LAHENDONG GEOTHERMAL FIELD BOUNDARY BASED ON GEOLOGICAL AND GEOPHYSICAL DATA

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ABSTRACT

Lahendong geothermal field is located in the northern part of Sulawesi island. The first exploration stage was started in the early 70's. Numerous geophysical investigation were carried out such as Gravity, Magneto Telluric (MT), Resistivity and Mise-á-la-masse (MAM) methods. However, the precise geothermal boundary is not identified clearly. This paper will emphasize on geophysical data processing in determining the geothermal boundary at Lahendong area.

In geothermal exploration, which use several geophysical methods, no single method can give satisfactory result in featuring the subsurface geometry. Therefore, we have to integrate all of the acquired geophysical data to get a realistic model for the studied geothermal field. The Lahendong geothermal field reality is unique, consequently our geophysical model parameter must be inferred from this unique realization. This paper, we demonstrated the advantage of integration the geological and geophysical data of Lahendong area. Knowledge of geology in the prospective area is fundamental to develop a correct model of the geothermal reservoir. Development of the geothermal models is an iterative process.

1. INTRODUCTION

Lahendong geothermal field is located approximately 30 km to the south of Manado city in Tomohon district, Minahasa, North Sulawesi province, Indonesia. Knowledge of geology in the prospective area is fundamental to develop a correct model of the geothermal reservoir. **Figure-1** shows the flowchart of the investigated area..

The average elevation is around 600-900 m above mean sea level **(Figure-2)**. The aim of this study is to evaluate and reprocess an existing data which had been collected. The first drilling stage in 1971 of LH-1, 2, and 3 around Linau lake was carried out by VSI (Volcanological Survey of Indonesia) in association with JICA (Japan International Cooperation Agency). Seven exploratory wells have been drilled by PERTAMINA (LHD-1 until LHD-7). The development well to provide steam for generating 20 MW power plant of PLN (Indonesian Electrical Company) was carried out adjacent to LHD-4, as a cluster drilling of LHD 8-15 done by PERTAMINA. In 1993, approximately 50 meter away from the LHD-5 wellhead, the 2.5 MW binary power plant of the pilot project is installed by in association with Thermodyn (French Company). Geothermal manifestations within this area are represented as fumaroles, hot mud ponds, hot spring water, and hydrothermaly altered rocks.

2. GEOLOGICAL FEATURES

The geothermal fields are mainly covered by Pre-Caldera formation (before the Pangolombian formation collapses) and Post Caldera formation. Post Caldera formation is divided into 3 sub-groups :

- Tamposo sub-group, in the eastern part of geothermal field is indicated as a central of young volcanic.
- Kasuratan sub-group, between Linau lake and Kasuratan village, is indicated as a central volcanic.
- Linau sub-group, located in the central geothermal field, consists of volcanic breccias and pyroclastics, which resulted from recent phreatic eruption (Linau lake).

Figure-3. shows the geological map of Lahendong area. The stratigraphy of older to younger sequence within the studied area is :

- Pre Tondano, andesites hyaloclastites with sediment intercalation.
- Tondano unit, tuff and ignimbrite.
- Pre Pangolombian formation (Post Tondano unit), basaltic, andesitic.
- Post Pangolombian formation, tuff and breccia

2.1. Well Data

Nowadays, there are 15 wells drilled within Lahendong geothermal area. Fifteen deep wells ranging between 910-2,475 m were drilled by PERTAMINA (LHD-1 until 15, 1972-1997), whereas three shallow wells ranging between 350-650 m (LH-1,2,3) located near to Linau lake were drilled by VSI-JICA. In those Pertamina wells top of each formation encountered at the following depth:

- Post Tondano/Pangolombian found around 0-850 m.
- Tondano found around 350-1,100 m.
- Pre Tondano around 1,100-1,600 m.
- Structural event found within wells located in the south (adjacent to LHD-4) at depth around 1,600 m.
- Predominantly argilitic alteration around 0-600 m, except for well LHD-3, all argilitic alteration (total depth 2,210 m).
- Predominantly prophylitic alteration below 600 m depth

The Pangolombian and Pre Tondano formation are two productive reservoirs. in Lahendong geothermal field. Subsurface temperature, and pressure distribution is constantly increasing towards the southern part. At level 400 and 200 m above mean sea level, the temperature distribution of 250 ^{o}C indicates the existing shallow reservoir surrounding the Linau lake. Deep reservoir is about 1,100-2,300 depth, while isobar map at level 500 m below sea level, shows strong geothermal fluid flow from south to north part.

The exploration well of LHD-1 was plug due to corrosive problem, whereas well production test of LHD-4 and LHD-5 are shows high permeability. However, the plan of steam supply for the 20 MW power plant is from LHD-8, 10, 11, 12, and 15. Plotting results of the pressure indicated that the pressure distribution is almost nearly to hydrostatic pressure. Therefore, we can predicted the reservoir fluid within Lahendong area are fluid dominated system. The charged current well data of LHD-1, 4 and 5 for Mise-a-la-masse measurement is shown in **Table-1**.

3. GEOCHEMICAL FEATURES

The location geochemical sampling of the spring water is shown in topographic map of **Figure-2**. According to Sudarman et.al. (1996), the localization of three main group samples is done using triangle diagram of Cl, SO_4, and HCO_3. it seems the water chemical data fall in the specific trends, which are well accordance with the localization of the triangle diagram. Neutral group with high salinity due to the significant CO_2 and H_2S, which flowing in highly altered rocks is located in the north and south part (water location no.5, 4, 19 and 20). Soda group predominantly encountered tends to have low salinity. This condition is caused by hydrothermal circulation in andesitic rocks rich in alkali (Pangolombian formation, no. 7 until 18). The high SiO_2 contents involves the alteration process of volcanic glass in ignimbrite and andesite of Pangolombian formation. Acid group, which characterized by high $CaSO_4$ content is located in the northern part only (no. 1, 2, 3 and 6). The high $CaSO_4$ content is derived from hydrothermal circulation in sedimentary rocks, which proven by drilling data of LHD-3 and LHD-2 at depth 1,000-1,200 m and 1,300-1,400 m, respectively. The characteristics of acid group are high sulfate contents, low temperature and it is usually encountered at outcrop which closed to the reservoir. The solubility of $CaSO_4$ is diminished with the increase of the temperature.

4. GEOPHYSICAL FEATURES

Geophysical survey carried out within this area are Gravity, Resistivity, and Magneto-Telluric and Mise-á-la-masse methods. The compilation map for delineating Lahendong geothermal field boundary is shown by **Figure-5**.

4.1. Gravity Data

The gravity data reduction was processed with a background density 2.67 g/cc. The bouguer anomaly value increases northward, varies between 128 mgal in the southern part and 150 mgal in northern part. Based on qualitative pattern recognition, the regional geologic map of the Lahendong caldera structure correspond to the bouguer anomaly map. Trend surface filtering methods is applied, for deriving regional anomaly map for 2-D gravity modeling. Regional bouguer anomaly map indicates almost NE-SW trend of synclinal basement, while the value is increasing northward from 130 mgal to 148 mgal.

Residual bouguer anomaly map is derived from the subtraction of regional bouguer anomaly from the observed bouguer anomaly. In the residual anomaly map, we can see a closure pattern coincident with the main exploration wells. Positive anomaly of ca. 7 mgal in the adjacent of Linau lake is correlating to the subsurface of plutonic intrusion. Two dimensional gravity modeling results are reconstructed based on forward modeling. The south-north section is double checked by LHD-4, 5, 2, and 3, while west-east section by LHD-1, 5, and 7. The advantage revealed by gravity modeling :

- The density contrast in this modeling is controlled by the exploration well data. Therefore, the certainty of the model is more reliable.
- Extension of the plutonic intrusion can be observed in several directions.

4.2. Resistivity Data

The apparent resistivity map are derived from Schlumberger resistivity survey. There are no significant differences between spacing AB/2 = 250, 500, and 1,000 m, especially in the area which has an apparent resistivity less than 10 Ωm. AB/2=1,000 m is representing the deeper electrical response within the area. Up flow area is estimated to be coincident with the low resistivity zone. This is also supported by the existing surface geothermal manifestations such as fumaroles and hot water springs. Apparent resistivity map with AB/2 = 250 m and 500 m are represented by the shallow reservoir with almost 5 km^2.

The prospective boundary limit is clearly observed, with the exception of the possible extension to southwestern and southern part. The possibility extension is also indicated by the relative higher resistivity gradient value at the southwestern and southern area. Unclear boundary prospect in the eastern part is due to recharge zone area of surface water, which is controlled by fault structures.

4.3. Magneto-Telluric Data

High alteration zone correlates with the apparent resistivity of 6 Ωm, which is extended and opened to the west-southwestern area. In the interpretation view we can predict the possibility of the extension of deep geothermal reservoir through this area.

Quantitative interpretation based on 1-D model of SW-NE section across LHD-7, 5, and 4 wells shows very conductive layer, less than 5 Ωm found at the depth 800 m adjacent LHD-5. The layer is thickening towards southwest area. Electrical discontinuity in NE and SW part indicating the layer transition to the higher resistive area (>10 Ωm) and can be assumed as the geothermal boundary limit of Lahendong area. At LHD-4, the resistive layer is encountered at 1,500 m depth. Therefore, the high resistivity layer acts as a reservoir, whereas the low resistivity layer as a cap rock with argilitic and prophylitic alteration.

4..4. 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 electrode potential P_1 is distributed around the charged well C_1 as shown in Figure 4. 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 LHD-1, LHD 4, LHD-5 well were selected for the charged current electrode C_1. The C_2 and the P_2 are almost 5 km and 3 km away from the well respectively. The equipment used in this survey has the capability of charging up to 2 Ampere current source using 1.5 K.Volt of direct current power. **Figure-4** shows the field survey layout design for the MAM data acquisition.

The promising resistivity anomaly is located in SW of LHD-4 and N-ESE of LHD-5, whereas LHD-1 is not extend widely as represented by the MAM processing result.

5. Discussion

The Lahendong structure is located within big Caldera, The latest volcanic activity was the eruption of G.Soputan (SW Tondano lake) in August 1995. There are 6 tectonic elements in the Lahendong geothermal field :

- Pangolombian structure, edge side of Caldera.
- NE-SW fault, correlates with the Tondano volcanic depression boundary, which is controlled by the formation of a pull apart basin.
- E-W fault, indicated as lateral fault and as pivot of secondary magmatic intrusion.
- NW-SE fault, tensional type, formed big Lahendong graben.
- N-S fault, young tectonic activity.
- Circular structure, interpreted as deep plutonic intrusion.

Soda type of hot spring water which is extensively distributed in Lahendong geothermal field, covers almost 70% from the existing 21 hot springs. This condition due to fluid circulation, which is associated with the alkaline volcanic rocks (Pangolombian formation, andesitic and basaltic rocks composition). Some of the hot spring water which shows Ca-sulfate anomaly is caused by thin layer of limestone or anhydrite at depth 1,300-1,400 m. Based on geophysical data we can, delineated prospective boundary area adjacent to LHD-1, 2, 5, 4 and 15 wells. The prospect area agreed with Schlumberger electrical mapping data. The lateral extension of heat source as diorite plutonic intrusion is approximated from the closure of gravity anomaly map. Based on combination of gravity and MT resistivity and MAM, we can predict the promising extension of geothermal field to southwestern area. Temperature and pressure distribution at several depths indicated the two types of reservoirs. The peak of shallow reservoir is adjacent to LHD-1 well. Deep reservoir is represented by the temperature and pressure distribution at specific depth. Temperature and pressure increases to the southern area.

Based on this study the Lahendong geothermal field development is recommended to be carried out in west area of LHD-4. The total depth of the LHD-6 is limited to 910 m only, due to the mechanical problems of the drilling machine. It would be worth if we redrill in this location to confirm the possibility of the deep reservoir extension.

Sudarman et.al. (1999), Sumintadireja et.al (1997, 1998,1999, 2000), Ushijima et.al (1996) discussed of the application of various geophysical method in the geothermal resource exploration. However, the geothermal exploration is very complex and dealing with the high uncertainty of the steam production results from the development well, even if the location is intensively studied by various geological and geophysical study. We have to improve a better drilling success ratio with doing a continuos integrated study. We can identified, that the geothermal reservoir distribution and also inferred the depth of prospective area by correlating the observed anomaly from various geophysical method. The MAM result is giving a higher resolution compare with the previous Schlumberger mapping. The geometry of hydrothermal reservoir in Lahrndong is the result of the complex interaction of active volcano-tectonic processes, older stratigraphy, and structure. The reservoir consists of strongly altered andesitic formations 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 a lapilli. The faults and fractures direction have a significant role in resulting a good steam production well.

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 the greater discharge. Knowledge of geology in the prospective area is fundamental to develop a realistic model of a geothermal reservoir.

6. Concluding Remarks

The history geophysical investigation of mapping and VES Schlumberger, CSAMT and MAM survey in Lahendong geothermal area is took more than 30 years period. However, all the survey is giving a slightly different features in delineating the promising geothermal area. The combination of several geophysical methods is the best way for revealing a clear subsurface condition such as the reservoir distribution, the production zone and the structural event. The MAM method is a quick mapping methods and can be use for localizing the fracture/fault zone, conductive area and predicting the reservoir extension. Heat source is produced dominantly in southern of Lahendong area and migrated to NW area through the structural fault.

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Table -1
Charged current well data of Mise-á-la-masse measurement.

Parameters	**LHD-1** TD. 2203 m, El. 750 m	**LHD-4** TD. 2307 m, El. 850 m	**LHD-5** TD.1897 m, El. 872 m
Temperature (^oC)	296	350	250
WHPmax (bar)	7	25	10.7
Enthalpy (kJ/kg)	1,100-1,700	2,050	1,100
Steam production (ton/hr)	30	44	40.6
Water flow rate (ton/hr)	70	81	150
Dehydration level (%)	29.9	66	18
Transmissivity	low	high	high
Gas contents (weight %)	-	0.56	0
Feed Zone 1 (Depth, m)	350-450	300-500	450-600
Feed Zone 2 (Depth, m)	650-850	1,100-1,200	1,150-1,250
Feed Zone 3 (Depth, m)	900-1,100	1,600-1,700	1,400-1,600
Feed Zone 4 (Depth, m)	-	2,200-2,300	-
Pressure (bars)	45	135-200	25-120
Structural Geology/Fault	-	1600-TD	-

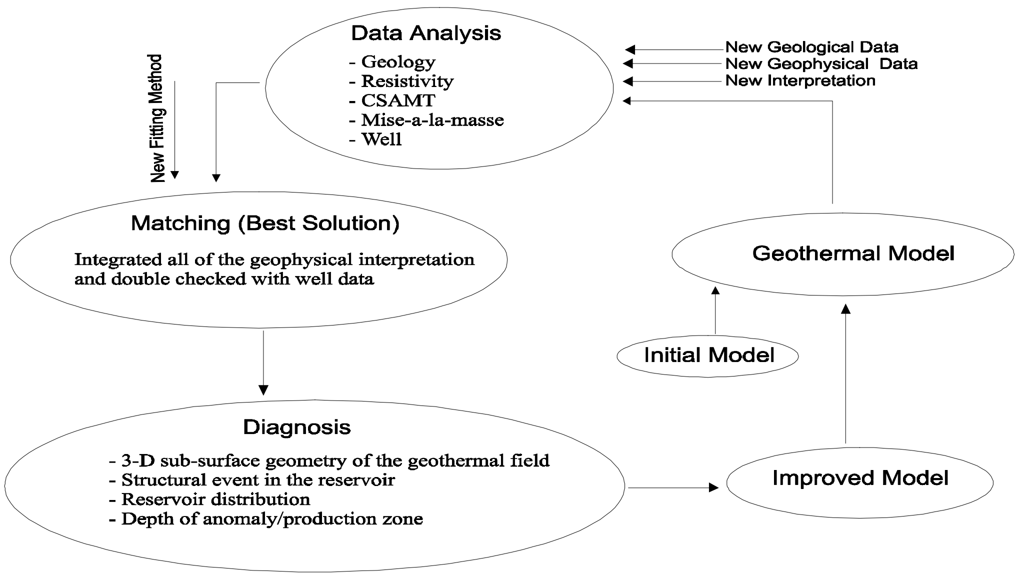

Figure-1
Iterative geological and geophysical study in Lahendong Area.

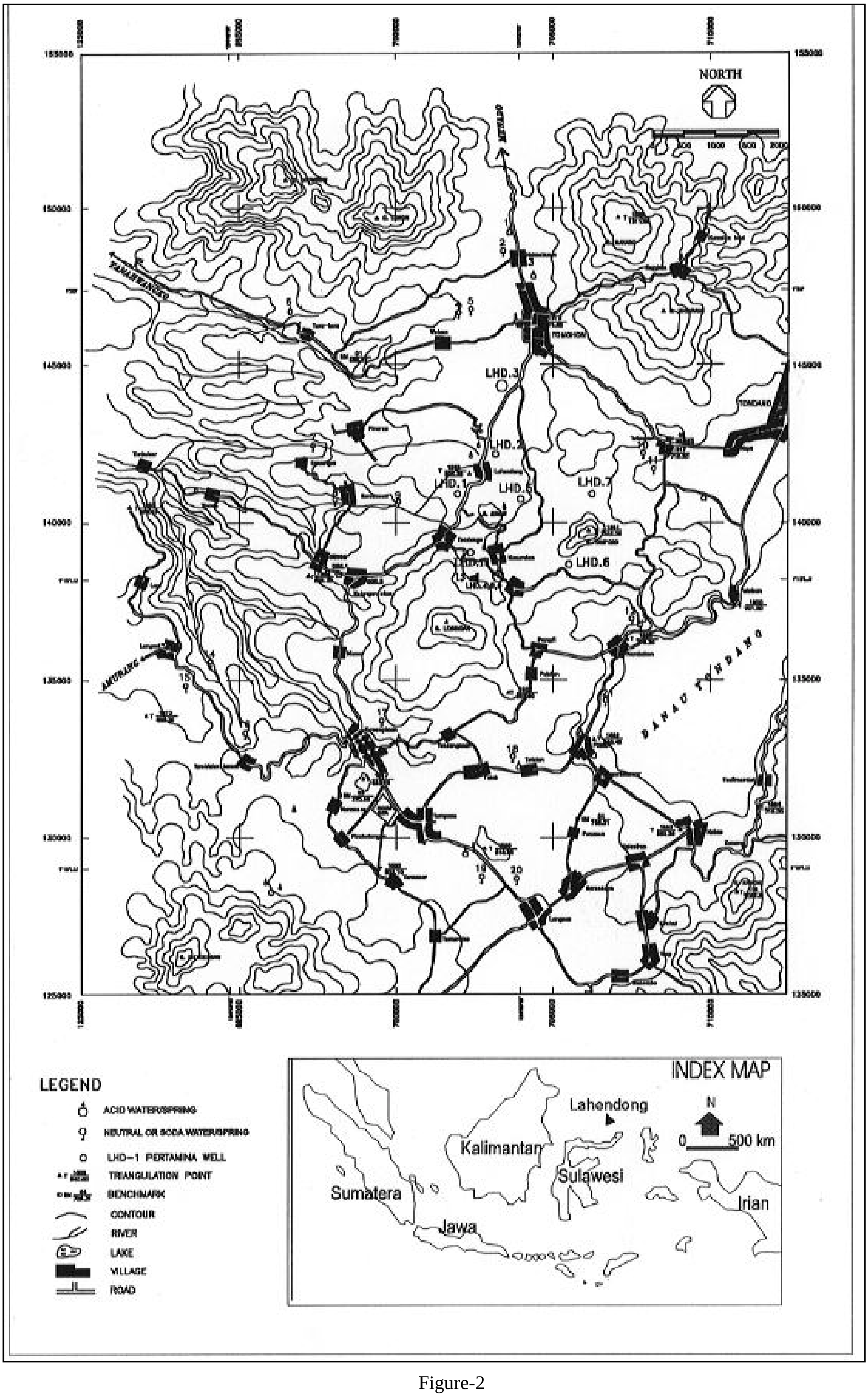

Figure-2
Geological Map of Lahendong Area.

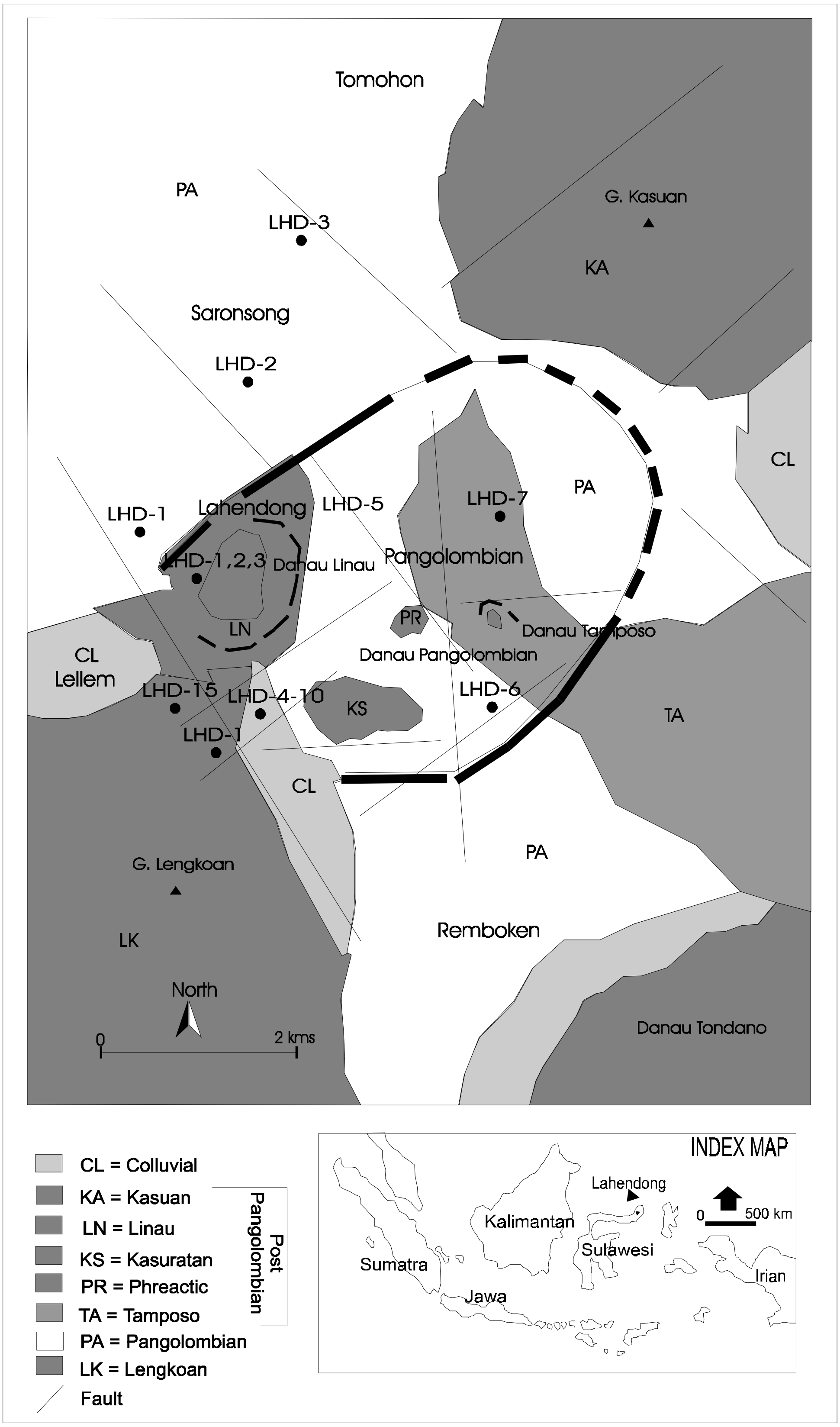

Figure-3
Geological Map of Lahendong Area

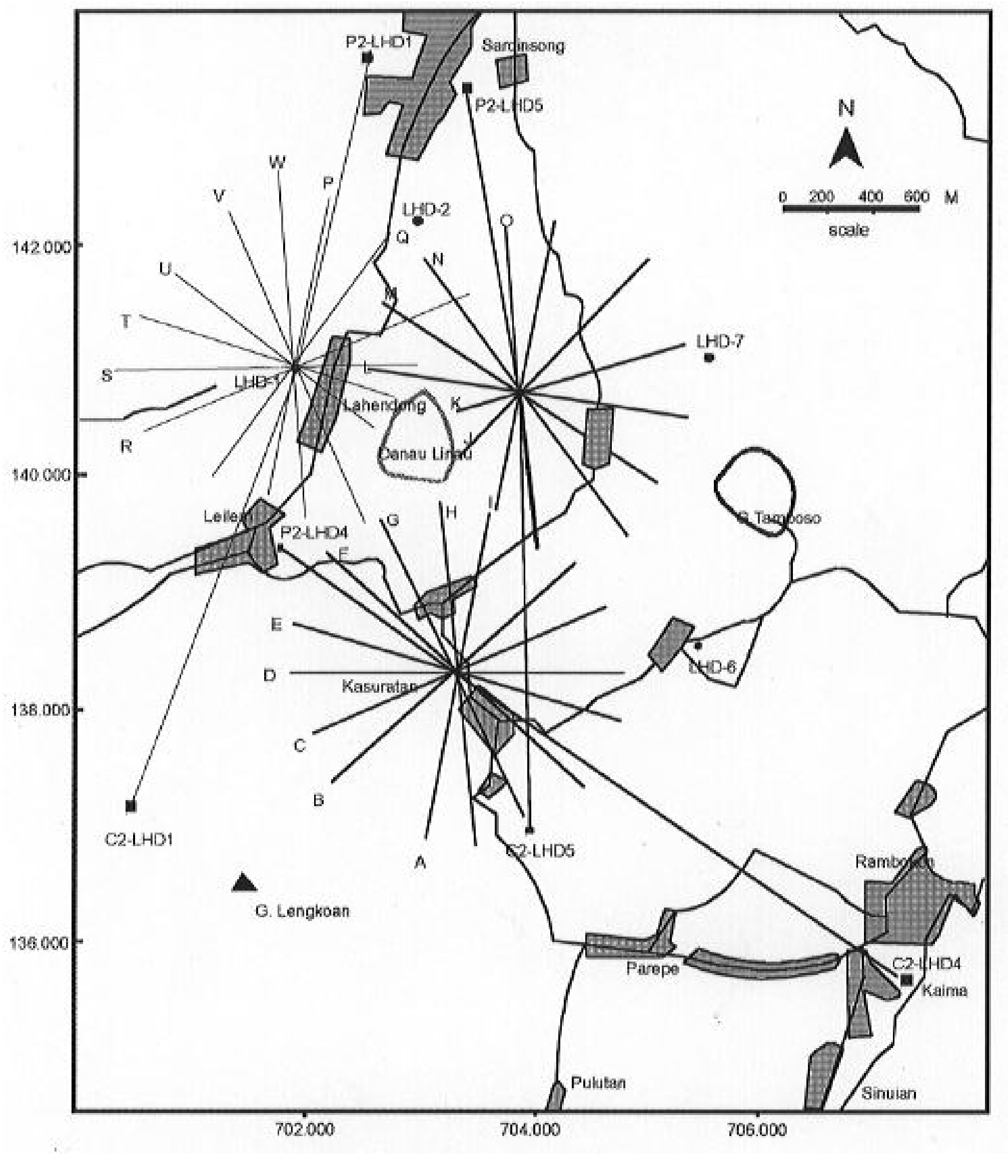

Figure-4
Mise-'a-la-masse Layout at Lahendong

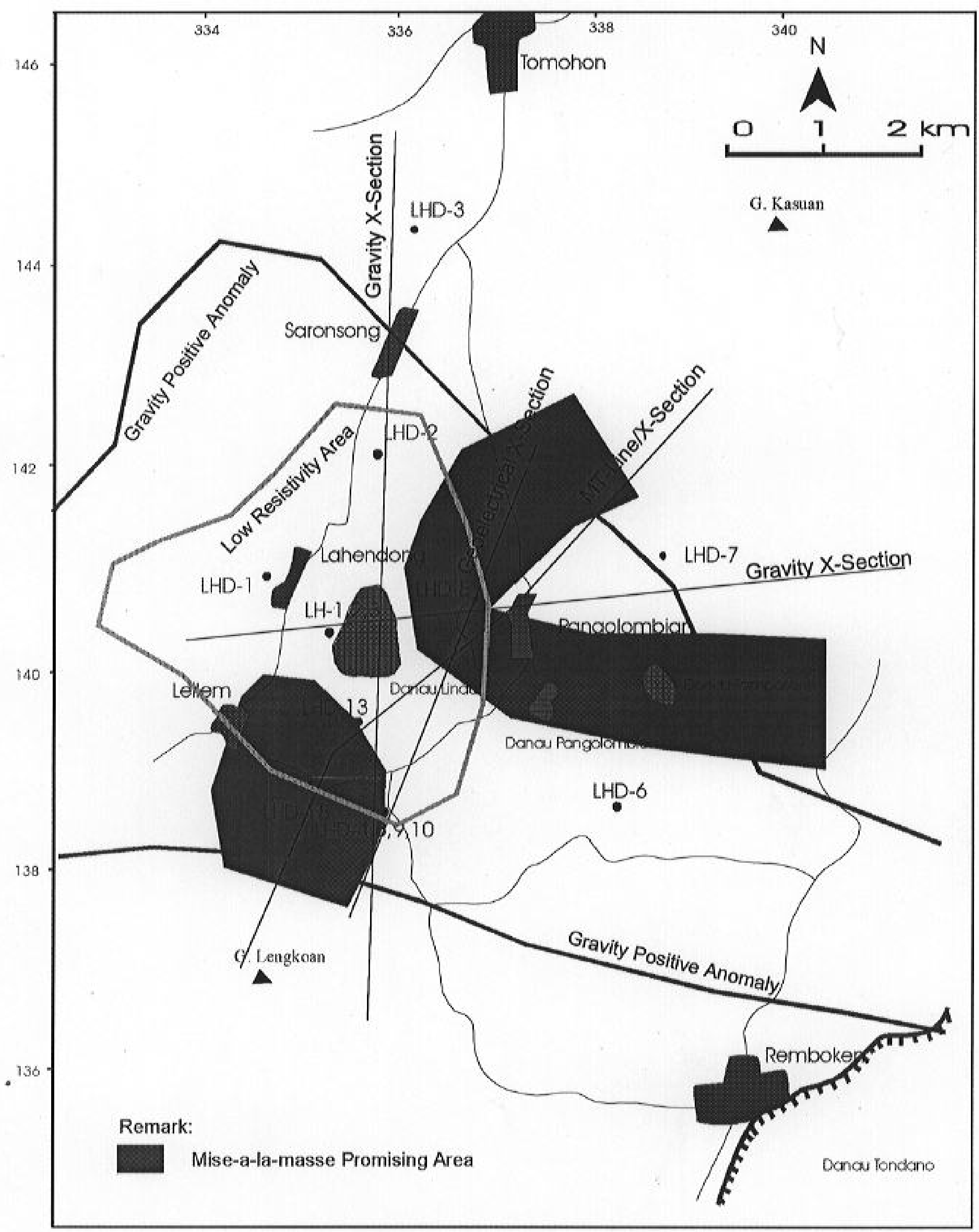

Figure-5
Compilation Map of Geophysical Interpretation