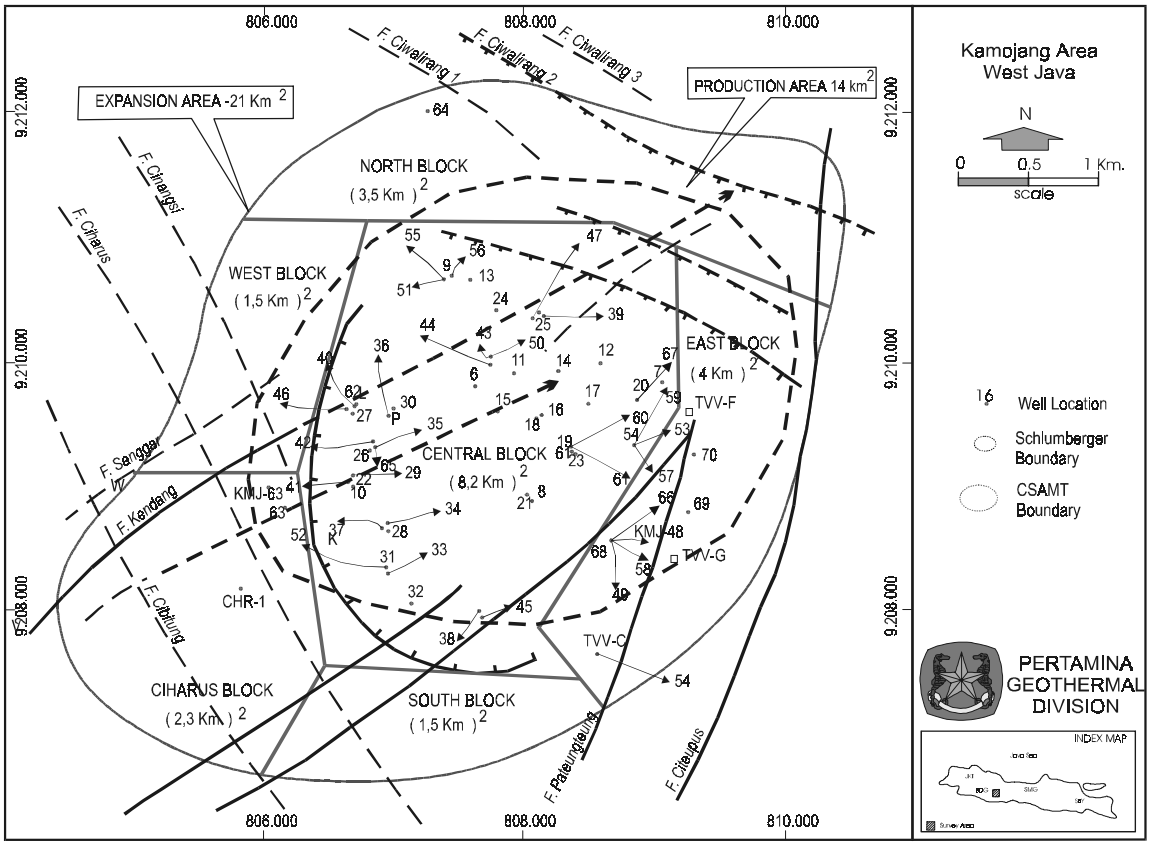


Figure 1. Geothemal Field Prospect in Kamojang Area (Compiled from PERTAMINA)

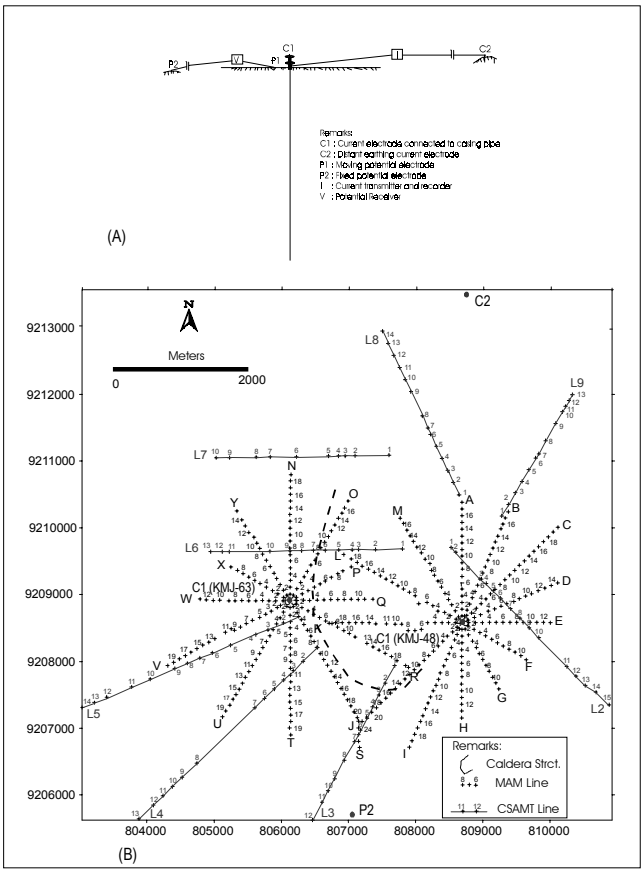


Figure 2. Field Layout of the Mise-á-la-masse Survey

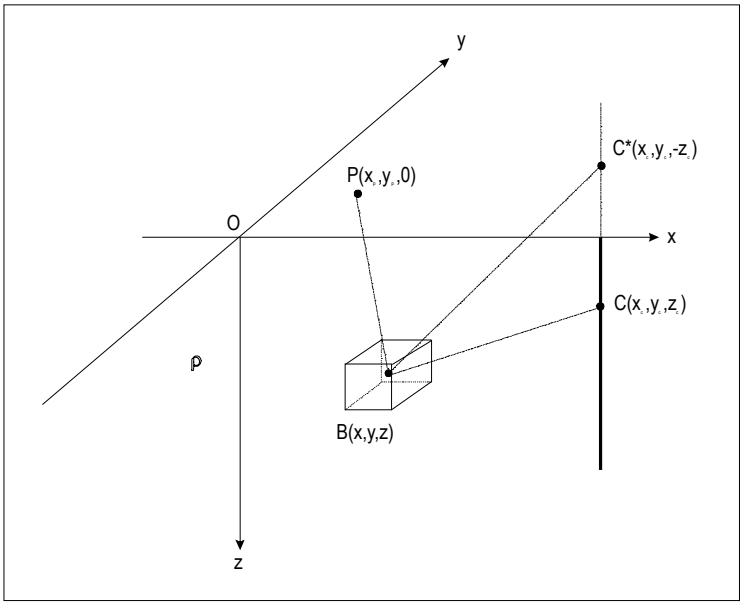


Figure 3. Line Source Model and the 3-D Resistivity Block

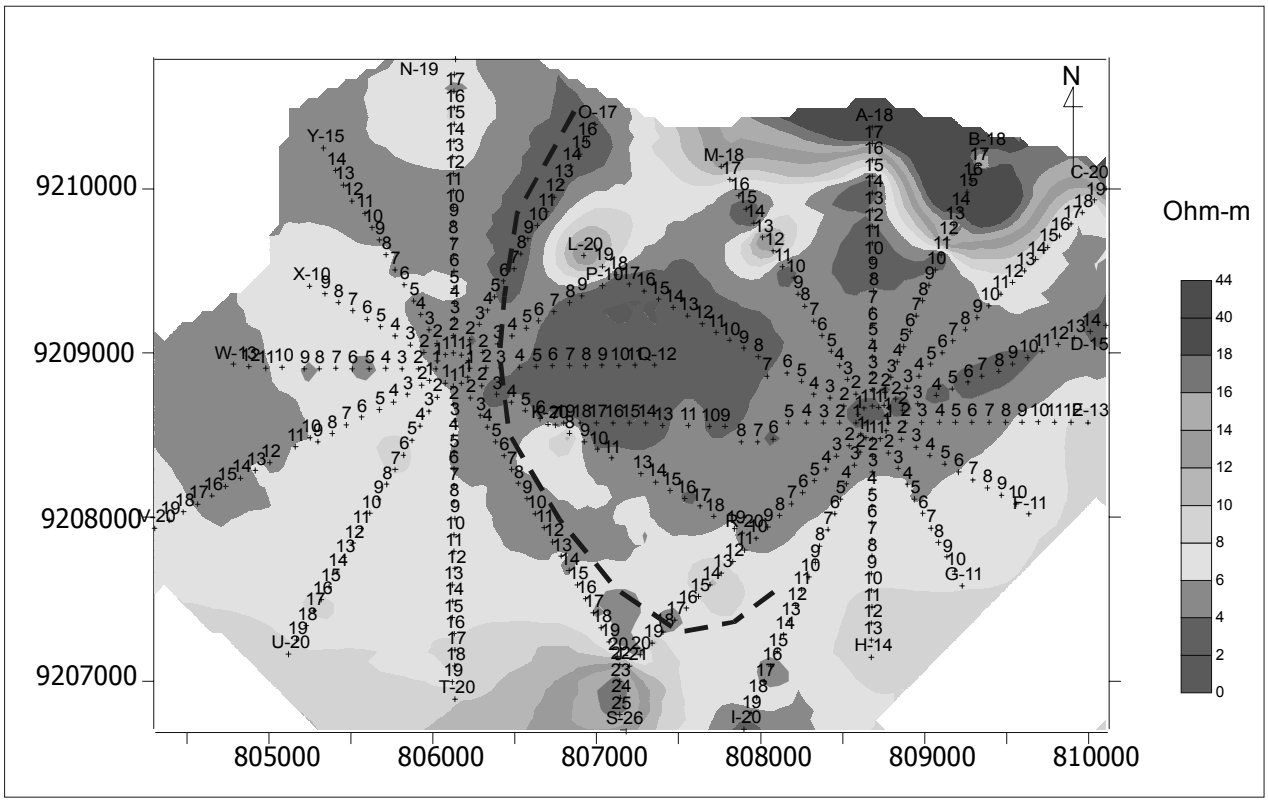


Figure 4. Combined Apparent Resistivity (ρ_a) Map of KMJ-48 and KMJ-63

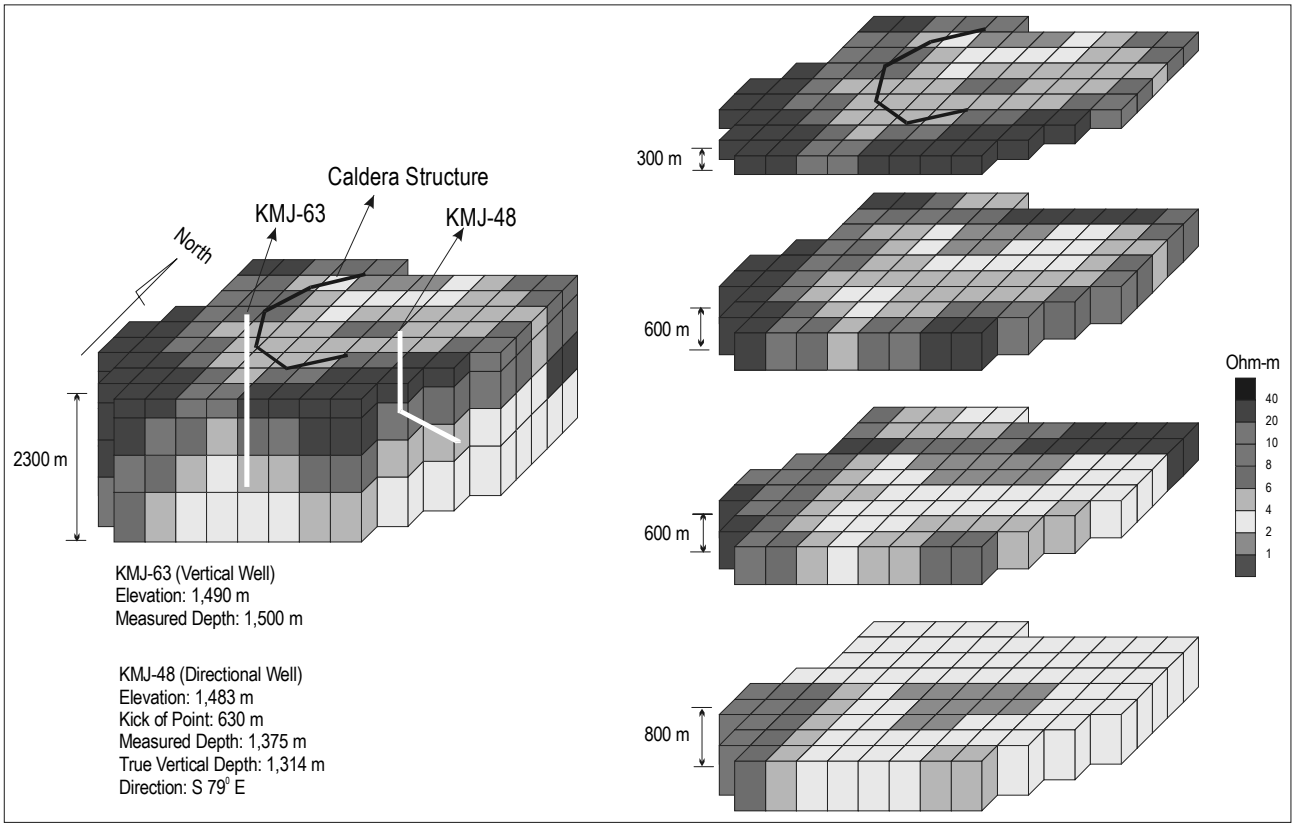


Figure 5. Resistivity Inversion Result

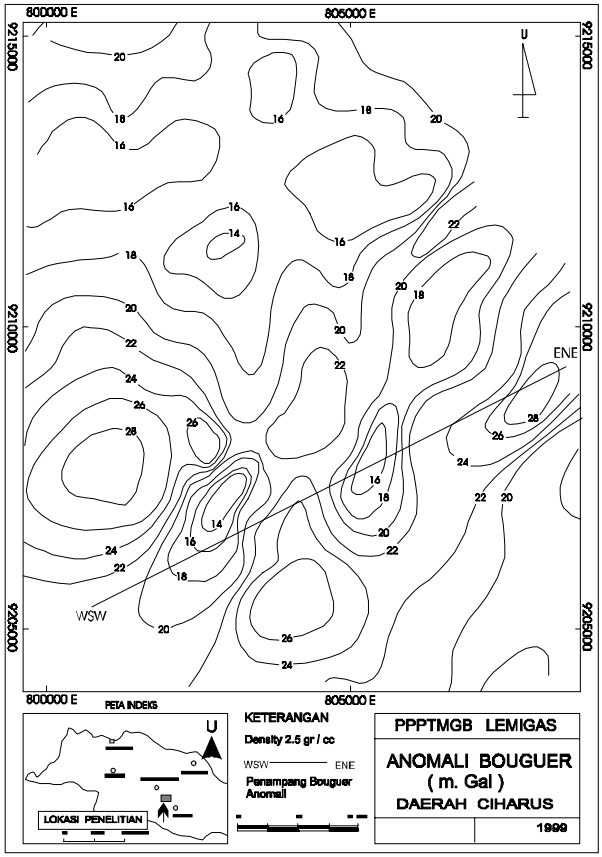


Figure 6. Bouguer Anomaly Map of West Kamojang Area (density=2.5 gr/cc)

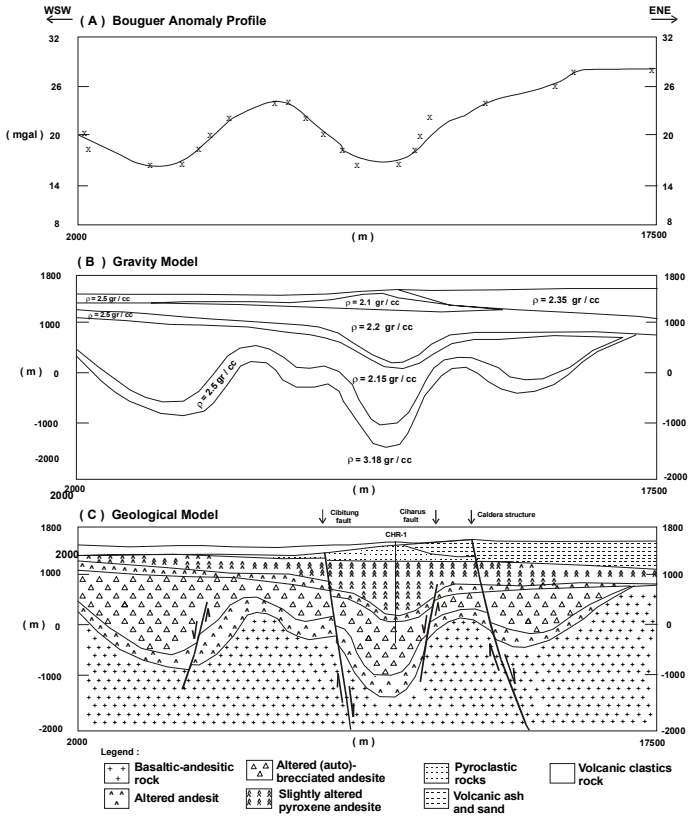


Figure 7. WSW-ENE Gravity Profile, Model and Interpretation