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Self-potential mapping of the Mataloko and Nage geothermal fields, central Flores, Indonesia for applications on reservoir modeling

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Abstract: Self-potential (SP) surveys were carried out in the Mataloko and Nage geothermal fields, Flores Island, East Nusa Tenggara, Indonesia. As a result, the highest positive SP anomaly in Mataloko was observed at the geothermal manifestation area. The numerical simulation result shows the limit of the upflow zone. On the other hand in Nage, no single clear positive anomaly can be seen. The SP profile along the Wae Bana River in Nage suggests the existence of multiple local discharge zones along the river.

1. Introduction

The SP surveys were carried out in 1998 and 1999 at the Mataloko and Nage geothermal prospects, Flores Island as a part of the Japan-Indonesia cooperative research project "The Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia". This project is conducted by the Geological Survey of Japan, New Energy and Industrial Technology Development Organization and Volcanological Survey of Indonesia. Throughout this project, geological, geochemical and geophysical surveys were widely performed in the middle part of Flores Island including a resistivity survey that is essential for detailed SP data analysis.

The SP survey has been widely conducted for geothermal field exploration. However most SP data have been interpreted merely qualitatively. Generally a positive SP anomaly is interpreted as a discharge zone and negative as a recharge zone. However the exact location of these flow zones are not necessarily corresponding to the biggest SP anomaly because of the heterogeneity of the subsurface physical structure (Yasukawa *et al.*, 1993). Therefore a SP data analysis in consideration of the hydrological and electrical structure is valuable for its interpretation (Yasukawa and Mogi, 1998).

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The first part of this paper presents the SP survey in the Mataloko geothermal area conducted in 1998. A two dimensional numerical model (cross-sectional model) of fluid flow and its induced SP along a survey line in Mataloko will be introduced. The result of this numerical simulation suggests the existence of a high permeability zone and indicates its extent. The SP survey in the Nage geothermal area in 1999 will be explained. At the end of this paper, the differences of the Mataloko and Nage geothermal fields based on the SP survey results will be discussed.

2. Mataloko and Nage geothermal prospects

The Mataloko and Nage geothermal fields are located about 10 km southeast of Bajawa town, in the middle of Flores Island, Nusa Tenggara, Indonesia (Fig. 1). Active volcanoes Inerie and Inelika exist south and north of Mataloko, respectively. The basin between these two volcanoes has a length of 10 km in the NNW-SSE direction. The older volcanoes exist only at the edge of this basin while younger volcanoes widely exist in the inner part. Therefore this basin is considered as a caldera (Muraoka *et al.*, 2000).

A surface manifestation of geothermal steam and hot springs can be seen in the Mataloko area (Fig. 2). The main manifestation area, which elevation is around 1000 m, is located along the valley of the

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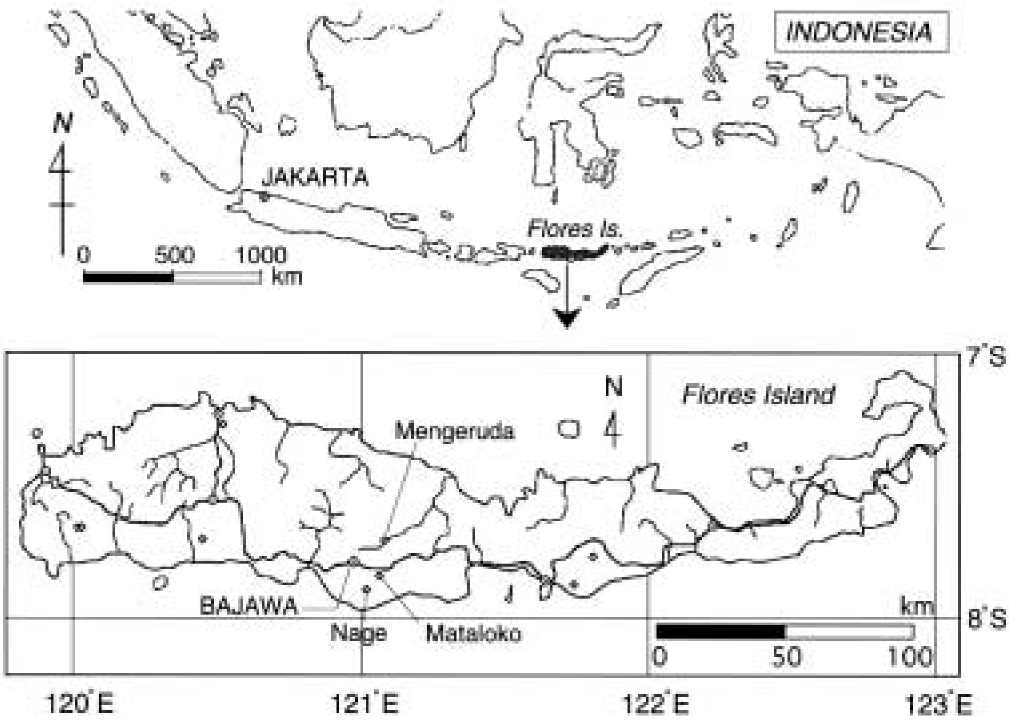

Fig. 1 Locations of the Mataloko and Nage geothermal fields.

Wae Luja River which runs eastward. Some alteration zones can also be seen around this river.

Nage, elevation is around 500 m, has a considerably large amount of geothermal manifestation along a valley, with a hot stream named Wae Bana. A vast alteration zone can be seen along the Wae Bana River.

3. SP survey in Mataloko

3.1 SP measurement and results

In July 1998, a SP survey in Mataloko was conducted in around the Wae Luja River, across the alteration zones identified by geological surveys. There were 430 SP measurement points with a spacing of 100 m along the survey lines. The surveyed area is about 5 km and 6.5 km in the E-W and N-S directions, respectively.

Figure 3 shows the location of the SP survey points around the Mataloko main manifestation area. The electric potential at the survey point P1 is assumed to be zero. Loop corrections were applied to thee measured SP data. Figures 4 and 5 show the resultant SP profiles along P and V survey lines, respectively. Dotted lines represent raw SP values and solid ones show the SP value after loop corrections. The contour lines shown in Fig. 3 are corrected SP in the Mataloko main area.

The highest SP anomaly in the Mataloko area is observed at P36 in the manifestation area along P and V lines. On the P line, which goes across Wae-Luja, a spike of a SP anomaly was observed. This positive anomaly is limited only to the vicinity of the stream. On the V line, which goes along the stream, a rather smooth slope can be seen east of the highest anomaly but a steep drop occurs to the west. This suggests that surface manifestations may be present east of P36. It is consistent with the fact that there are some hot springs in the east but none have been identified in the west.

A large negative anomaly, not corresponding to the topography, was observed around Y8 east of the main manifestation area. A SP profile across this zone is numerically analyzed in the next section. The other SP profiles are rather flat and the main causes of the anomalies are topographic effects or artificial noise around residential areas.

3.2 Two dimensional modeling of subsurface fluid flow and surface SP

A two-dimensional SP model was completed along an E-W survey line (line C' in Fig. 3) with a coupled fluid flow and SP simulator PTSP (Yasukawa *et al.,* 1993). Line C' is located approximately 500 m north of resistivity survey line C conducted by VSI (Andan *et al.,* 1997), which crosses the main manifestation area. The solid red line in Fig. 6 shows the observed SP profile along line C'. This SP profile is clearly different from the pattern expected from its topography: the higher the elevation, the lower the SP. Therefore effects of heterogeneity of physical properties may exist.

In PTSP, temperature and pressure distributions in a system are calculated based on the energy and mass conservation equations for proper boundary conditions. The distribution of the fluid velocity is

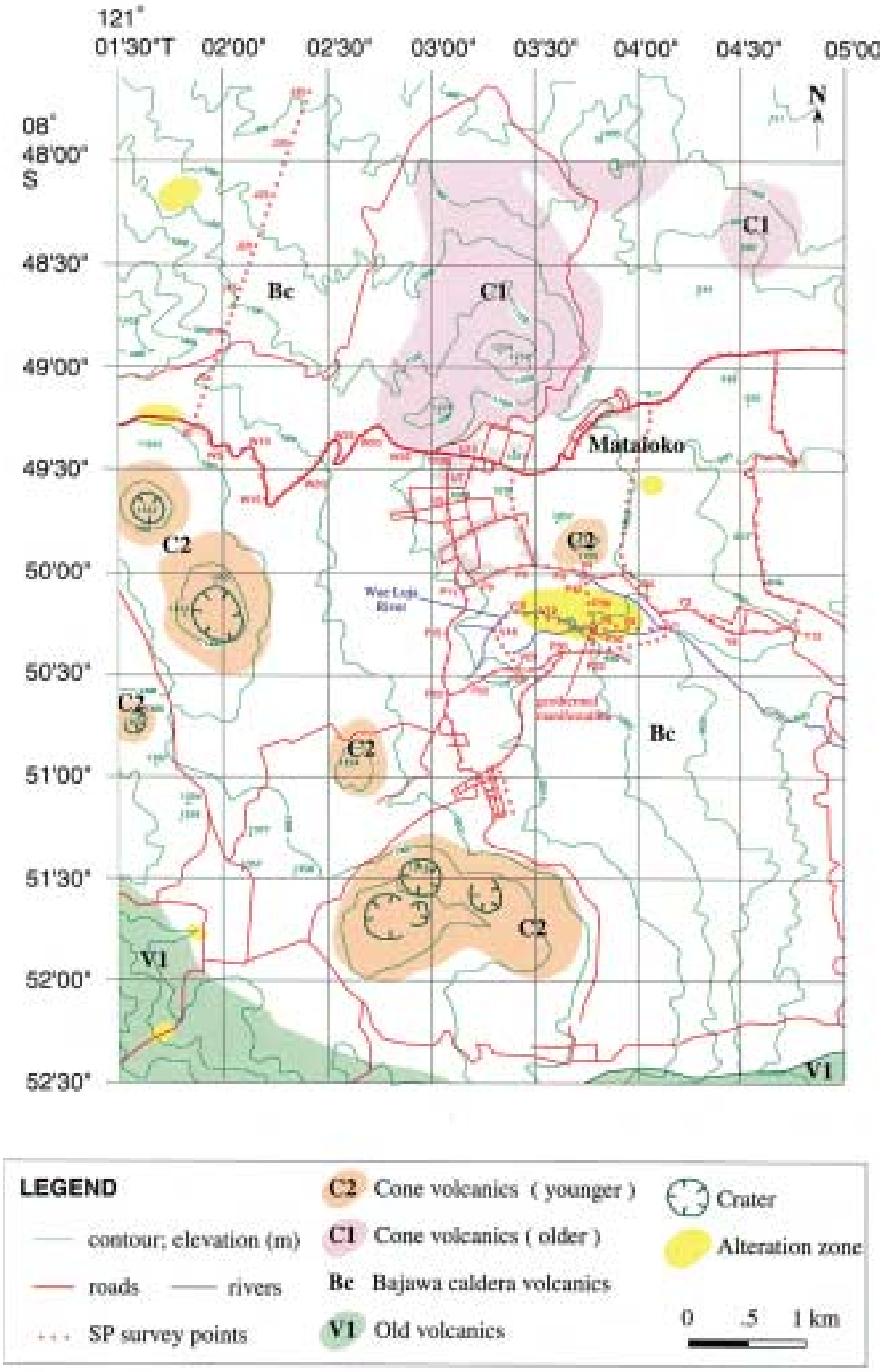

Fig. 2 Geological map around the Mataloko area (after NEDO *et al.*, 2000).

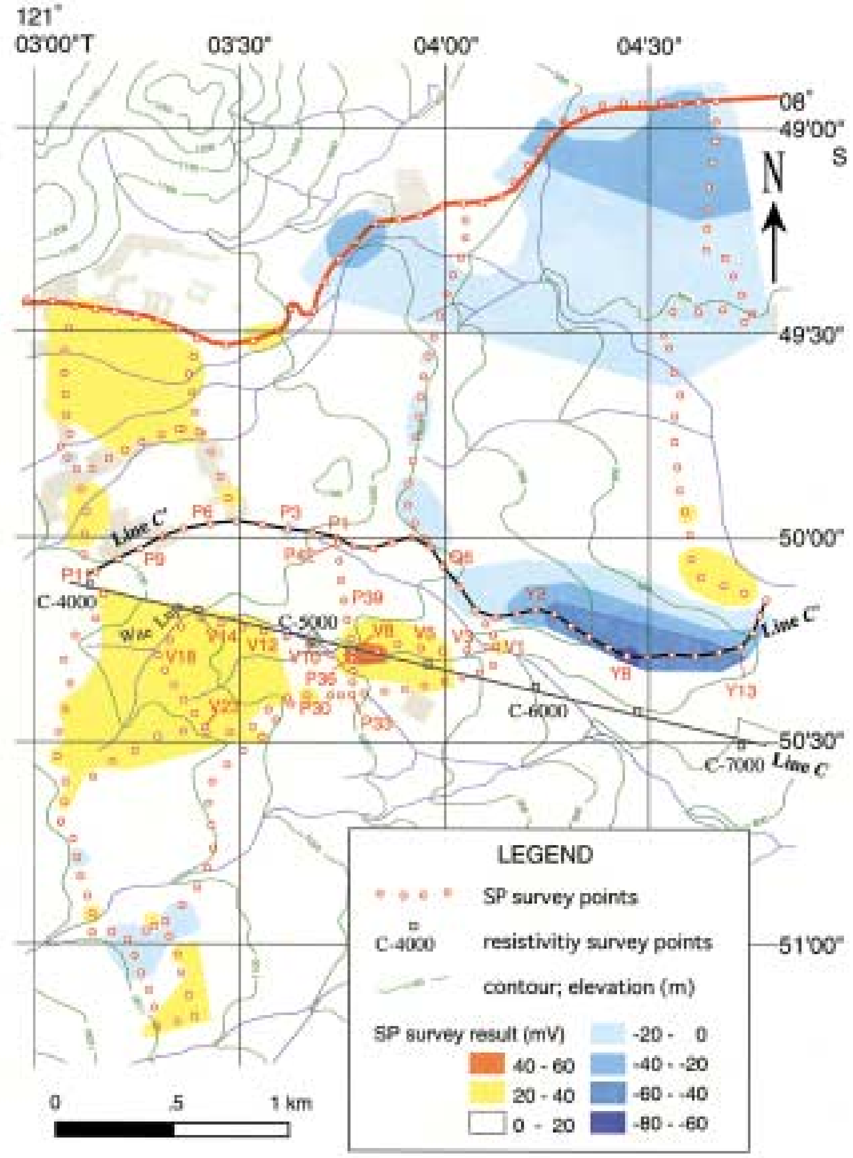

Fig. 3 SP survey points (o) in the Mataloko area.

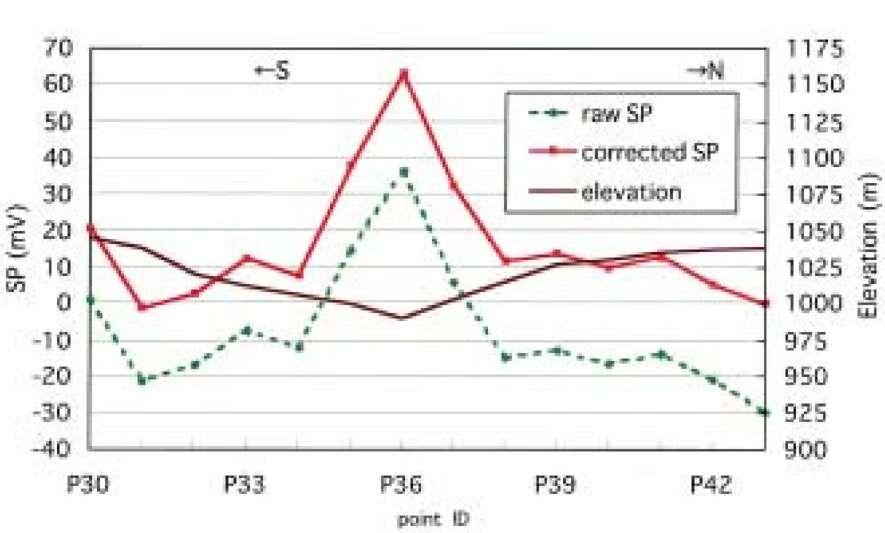

Fig. 4 Observed SP and elevation profiles; P-line.

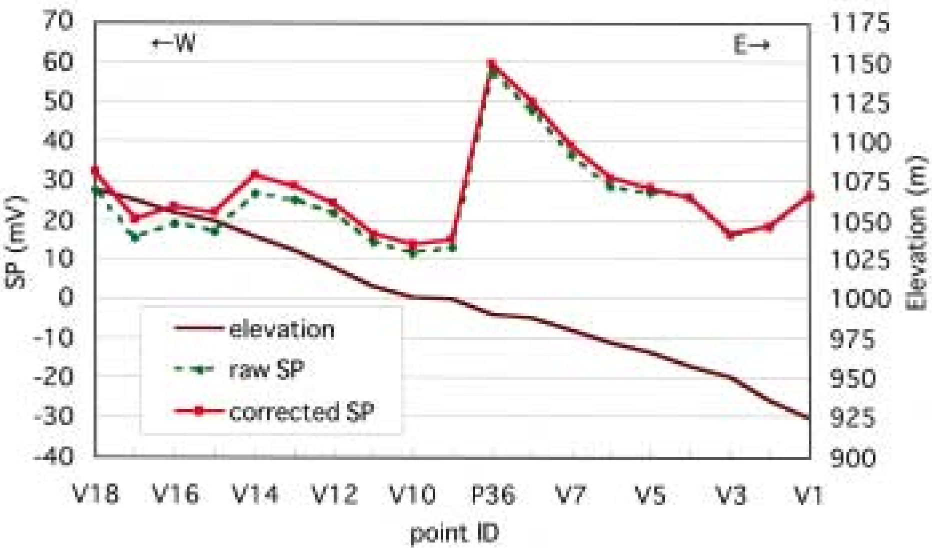

Fig. 5 Observed SP and elevation profiles; V-line.

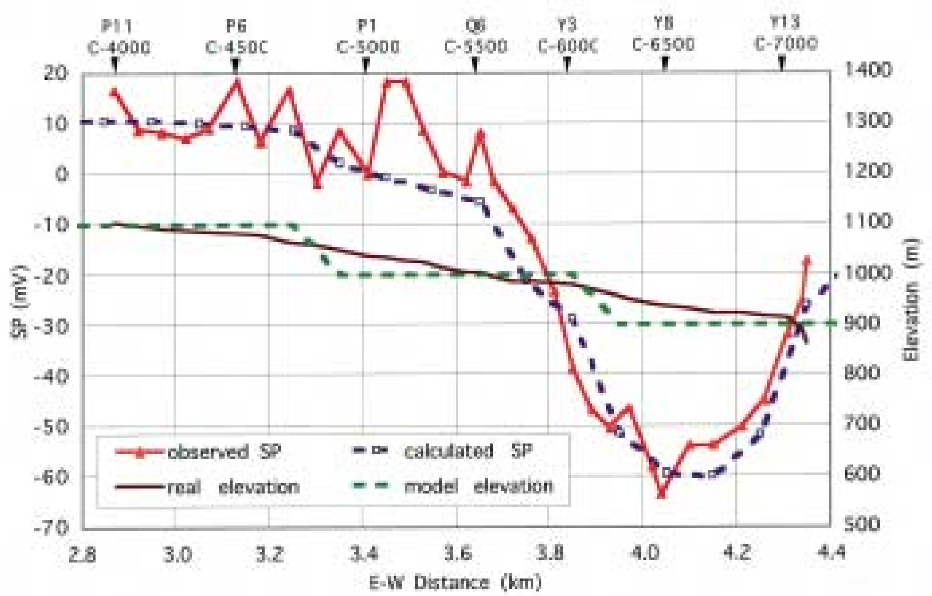

Fig. 6 Comparison of observed and calculated SP profiles along C'-line.

thus obtained and the current source distribution caused by fluid flow is calculated for a given electro-kinetic cross-coupling conductivity as follows;

$$S = -\nabla L_V \cdot \boldsymbol{u} - L_V \nabla \cdot \boldsymbol{u} \qquad (1)$$

where S, L_V *and* $\boldsymbol{u}$ are electrical current per unit volume (Amp/m^3), velocity cross-coupling conductivity (Amp-sec/m^3) and velocity field (m/sec), respectively. The induced SP distribution is then calculated for a given resistivity structure. Therefore input data of permeability, resistivity and cross-coupling conductivity distribution, in addition to boundary conditions are required for the calculation by PTSP. For more details, see Yasukawa *et al.* (1993).

In PTSP, the temperature dependence of cross-coupling conductivity will be automatically calculated. According to Sill (1983), the variation of L_V with temperature T below 300 ℃ is approximately described by;

$$L_V(T) = L_{V0}(1 + C\Delta T), \quad \Delta T = T - T_0 \qquad (2)$$

where C is a constant and subscript 0 indicates the reference temperature T_0. This equation is introduced in PTSP with the constant C = 0.01 (℃$^{-1}$), which is consistent with the experimental results of Ishido and Mizutani (1981), as well as those of Morrison *et al.* (1978).

The upper part of Fig. 7 shows the resistivity grid of the numerical model. It is based on the result of resistivity surveys conducted by VSI (Andan

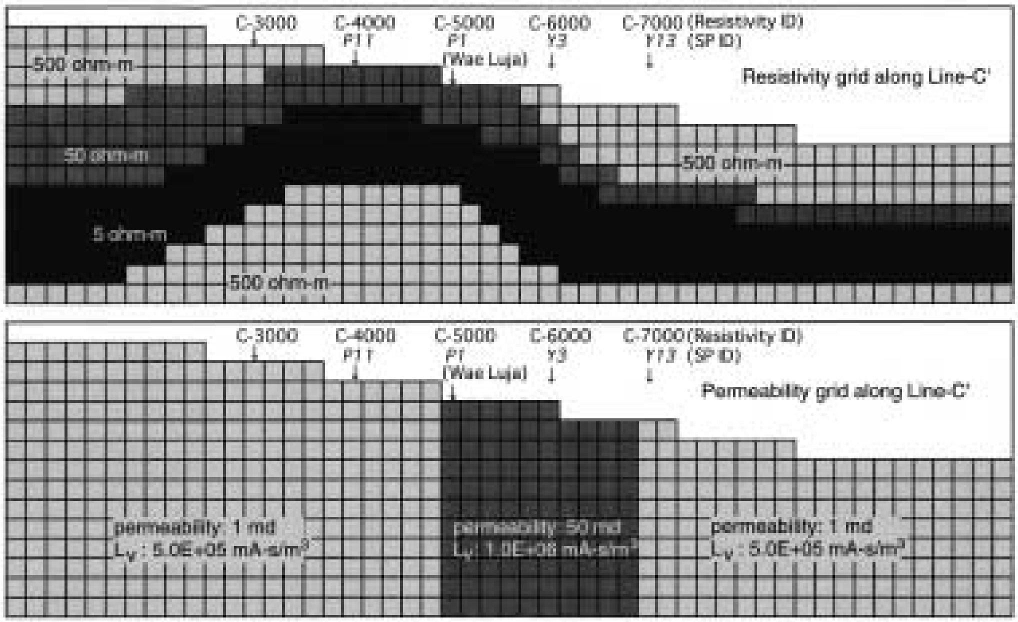

Fig. 7 Physical property grids of the model.

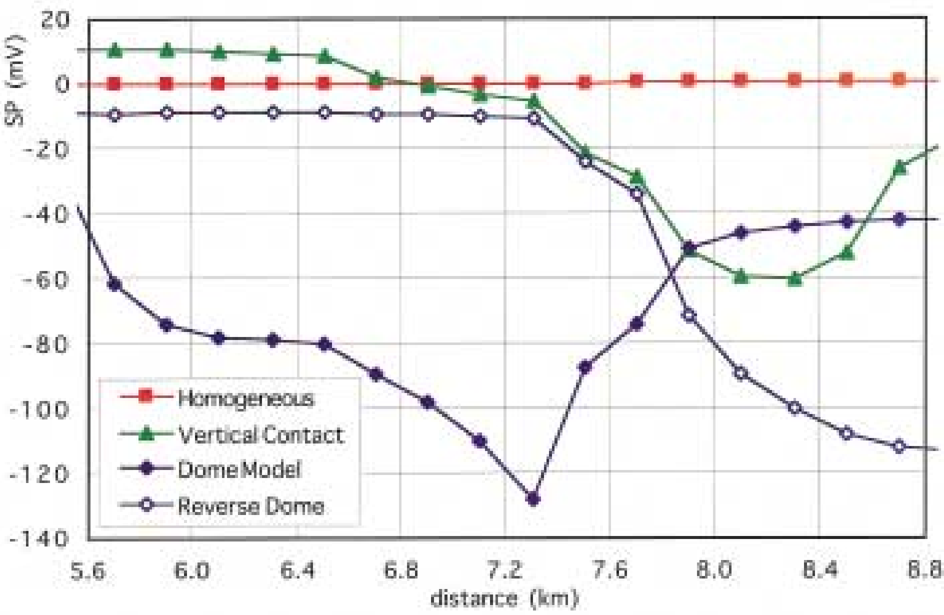

Fig. 8 Calculated SP profiles for different permeability models.

et al., 1997). A low resistivity layer (5 ohm-m) reaches to a shallower depth at the vicinity of Wae-Luja. Since a negative SP anomaly on a topographic slope cannot result from a resistivity structure alone (Yasukawa and Mogi, 1998), a permeability model was also introduced.

A homogeneous permeability model and heterogeneous permeability models with a dome-shaped geometry same as the resistivity model were applied. The calculation results of these models are shown in Fig. 8 as "homogeneous" permeability model, "dome" model and "reverse dome" model, respectively. However, the SP anomaly shown in Fig. 6 was not reconstucted by these homogeneous or dome-shaped permeability models. The permeability values adopted for these models and their calculation results are shown in Table 1 and Fig. 8, respectively. The cross coupling conductivity L_V is homogeneous for these models. Whereas even with different L_V values for each layer, the tendency of the calculated SP profiles are still the same.

Therefore a vertical contact model was considered; a higher permeability column was assumed near the negative anomaly zone. This model represents subsurface structures such as vertical faults. The calculation result for this model is shown as a "vertical contact" model in Fig. 8 matched with the observed SP profile. A lower permeability column was also

Table 1 Physical property values applied for the homogenous and "dome" models.

Models	Permeability (md) for grid with R=			Lv
	500 (Ω-m)	50 (Ω-m)	5 (Ω-m)	(mA-sec/m³)
Dome Model	1	100	100	1.00E+07
Reverse Dome	10	1	0.1	1.00E+07
Homogeneous	10	10	10	1.00E+08

tested, but the SP profile shown in Fig. 6 was reconstructed only with a higher permeability column. The width and the contrast of the high permeability zone were adjusted until the resulting SP profile reaches a good match with the observations. Permeability in Fig. 7 is thus obtained as the finalmodel.

For the fluid flow calculation, the following boundary conditions were adopted; a constant pressure and temperature surface (1 atm, 20 ℃), impermeable side boundaries and a constant temperature bottom (70 ℃), which gives a normal geostatic temperature gradient. The L_{V0} is assumed as a function of permeability because its variation is mainly caused by the chemical components, which change is considered to be small in a single reservoir.

The comparison of the observed and calculated SP is shown in Fig. 6. A quite good match was obtained for this grid size (100 x 100 m^2). High frequency anomalies in the observed SP are probably caused by the shallower features. The location of the high permeability zone is consistent with the fact that no hot springs occur west of P1 while some hot springs are present east of P1. However, according to the fluid flow simulation, the fluid in this zone flows downward. Therefore the surface manifestations near this line must be a quite local phenomena. In most of the high permeability zone, the fluid is considered to flow downward. A large negative SP anomaly along line C' is thus caused by this downflow.

4. SP survey in Nage

The SP survey in the Nage geothermal field was conducted in August to September, 1999. Figure 9 shows the SP survey points in Nage and its resultant SP distribution. Twenty-two survey points out of forty-two are located along the Wae Bana River.

The Wae Bana River runs northeast to southwest. At the upper stream around C3, the river is merely a narrow cold stream. When the stream is mixed with geothermal hot springs around A0, it results in a hot river with a width of about 10m at A16.

Natural hot spring sources are identified near A2, B0 and C1. There might exist some other hot fluid discharges around these points. The water temperature around A0 is 70 to 80 ℃ while that around A16 is about 50 ℃. Therefore, mixing with the cold discharge might also be occurring between A7 to A16 beside the atmospheric cooling effect on the river.

Figure 10 shows the observed SP profile along the Wae Bana River. The general trend of SP, increasing in the downstream, is considered to be caused by the topographic effects: higher the elevation, lower the SP for homogeneous ground. The sharp positive anomaly at C1 and A1 might correspond to the surface discharge points. The other positive SP anomaly might also indicate possible discharge zones (or negative points be recharge zones), but their anomaly is not as clear as C1 or A1 so that they are not necessarily corresponding to fluid flow (discharge or recharge zones).

Contour lines in Fig. 9 shows that the northeastern area, where some hot spring sources exist, is not the highest SP zone of the whole survey area. Southern survey points along the road have higher SP even though their elevations are about 10 m higher than the survey points along the Wae Bana River. It is the opposite tendency of the topographic effect. This result suggests, on a larger scale, a considerable amount of upflow from a deep thermal fluid source exists not under the manifestation zones, but in the southern part of the area.

5. Discussion

In Mataloko, a single sharp positive SP anomaly was observed at the surface geothermal manifestation zone. That is the highest SP anomaly observed in the Mataloko area.

In the numerical modeling of Mataloko, the possible permeability model that can achieve the SP profile matching with the observed data is not unique. The vertical extent of the high permeability zone might possibly be shallower. However, the SP numerical modeling proves the existence of a high permeability zone and suggests the surface extent of this zone. Therefore the combination of a resistivity survey and SP survey is quite convenient to investigate the permeability structure.

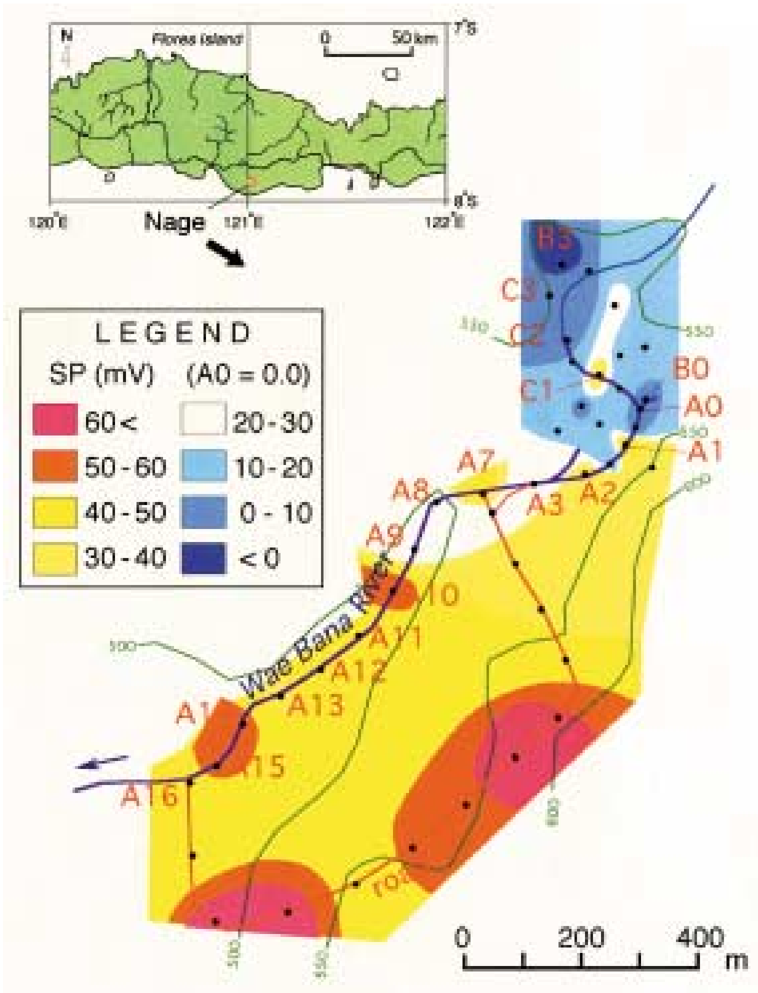

Fig. 9 SP contour map of the Nage geothermal field observed in 1999.

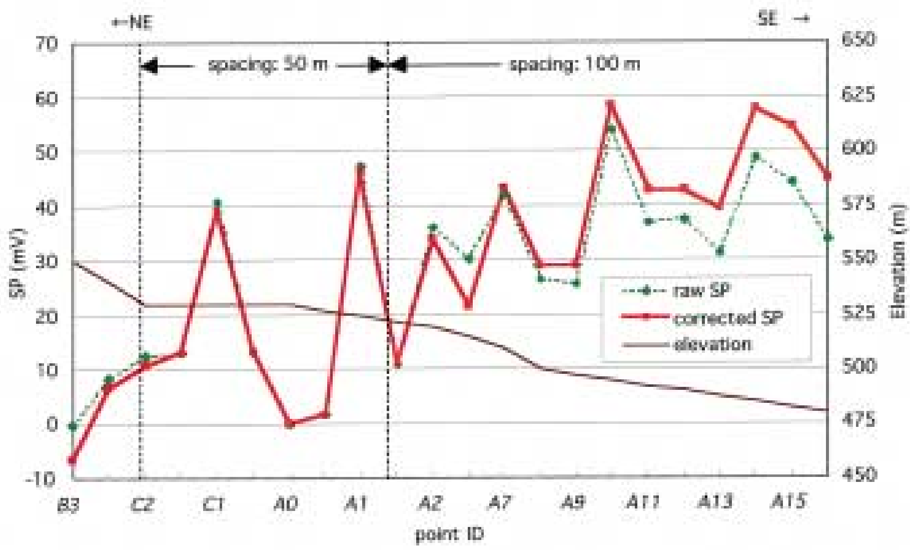

Fig. 10 SP profile along the "Wae Bana" River.

For this numerical model, no hot fluid source was assumed because there is no clear surface manifestation along the C' line. This SP modeling was performed assuming the SP anomaly is caused only by topographic effects, resistivity structure and permeability structure. Since the SP profile along the C' line was constructed by a model without an upflow from a depth, this modeling suggests that the surface discharge is a local phenomenon.

In Nage, the highest SP was observed at a higher elevation along a road in a zone with no manifestations. The surface discharge identified along the Wae Bana River might be constrained by the topography and near surface structure; an upflow zone from a depth might exist south of discharge zone, where a higher SP was observed.

6. ConclusIons

The SP survey was conducted in the Mataloko and Nage geothermal areas. In Mataloko, the highest positive anomaly was observed at the main geothermal manifestation area along the stream "Wae-Luja" running eastward. The SP value drastically drops toward the north, south and west while the value gradually decreases toward east. It is consistent with the fact that there exist some more hot springs only east of the main manifestation area.

A two-dimensional numerical model for hydrological and electrical structure was constructed for an east-west cross-section, which is parallel to the C line of the resistivity survey. The permeability structure of this model was improved by the trial-and-error method to obtain a good match with the observed data while the resistivity structure is simply adopted from the result of the resistivity survey. The result suggests existence of a high permeability zone around the main manifestation area. However the surface discharge is considered to be merely a local phenomenon.

On the other hand, in Nage, the geothermal discharge zone does not correspond to the highest positive SP anomaly in this area. The sharp anomalies along the Wae Bana River might correspond to the surface discharge zones. An extensive upflow zone from a deep thermal fluid source might exist in the southern part of the survey area.

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貯留層モデリングのためのインドネシア・フローレス島のマタロコ及びナゲ地熱地帯における自然電位マッピング

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要　旨

インドネシア・東ヌサテンガラ諸島・フローレス島のマタロコ及びナゲ地熱地帯において自然電位（SP）調査が行われた．その結果，マタロコ地域では，地熱徴候地において最大の SP 正異常が観測された．数値シミュレーションの結果は，上昇流域の範囲を示している．一方，ナゲにおいては，明白な正異常を示す特異な 1 観測点は存在しなかった．ナゲのワエバナ川に沿った SP プロファイルは，局所的な流出ゾーンが川に沿っていくつも存在していることを示している．