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Interpretation of DC resistivity data in the Bajawa geothermal field, central Flores, Indonesia

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Abstract: We have performed two-dimensional (2-D) interpretation of the Schlumberger sounding and mapping data that were obtained by the Directorate of Mineral Resources Inventory, Indonesia in the Bajawa geothermal field, central Flores Island, eastern Indonesia. There are three major surface geothermal manifestations, Mataloko, Nage and Bobo, in the study area. The aim of the Schlumberger survey was to investigate the deep resistivity structure for exploration of geothermal reservoirs in these areas. The 2-D resistivity models were obtained for ten, two and four survey lines in Mataloko, Nage and Bobo, respectively. Resistivity models of most lines have a surface high-resistivity layer that corresponds to less-altered young volcanic rocks, and a low-resistivity thick second layer that corresponds to alteration zones where conductive clay minerals might be abundant. A high-resistivity deep layer (resistivity basement) was recognized at a few zones including the Mataloko manifestation zone. The resistivity structure at the Mataloko manifestation, which is characterized by a very low-resistivity layer above the high-resistivity basement, suggested an existence of a potential geothermal reservoir system. However, the investigation depth of the Schlumberger measurement, with a maximum electrode spacing *AB/2* of 1,000 m or 2,000 m, was not sufficient to detect another deep high-resistivity layer that indicates an existence of geothermal reservoir.

1. Introduction

Electric and electromagnetic methods are intensively applied in geothermal exploration to delineate the resistivity structure of geothermal reservoirs. The reason is that the resistivity structure is one of the most important factors for understanding the structure of geothermal reservoirs. Schlumberger sounding is the most popular method among DC resistivity methods that have been used for this purpose in the past few decades, mainly because of its large investigation depth.

The DC resistivity surveys were carried out by the Directorate of Mineral Resources Inventory, Indonesia (DMRI) in the Bajawa geothermal field, central Flores, eastern Indonesia, in 1997 (Andan *et al.,* 1998) and 1998. The surveys consisted of Schlumberger sounding, Schlumberger mapping and head-on resistivity profiling. We have conducted a two-dimensional (2-D) inversion of the Schlumberger data and compared the resistivity models with the results of magnetotelluric (MT) surveys (Uchida *et al.*, 2002) and other geoscientific studies for the interpretation of geothermal reservoirs in the area.

2. Data

The Bajawa geothermal field is located in the central part of the Flores Island, Nusa Tenggara Timur (NTT) Province, eastern Indonesia (Fig. 1). The survey area is on a high land whose average elevation is approximately 1,000 m. The area is underlain mostly by young volcanic formations (WestJec and MRC, 2000; Muraoka *et al.,* 2000). An active volcano, Mt. Inerie, is located west of the survey area. There are numerous small volcanic cones that are younger than 0.5 Ma. Three major surface geothermal manifestations, Mataloko, Bobo and Nage, are located in the study area. The Schlumberger surveys were conducted to investigate the structure of these manifestation areas.

Figure 1 shows the Schlumberger sites that were

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used for the 2-D interpretation. Among the ten survey lines in the Mataloko area, Lines B, C and D are approximately in the east-west direction, and the rest are oriented approximately in the north-south direction. There are 19 Schlumberger sounding stations. The current-electrode spacing, *AB/2*, for the sounding varies from 1.6 m to 2,000 m. There are 81 mapping sites including the sounding stations. The interval of the mapping sites is 500 m along the survey lines. The electrode spacing *AB/2* for mapping are 250, 500, 750 and 1,000 meters. The expansion of the electrode array at each station is along the survey line for both sounding and mapping. The subsequent magnetotelluric survey in 1999 was more concentrated in the southern half of the Schlumberger survey area (Fig. 1; Uchida *et al.*, 2002).

In the Nage area, two survey lines were interpreted. There are two sounding stations whose electrode spacing varies from 1.6 m to 1,000 m. There are eight mapping sites including the sounding stations. The electrode spacing for mapping is the same as the Mataloko area.

In the Bobo area, four survey lines were inter-

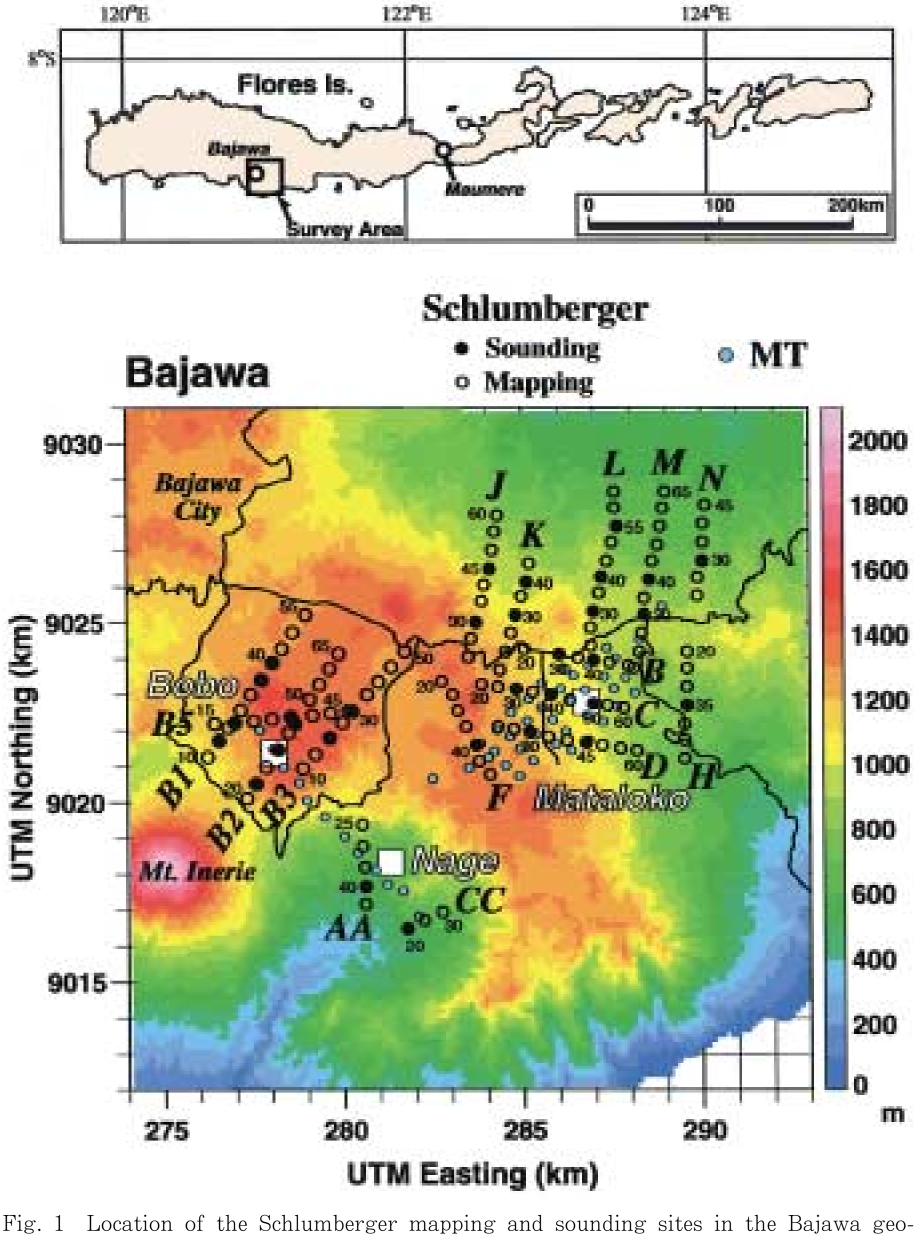


Fig. 1 Location of the Schlumberger mapping and sounding sites in the Bajawa geothermal field. Top figure shows the Flores Island and neighboring islands, eastern Indonesia. In the bottom figure, solid black circles are Schlumberger sounding sites, open black circles are Schlumberger mapping sites, and blue circles are MT stations. The background is topography contours, white squares are surface manifestations, and black lines are major local roads.

preted. There are ten sounding stations, whose electrode spacing varies from 1.6 m to 1,000 or 2,000 m. The number of mapping sites is 37 including the sounding stations. The electrode spacing for mapping is the same as the Mataloko area.

The field instruments used for the data acquisition are a DMRI-designed transmitter for sending current into the earth and an analog chart recorder for measuring the potential difference on the surface.

3. 2-D Inversion Scheme

We have applied 2-D inversion to ten survey lines (B, C, D, F, H, J, K, L, M and N) in Mataloko, two lines (AA and CC) in Nage, and four lines (B1, B2, B3 and B5) in Bobo (Fig. 1). All the sounding data and mapping data along these survey lines were used for the inversion.

In the Schlumberger sounding measurement, we usually have several segments of apparent resistivity curves for one sounding, which correspond to different potential electrode spacings, *MN/2*. We shifted those segments along the apparent-resistivity axis of the sounding curve toward the larger *MN/2* segments to produce a single continuous sounding curve.

The 2-D inversion method used here is based on Uchida (1991, 1993a, 1993b). It utilizes the conventional linearized least-squares scheme and applies a smoothness regularization for stabilizing the ill-posedness of the problem. The minimization of data misfit and model roughness are simultaneously achieved by introducing the Bayesian likelihood (Uchida, 1993a, 1993b).

The forward modeling utilizes the finite-element method. Therefore, topography can be incorporated in the modeling. The elevation data of the mapping/sounding sites were provided by the DMRI's geodesy survey. Starting with a homogeneous earth of 10,000 ohm-m with the topography as an initial model, the iterative inversion procedures almost converge after several iterations.

4. 2-D Interpretation

4.1 Mataloko Area

Figure 2 shows 2-D models of the Lines B, C, D and F. Figure 3 shows observed and modeled sounding curves of Lines B, C and D. Note that the reliability of resistivity distribution beneath the mapping sites may be poor in both shallow (less than 150 m depth) and deep portions (greater than 600 - 700 m depth), because those sites only have four different electrode spacings. Resistivities of these portions were determined in conjunction with the data of the neighboring sounding sites. The quality of the data with large electrode spacings is sometimes poor because of rough terrain and low signal levels. However, as we can recognize in Fig. 3, the fitting between the observed and calculated apparent resistivities is very fine for both mapping and sounding sites.

Resistiviy structure of these lines can be summarized as follows.

- Almost all sites are underlain by a surficial resistive layer of approximately 50 - 300 ohm-m. The thickness of this resistive layer gradually changes from site to site, from less than 100 m to approximately 500 m. The surficial resistive layer is very thin beneath Sites C-51 and C-55 on Line C, where the surface manifestation is located.
- Below this resistive layer is a conductive layer that is distributed along all the lines. Resistivity of this conductive layer is mostly below 10 ohm-m. Very conductive anomalies are seen beneath sites in the eastern part of Line C and western part of Line B.
- There is a high-resistivity basement beneath the eastern half of Line C. The sounding curves at Sites C-40 and C-51 clearly support this model (Fig. 3). Other lines do not indicate the existence of the high-resistivity basement.

Figure 4 shows 2-D models of six north-south lines at the Mataloko area. The data of Lines H and N were simultaneously inverted. Resistivity structure of these lines are similar to the west-east lines in Fig. 2. Most sites have a high-resistivity surface layer and low-resistivity second layer. Curves at the sounding sites K-30, K-40 and N-30, indicate the existence of a high-resistivity basement. Other soundings do not show such resistivity curves. A small alteration zone was found between K-25 and K-30 by a surface geological survey (WestJec and MRC, 2000). Smectite was identified by X-ray analysis of a rock sample from the surface. The very low resistivity anomaly may be associated with hydrothermal activity that created the alteration zone.

Figure 5 shows depth slice sections of a three-dimensional (3-D) inversion model of MT data at Mataloko (Uchida *et al.*, 2002). Figure 6 compares Schlumberger 2-D models of Lines B, C and D with the corresponding cross sections extracted from the MT 3-D model in Fig. 5. Line C crosses the Mataloko manifestation zone, while Lines B and D are located north and south of the manifestation, respectively.

The surficial high-resistivity layer is distributed along these three lines, except at the location of the manifestation. These features are easily detected by both Schlumberger and MT models. However, this resistive layer is generally thicker in the Schlumberger models than the MT models. Two possible reasons are; 1) the MT signal, with the highest frequency of 120 Hz (Uchida *et al.,* 2002), is less sensitive to the surface high-resistivity layer and hence the layer was not properly interpreted in the inversion, and 2) both Schlumberger and MT apparent resistivities are contaminated by static shifts or other biases and they were not satisfactorily explained by the 2-D or 3-D models.

In the MT model, the low-resistivity second layer is distributed beneath all three lines, and it is underlain by a high-resistivity basement layer. The low-resistivity layer is thin in the eastern part and gradually increases to the west. However, in the Schlumberger model the high-resistivity basement layer is seen only beneath Line C. Resistivity and shape of the low-resistivity layer of Line C is similar between the Schlumberger and MT models. As we can recognize in the MT models (Fig. 5), the high-resistivity basement is the shallowest, approximately a depth of 600 m, at Line C near the manifestation, if we define a layer of several tens of ohm-m is resistive. Therefore, the maximum electrode spacing *AB/2* of 2,000 m was enough to detect the high-resistivity basement at Sites C-40 and C-51.

On the other hand, the high-resistivity basement can not be observed in the Schlumberger models for

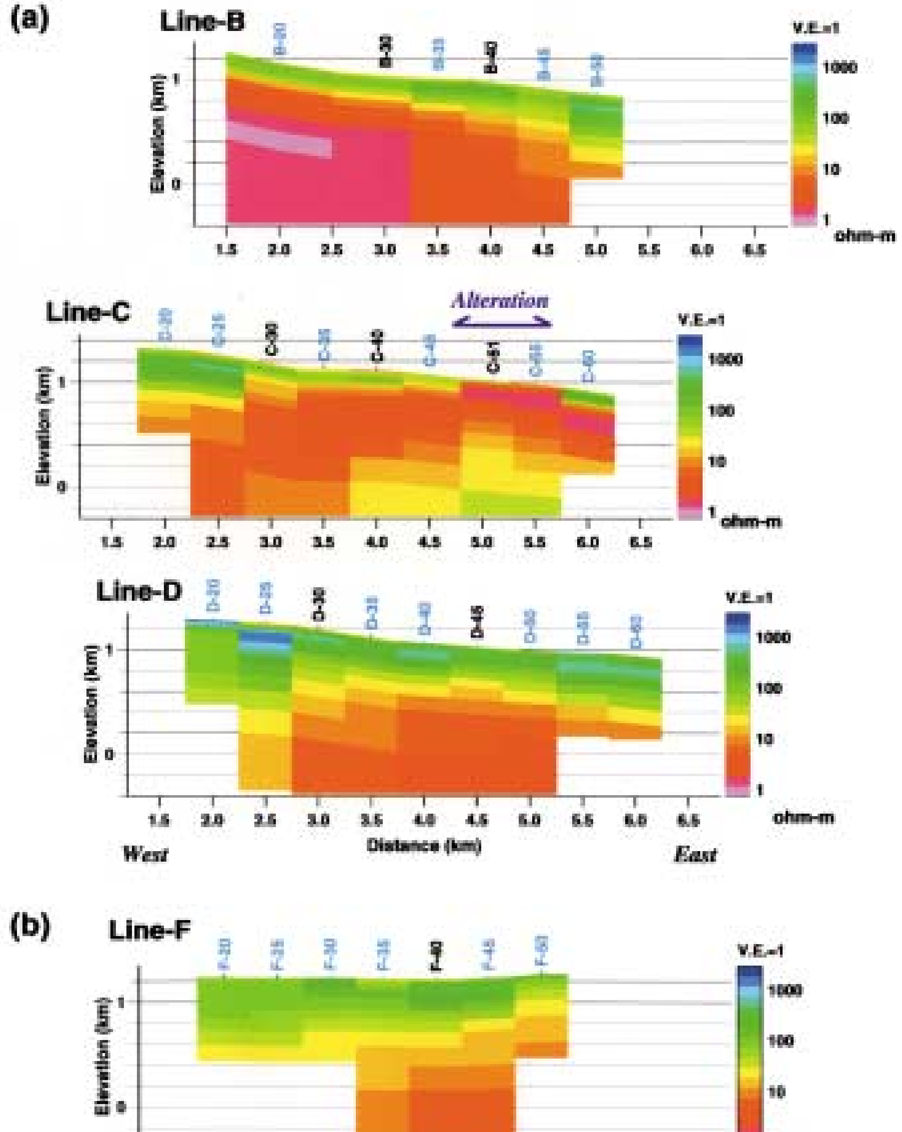
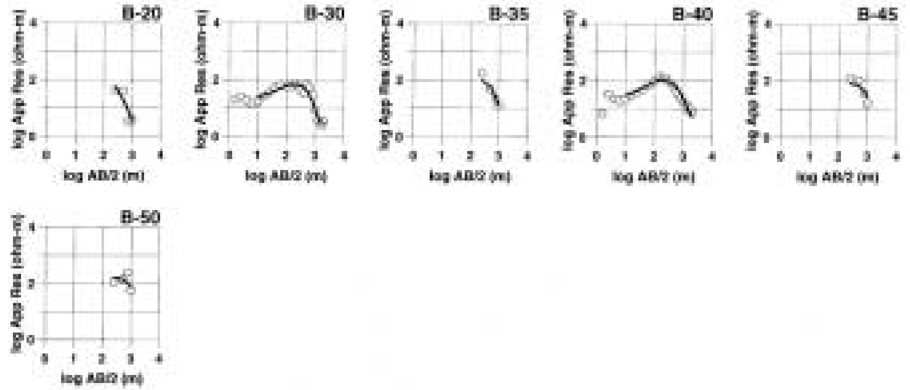
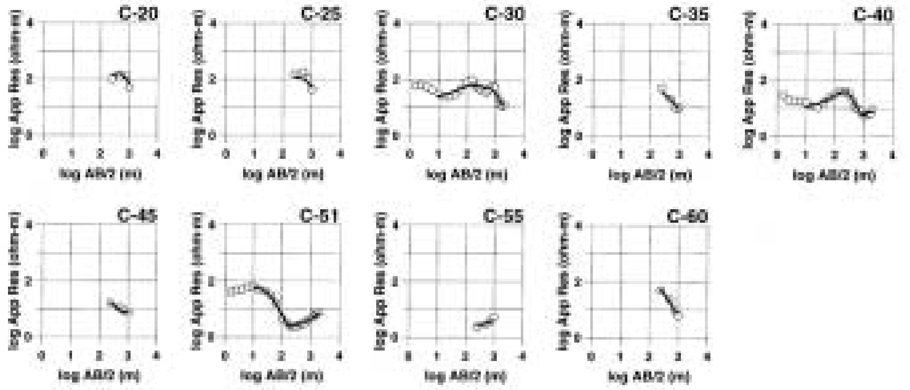


Fig. 2 The 2-D models of the Schlumberger data in Mataloko for (a) east-west lines: B, C and D, and (b) NW-SE line (Line F). Black site numbers indicate sounding sites, while blue numbers are mapping sites. No vertical exaggeration is applied.

(a) Line-B



(b) Line-C



(c) Line-D

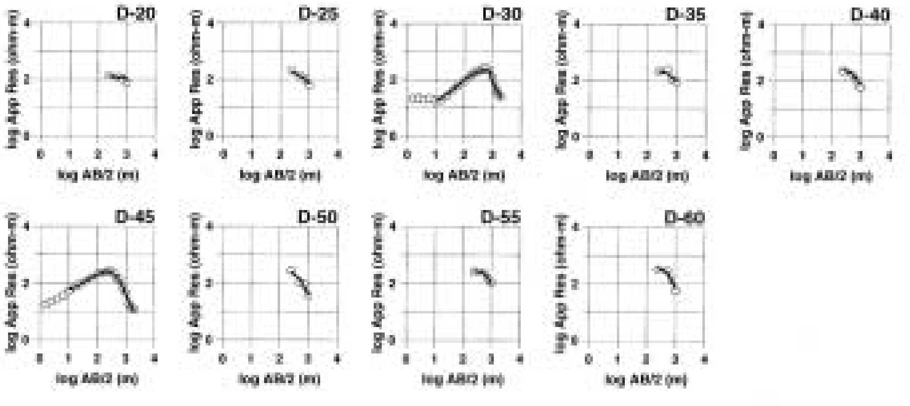


Fig. 3 Schlumberger sounding curves of Lines B, C and D with observed data (open circles) and theoretical values obtained from the models in Fig. 2a (Solid lines).

Lines B and D. The low-resistivity second layer is very thick in these models. The depth of the basement in the MT model is approximately 800 m in the eastern part of Lines B and D. Although the basement is deeper only by a few hundred meters than Line C, the Schlumberger investigation depth is not sufficient to detect the basement beneath Lines B and D. If we have the data with a larger electrode spacing on these two lines, we may have obtained similar models as Line C, by having a more conductive thinner low-resistivity layer.

4.2 Nage Area

Figure 7 shows 2-D models of Lines AA and CC in the Nage area, together with the MT model of the Bobo-Nage line (Uchida *et al.*, 2002). Since the maximum current-electrode spacing *AB/2* is 1,000 m, we only have a shallow investigation depth.

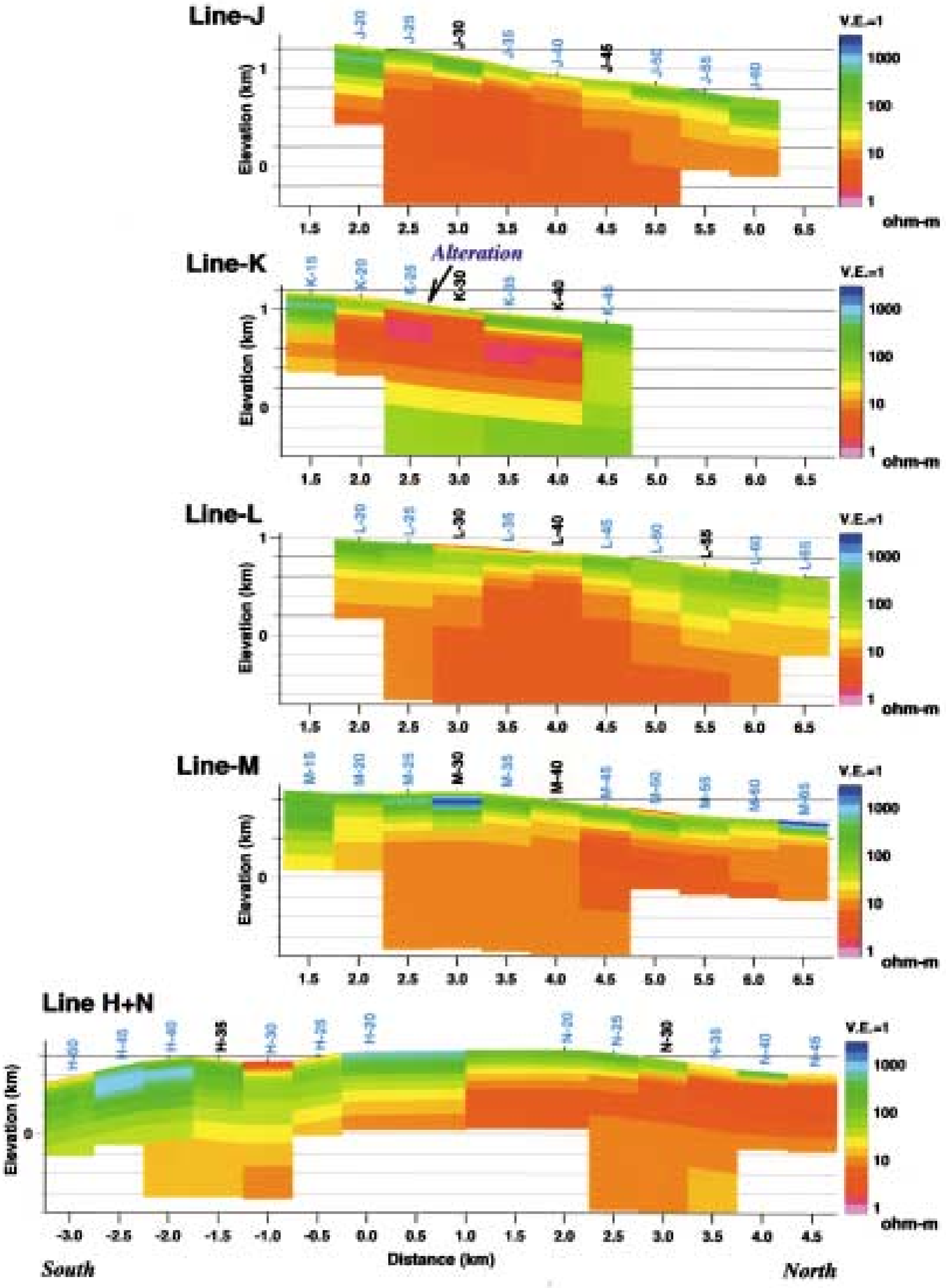


Fig. 4 The 2-D models of the survey lines in the N-S direction in Mataloko: Lines J, K, L, M, H and N. The data of Lines H and N were inverted simultaneously. Black site numbers indicate sounding sites, while blue numbers are mapping sites.

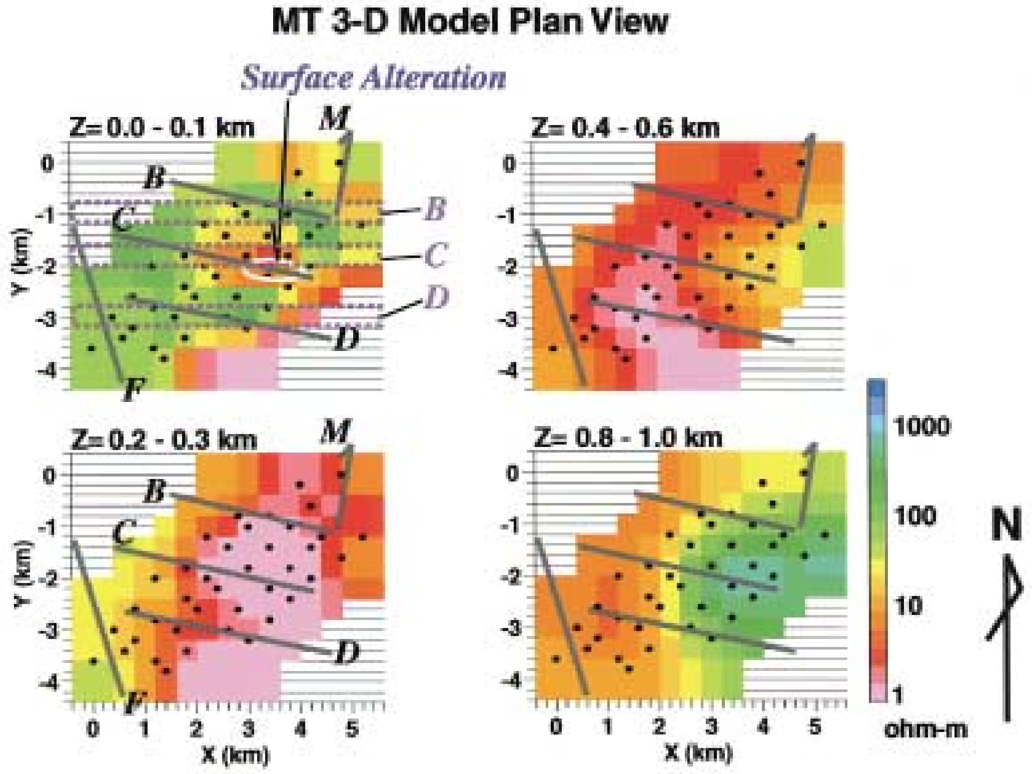


Fig. 5 Depth slice sections of the MT 3-D model at four depth levels (Uchida *et al.,* 2002). Black dots are MT stations, and thick gray lines are the Schlumberger lines. In the upper-left figure, the white line indicates the zone of surface alteration, and purple dashed rectangles indicate the blocks for the section display of the 3-D model in Fig. 6.

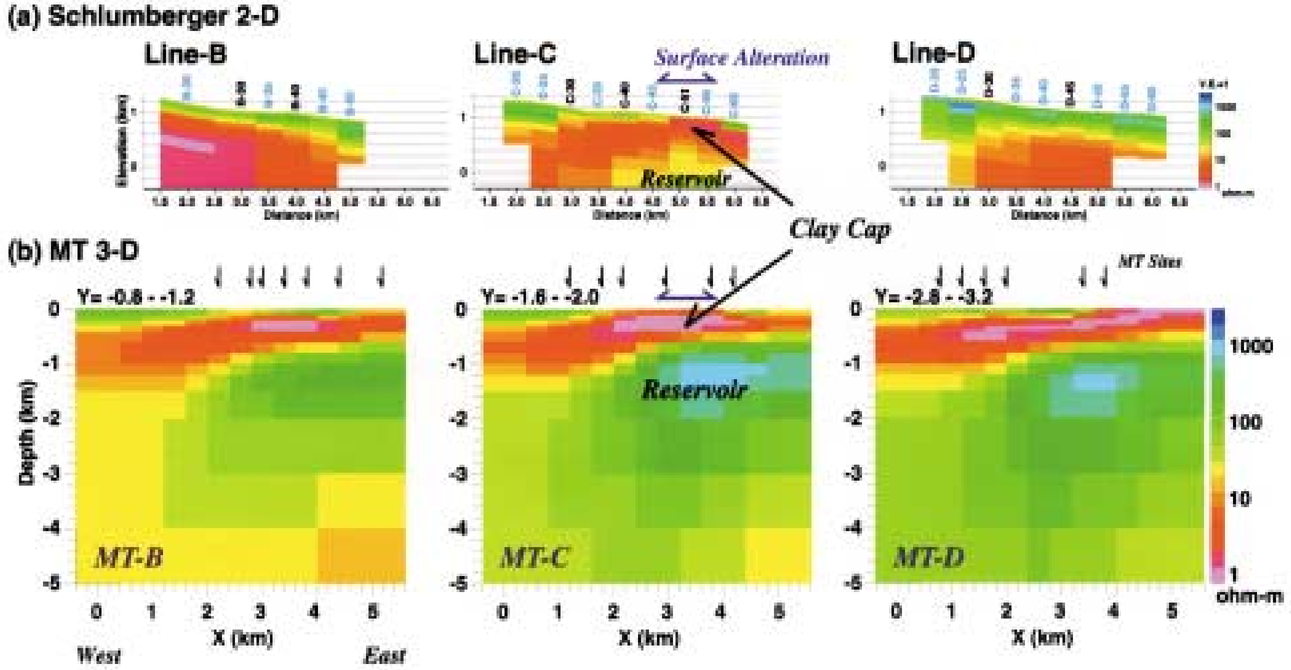


Fig. 6 Comparison of Schlumberger 2-D models of Lines B, C and D in Mataloko with the corresponding cross sections of the MT 3-D model. Location of the sections are shown in Fig. 5. Note that the direction of the Schlumberger lines is not exactly east-west.

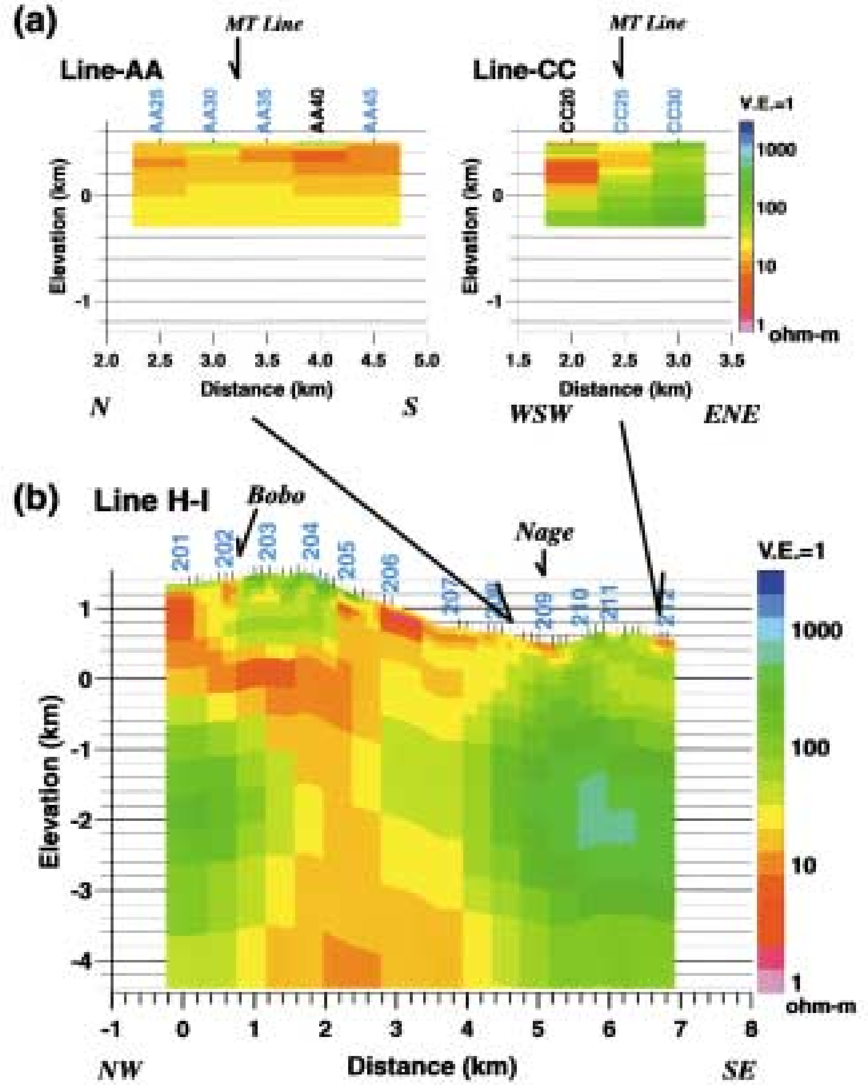


Fig. 7 (a) The 2-D models of the Schlumberger lines in Nage, (b) the 2-D model of the MT data on the Bobo-Nage line (Uchida *et al.*, 2002). Line AA is in the N-S direction, Line CC is in the WSW-ENE direction, and the MT line is in the NW-SE direction. In the Schlumberger models, black site numbers indicate sounding sites, while blue numbers are mapping sites.

The resistivity of Line AA is generally low. The minimum resistivity is found at a 200 - 300 m depth, and the resistivity increases below that depth. However, the minimum resistivity is approximately 10 ohm-m, which is not as low as Line C in Mataloko. Line CC is mostly underlain by a resistive layer except at Site CC-20.

Line AA crosses the MT line between Sites 208 and 209, and Line CC crosses at around Site 212 (Fig. 1). In the MT model, the shallow low-resistivity anomaly is very small at the Nage manifestation zone, and resistivity below sea level is high in the eastern part of the MT line. These results correspond well to the models of Lines AA and CC. The shallow low resistivity anomaly at Site 212 in the MT model is similar to Site CC-25 in the Schlumberger model.

Although the investigation depth of the Schlumberger data is limited, the Schlumberger models are very consistent with the MT 2-D model and representing the shallow resistivity features of the Nage area very well. It is recognized from both Schlumberger and MT models that there are only small low-resistivity anomalies beneath the Nage area.

4.3 Bobo Area

Figure 8 shows four 2-D sections in the Bobo area; three survey lines are in the SW-NE direction and one line (Line B5) in the E-W direction. Almost all the sites have a resistive surface layer and conductive second layer. One exception is that a conductive anomaly is seen from the surface at Site 30

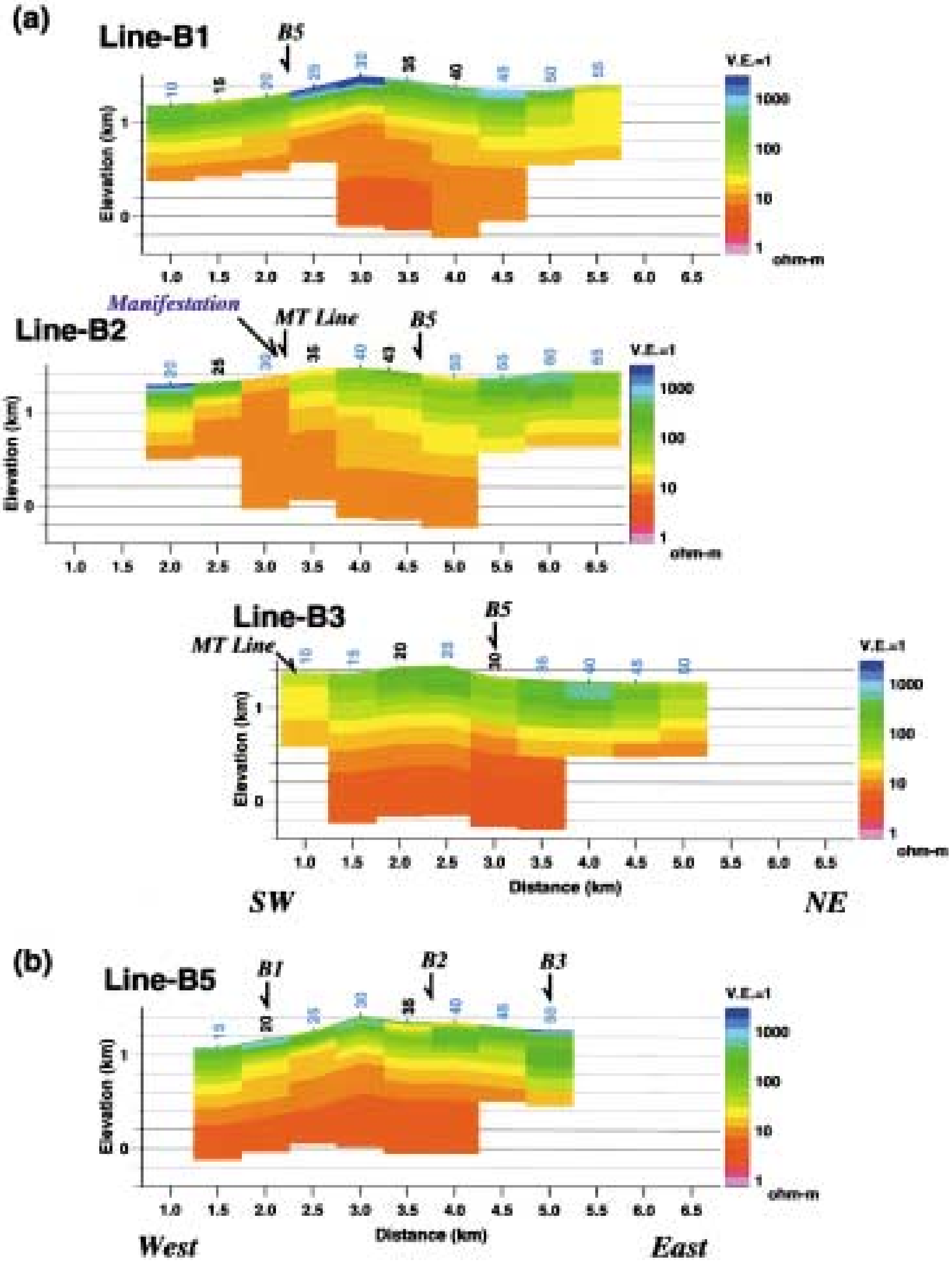


Fig. 8 The 2-D models of the Schlumberger data in Bobo for (a) SW-NE lines: B1, B2 and B3, and (b) east-west line (Line B5). Black site numbers indicate sounding sites, while blue numbers are mapping sites.

of Line B2, where the Bobo manifestation is located. This anomaly is also recognized in the MT model in Fig. 7.

Central portions of the Bobo lines are on young volcanic cones. The resistive surface layer is associated with non-altered volcanic formations near the surface. The low-resistivity second layer is possibly indicating alteration zones, which is the same as the resistivity models in the Mataloko area. However, the resistive basement was not recognized in the Bobo area because the investigation depth of the Schlumberger soundings was not sufficient.

5. Preliminary Interpretation and Conclusions

When we apply electric and electromagnetic surveys in geothermal exploration, the existence of a geothermal reservoir is typically characterized by a sequence of a very conductive shallow layer that corresponds to clay-cap and a resistive basement layer that corresponds to the reservoir zone.

The Schlumberger surveys in the Bajawa area revealed a low-resistivity second layer beneath all survey lines in Mataloko and Bobo. However, most sounding sites did not have sufficient investigation depth to detect the resistive basement beneath the low-resistivity clay cap, although the maximum electrode spacing *AB/2* was 1,000 m or 2,000 m.

An obvious exception is the eastern part of Line C in the Mataloko area. A resistivity structure with a low-resistivity second layer and high-resistivity third layer were found. A pilot drilling that was conducted in 2000 to a depth of approximately 200 m indicated the existence of smectite in a shallow zone of the area (WestJec and MRC, 2001). The low-resistivity layer corresponds to the clay-rich zone.

Also, smaller but similar resistivity patterns are recognized on Line K and Line N in the Mataloko area. A very low-resistivity layer is interpreted beneath Line K, where smectite was found by an analysis of a rock sample from the surface alteration zone (WestJec and MRC, 2000). This may be an indication of another hydrothermal system other than that in the central Mataloko beneath Line C.

The pilot drilling in the Mataloko manifestation area successfully produced steam from a shallow zone in 2001 (WestJec and MRC, 2001). The interpretation of a low-resistivity clay-cap and high-resistivity reservoir zone is applicable to the evaluation of the geothermal resources in this area. Therefore, the Schlumberger models have taken an important role in the integrated interpretation of the reservoir system in the Mataloko area.

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インドネシア東部フローレス島バジャワ地熱地域における比抵抗法データの解析

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要　旨

インドネシア東部に位置するフローレス島バジャワ地熱地域においてインドネシア鉱物資源調査局が取得したシュランベルジャ法電気探査データについて2次元解析を実施し，地熱貯留層に関する考察を行った．当該地域にはマタロコ，ナゲ，ボボといった比較的規模の大きい地表徴候地がある．電気探査はそれらの場所における貯留層構造の解明を目的として行われた．2次元解析はマタロコ地区10測線，ナゲ地区2測線，ボボ地区4測線に対して行った．大部分の測線では，地下浅部に高比抵抗層が分布し，これは変質をあまり受けていない新期火山噴出物層に対応するものと解釈される．その下部には厚い低比抵抗層が広がっており，これは低比抵抗の粘土鉱物に富む層であると判断される．マタロコ徴候地を含むいくつかの箇所では，深部に高比抵抗基盤を捕らえた．マタロコ徴候地では，低比抵抗層の比抵抗は非常に小さく，高比抵抗基盤が存在することを考慮すると，下部に有望な地熱貯留層が存在するものと推測される．しかし，本シュランベルジャ法電気探査の最大電極間隔AB/2は1000 mあるいは2000 mであり，探査深度は十分とはいえず，他の場所で地熱貯留層の存在を示唆する高比抵抗基盤の存在を確認することはできなかった．