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Geology and hydrothermal alterations, and those correlations to physical properties obtained from gravity and resistivity measurements in the Mataloko geothermal field

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Koichi TAGOMORI, Hiroki SAITO, Takehiro KOSEKI, Hiroshi TAKAHASHI, Sjafra DWIPA, and Masao FUTAGOISHI (2002) Geology and hydrothermal alterations, and those correlations to physical properties obtained from gravity and resistivity measurements in the Mataloko geothermal field. *Bull. Geol. Surv. Japan,* vol. 53 (2/3), p. 365-374, 8 figs.

Abstract: Several geoscientific studies were conducted to delineate the geothermal structure in the Mataloko geothermal field, central part of Flores, where geothermal energy is expected to be abundant and has not commercially developed yet. From the surface geologic features, various types of hydrothermal alteration zones are recognized in the areas including Mataloko, Wolo Bobo, Wolo Rhea and Gou fields. All these thermal fields are situated in a caldera-like structure (referred as "Bajawa Caldera") derived from gravity contours and geographical features. Thermal manifestations in Mataloko are distributed at the southeast margin of the Bajawa Caldera. The alteration mainly consisting of kaolinite and alunite extends in the NW-SE direction about 1,200 m long. A very low resistivity zone is extensively distributed coincidentally with those thermal manifestations and expected high temperature near the surface. Therefore, the subsurface around the site at southeast margin of the Bajawa Caldera, where the Wae Luja fault trending NW-SE intersects the N-S electrical and gravity lineaments, is expected to form a major geothermal reservoir.

1. Introduction

Apart from regional studies conducted by Geological Survey of Japan (GSJ), WJEC and MRC (referred to as "the NEDO team") conducted detailed studies from 1998 to 2000 to delineate the geothermal structure of the Mataloko geothermal field (referred to as "the Project Area") with the aim of promoting rural electrification utilizing geothermal energy. In and around the Mataloko geothermal field, there are many indications of the existence of major geothermal resources including active volcanoes and hydrothermal manifestations. The heat extractable from these thermal manifestations is abundant, but only a few manifestations are utilized for bathing by the local residents.

As for geophysical techniques, gravity and CSMT/MT surveys were applied to delineate the local geothermal structure and extract deep indications related to the system of the geothermal field. The results were interpreted to select exploratory well locations. The geophysical data were analyzed with regional gravity and MT information from studies done by Dr. Masao Komazawa and Dr. Toshihiro Uchida of GSJ in the central part of Flores (referred to as "the Regional Area") during the same period. Other geoscientific information such as geological survey done by Dr. Hirofumi Muraoka, and SP survey by Dr. Kasumi Yasukawa of GSJ were referred to study the relation between geology and physical anomalies.

2. Geology

2.1. Volcanic stratigraphy

The stratigraphic units of volcanic rocks in the studied area are divided into five units such as: V1,

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Keywords: gravity measurement, resistivity measurement, geology, hydrothermal alteration, geology alteration, geothermal field, Mataloko, Flores Island

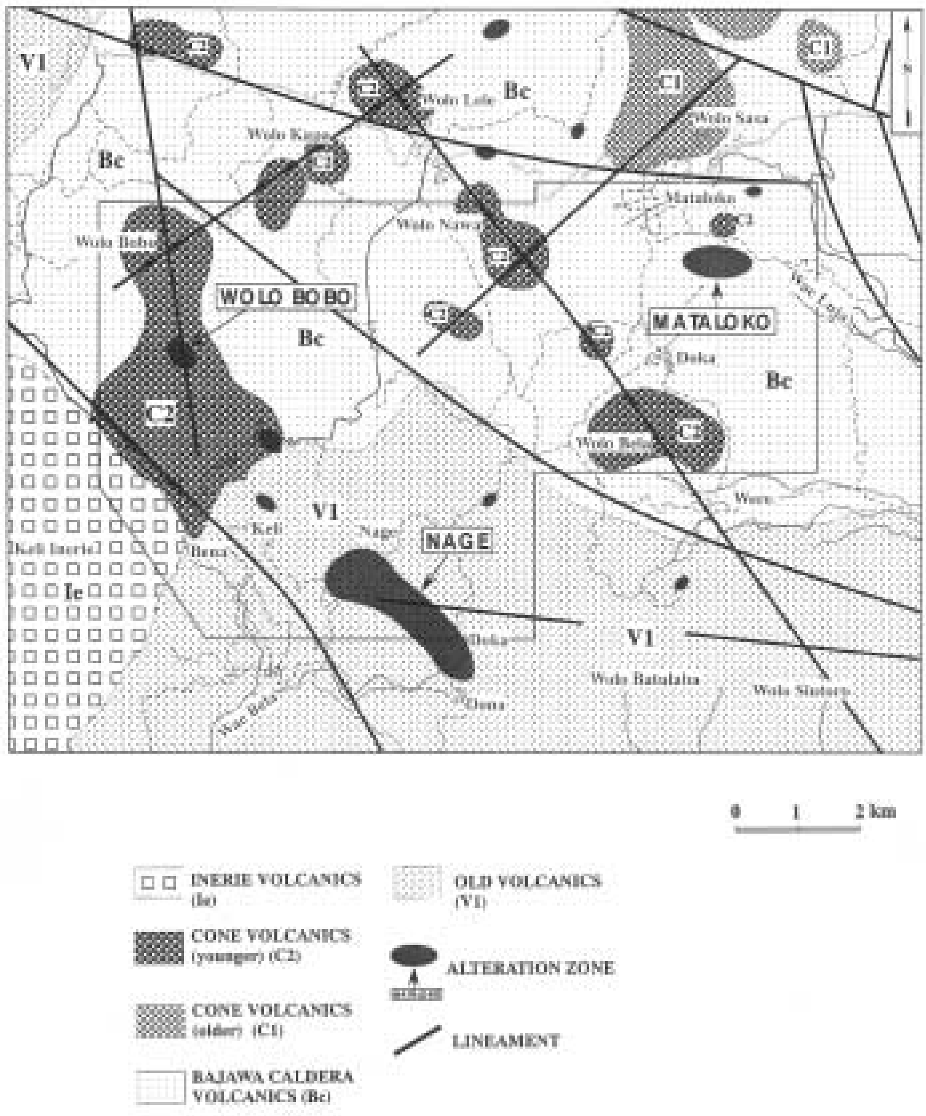

Fig. 1 Geologic map of "the project area" and surroundings.

Bc, C1, C2 and Ie in ascending order (Fig. 1). The V1 unit is correlated with older volcanic rocks (Vo) that are interpreted from satellite image, while the Bc, C1, C2 and Ie units can be correlated with younger volcanic rocks (Vy) analyzed in the same manner.

(1) Old Volcanics (V1)

The V1 unit is distributed extensively including the surroundings of the Mataloko area. This unit consists mainly of pyroxene andesite lava, pyroclastic rocks, lahar deposits and old-basalt. The K-Ar ages of andesite lava range from 1.1 Ma to 1.6 Ma.

(2) Bajawa Caldera Volcanics (Bc)

The Bajawa Caldera is located north of Bajawa town, and the Bc unit is exposed in the Caldera. This unit consists mainly of pyroclastic flow and pyroxene andesite lavas. The K-Ar ages of andesite lava are less than 0.15 Ma.

(3) Cone Volcanics (C1, C2)

The post-caldera volcanic cones (C1, C2) show a well-preserved topography, which are distributed in the southern and northern parts of Bajawa town and around Mataloko village. The volcanic cones run in the northwest to southeast direction in and around Mataloko. This unit consists of pyroxene andesite lava, pyroclastic rocks and pumice/scoria fall deposits. The K-Ar ages of andesite lava are less than 0.15 Ma.

(4) Inerie Volcanics (Ie)

The Ie unit forms Mt. Inerie. This unit consists of andesite lava and pyroclastic flows (Takahashi, *et al.,* 2000).

2.2. Satellite image

The JERS-1/SAR images (Urai, Muraoka and

Nasution, 2002) were adapted to interpret geologic components in the area. The geological information derived from the satellite image is drainage pattern, landform (resistance), tone, texture, and lineaments. The volcanic rocks can be divided into two groups in the area: Vo (older volcanic rock) and Vy (younger volcanic rock). The Vo has a sub-parallel drainage pattern with high density, rough texture and high resistance, while Vy has a radial drainage pattern consisting of low density, smooth texture and low resistance.

3. Hydrothermal alterations

Many hydrothermal alteration zones are confirmed in the Bajawa caldera such as Mataloko, Wolo Bobo, Wolo Rhea and Gou. The Mataloko alteration zone trends in the northwest to southeast direction extending about 1,200 meters long. This alteration zone is characterized by intensive argillization, where hot springs (acidic SO_4 type, over 77 - 89 ℃) are distributed. In addition, a number of alteration minerals such as quartz, α-cristobalite, smectite, kaolinite, alunite, jarosite, pyrite and sulfur are identified.

In the Mataloko field, hot spring water of acid SO_4 type resulted from heated shallow groundwater by mixing gases containing H_2S and CO_2 from the depths. The shallow groundwater is considered as being recharged from the surrounding area. From the alteration minerals, it is also considered that low temperature acidic hydrothermal water (about 100 ℃) is contributed to form hydrothermal alteration zones. The development of the alteration cap rock should be related to generation of the low temperature acidic hydrothermal water recognized in the Mataloko field.

The geothermal brine of the Mataloko field is expected to be formed after the meteoric water recharges to the deep zones in the Bajawa Caldera, and then flows toward the southeast. The heat source of the geothermal system inside of the Bajawa caldera is expected to be residual magma under the young volcanic cones. The brine seated at depth in the Mataloko geothermal field is assumed to be neutral pH because contribution of magmatic gases containing HCl, SO_2 and HF is not detected. The temperature of the deep geothermal reservoir is estimated to be 270 - 300 ℃ from a gas geothermometer.

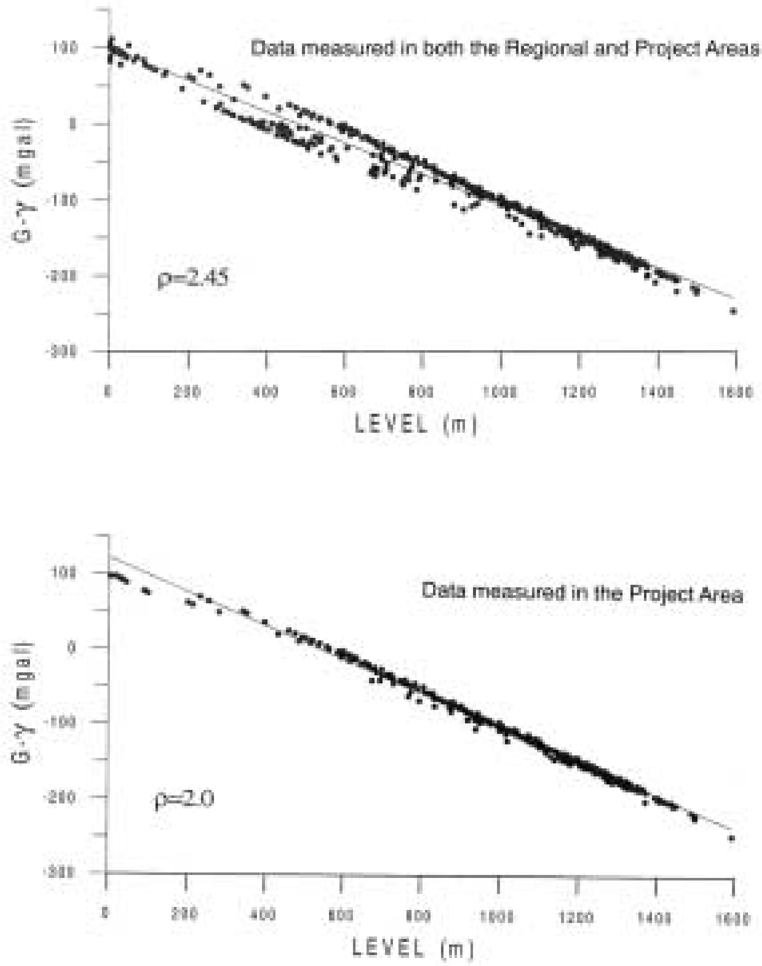

Fig. 2 G-H correlation graph.

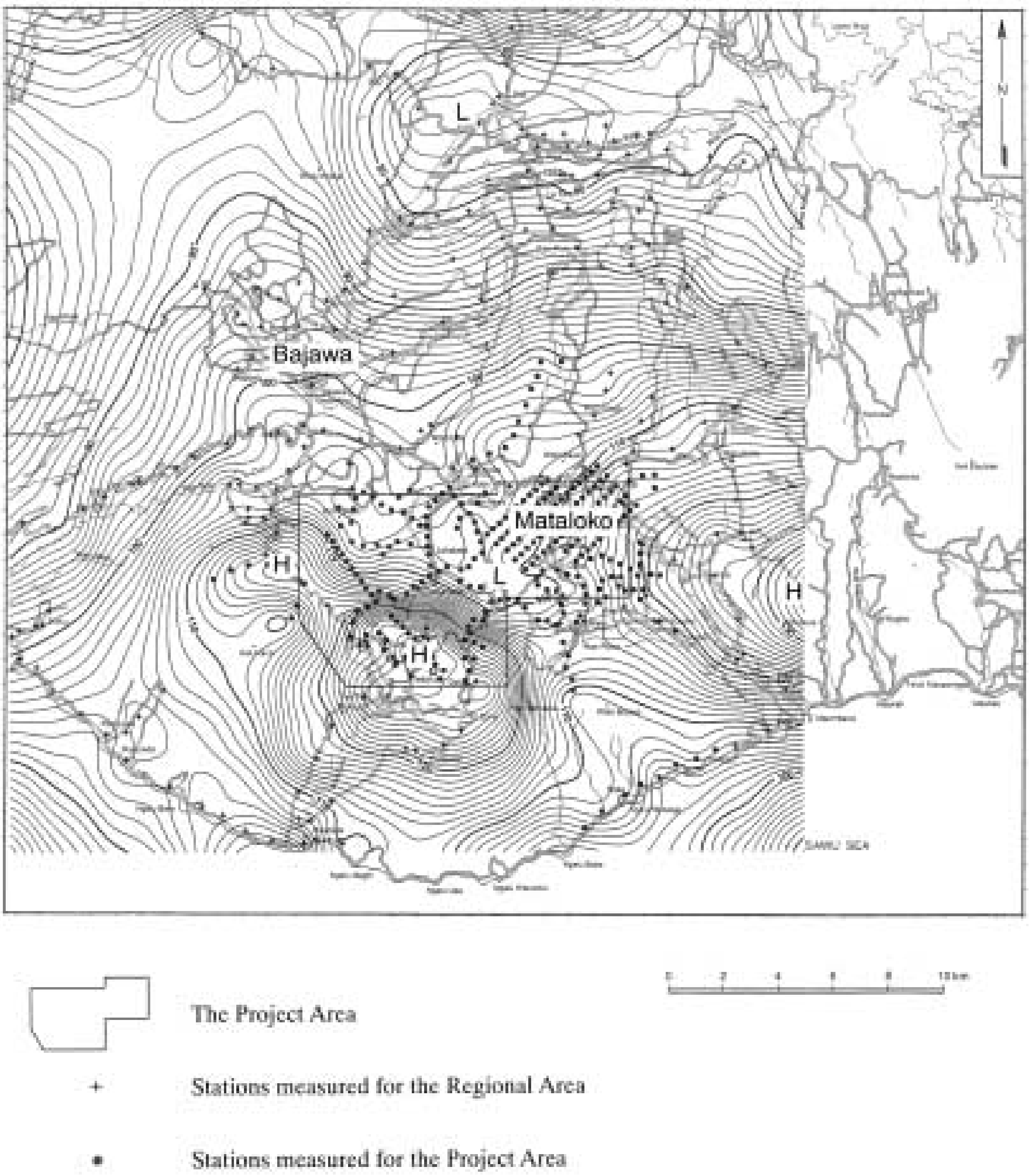

Fig. 3 Bouguer anomaly map of "the regional area" (ρ=2.4 g/cm^3).

These hydrothermal features may be applied "the low-sulfidation type" suggested by Hedenquist and Lowenstern (1994), and the hydrothermal water shows slightly reduced conditions and is neutral (Hedenquist and Lowenstern, 1994).

4. Gravity

4.1. Bouguer anomaly

Gravity surveys were conducted with a Lacoste & Romberg gravimeter in "the Project Area" by the NEDO team, and the data were compiled with the Regional Area data measured by GSJ in the same period. Figure 2 shows the Gravity-Height (G-H) correlation graphs of "the Regional Area" (upper one) and "the Project Area" (lower one). The upper graph includes all the data measured in both "the Regional Area" and "the Project Area", but the lower graph shows solely the data of "the Project Area" measured by the NEDO team.

Several Bouguer anomalies were drafted using correction densities from ρ=1.9 g/cm^3 to 2.4 g/cm^3. From the G-H correlation analyses as shown in Fig. 2, the value of ρ=2.4 g/cm^3 was judged to be the optimum correction density for "the Regional Area". However for "the Project Area", ρ=2.0 g/cm^3 was selected to be optimum value to study the detailed gravity feature that is related to the local geothermal system.

As shown in Fig. 3, the Mataloko geothermal field is situated between high gravity anomalies that are located roughly southwest of Bajawa town

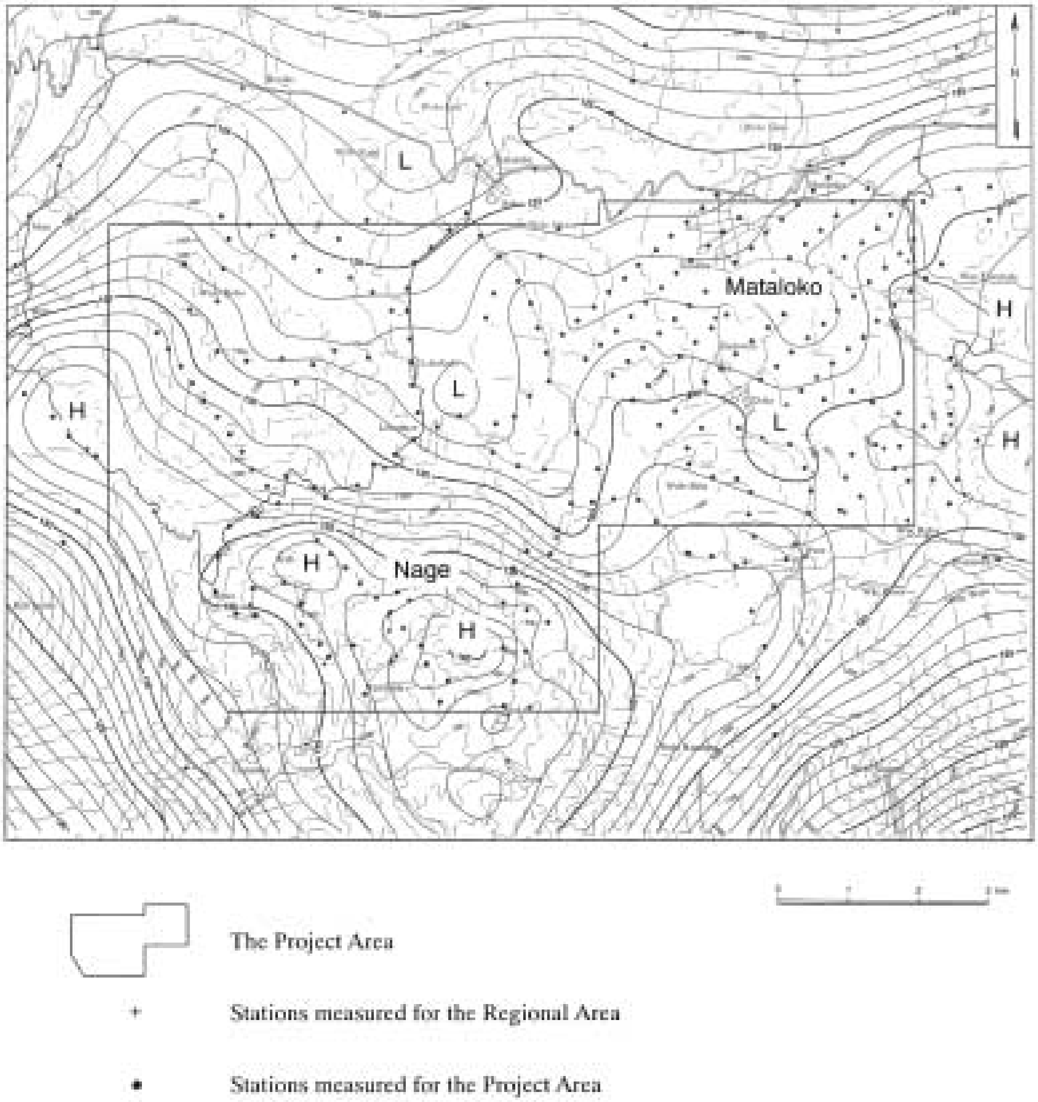

Fig. 4 Bouguer anomaly map of "the project area" (ρ=2.0 g/cm^3).

and east of "the Project Area". From Satellite images, the Bajawa caldera is estimated in the northern part of Bajawa town, and Mataloko is located at the southern edge of this caldera. "The Project Area" is characterized by the filling of low-density rocks probably due to hydrothermal alteration, fractures, and geothermal aquifers. The high gravity anomalies southwest of Mataloko roughly correspond to the alignment of young volcanic cones such as Wolo Nawa, Wolo Riti, Wolo Bina, Wolo Hoge and Wolo Bela, which almost trend in NW-SE direction. The Nage geothermal field is located in high gravity anomalies, and it suggests some relation to younger volcanic activities.

Figure 4 shows the bouguer anomaly map of "the Project Area" based on the correction density of ρ= 2.0 g/cm^3. The Mataloko geothermal field in the eastern part is characterized by distorted contours indicating that the area is filled with rather low-density and geologically complex compared with surrounding area. From the trend of the contour distortion and gradient, we can recognize some linear trends such as the N-S direction in the eastern part and NW-SE direction in the southwestern part.

4.2. Gravity lineaments

From the JERS-1/SAR image studies, lineaments are found along the N-S, NW-SE, NE-SW and E-W directions in the whole regional area, and N-S and NW-SE lineaments are thought to indicate the arrangement of volcanoes.

In the Mataloko geothermal field and its surroundings, the residual Bouguer anomalies indicate lineaments in the NW-SE direction at the shallow part. The lineaments of NS direction are assumed to be deep. These lineaments are well correlated with results of satellite images and considered to be a reflection of the important geological structures that control the behavior of geothermal fluids of "the Project Area".

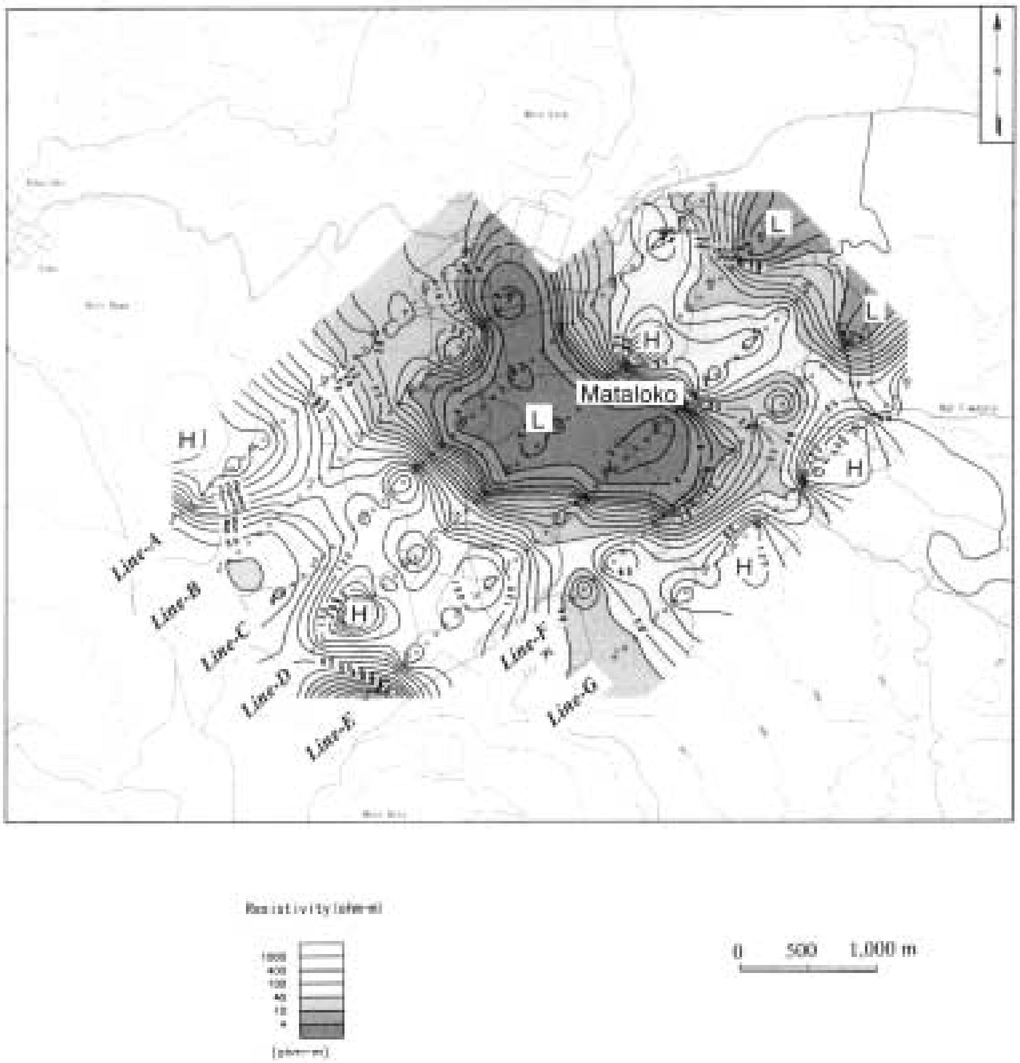

Fig. 5 Iso-resistivity map obtained from 2D analysis in the Mataloko geothermal field.

5. Resistivity survey

The resistivity structure of "the Project Area" can be classified into three layers. The structure consists of "resistive overburden" as surface layers (higher than 100 Ωm), "conductive layer" as middle layers (lower than 10 Ωm), and "resistivity basement" as deep layers (higher than 100 Ωm). It is assumed that the resistive overburden reflects young volcanic rocks with less alteration. The conductive layer is widely distributed in the area, and it is interpreted as hydrothermal alteration cap rocks. Relatively low resistivities in the resistivity basement are coincident with a low gravity anomaly distributed mostly along the Wae Luja river.

5.1. Resistivity distribution (100 meter deep)

Figre 5 shows the interpreted resistivity distribution at a 100 m depth in the Mataloko geothermal field based on two-dimensional analysis obtained from the MT/CSMT measurement referring to MT data measured in the same period in "the Regional Area". A low resistivity anomaly showing less than 10 Ωm is located close to the Mataloko field where hydrothermal alterations, hot springs and steam fumaroles are widely spread and extend in the NW-SE direction. This low resistivity anomaly also shows an elongation in the NW-SE direction. The geothermal structure at the shallow zone in Mataloko seems to be controlled by fractures that are well developed in the NW-SE direction.

Some resistivity discontinuities (resistivity lineaments) can be delineated from steep boundaries between low and high resistivity anomalies. These discontinuities are assumed to be reflecting faults and associated fractures, which control at least the shallow geothermal water movement. High resistivity anomalies west of the survey area correspond roughly with volcanic cones that are aligned in the NW-SE direction.

5.2. Resistivity distribution (ASL 0 m)

Figure 6 shows the interpreted resistivity map of

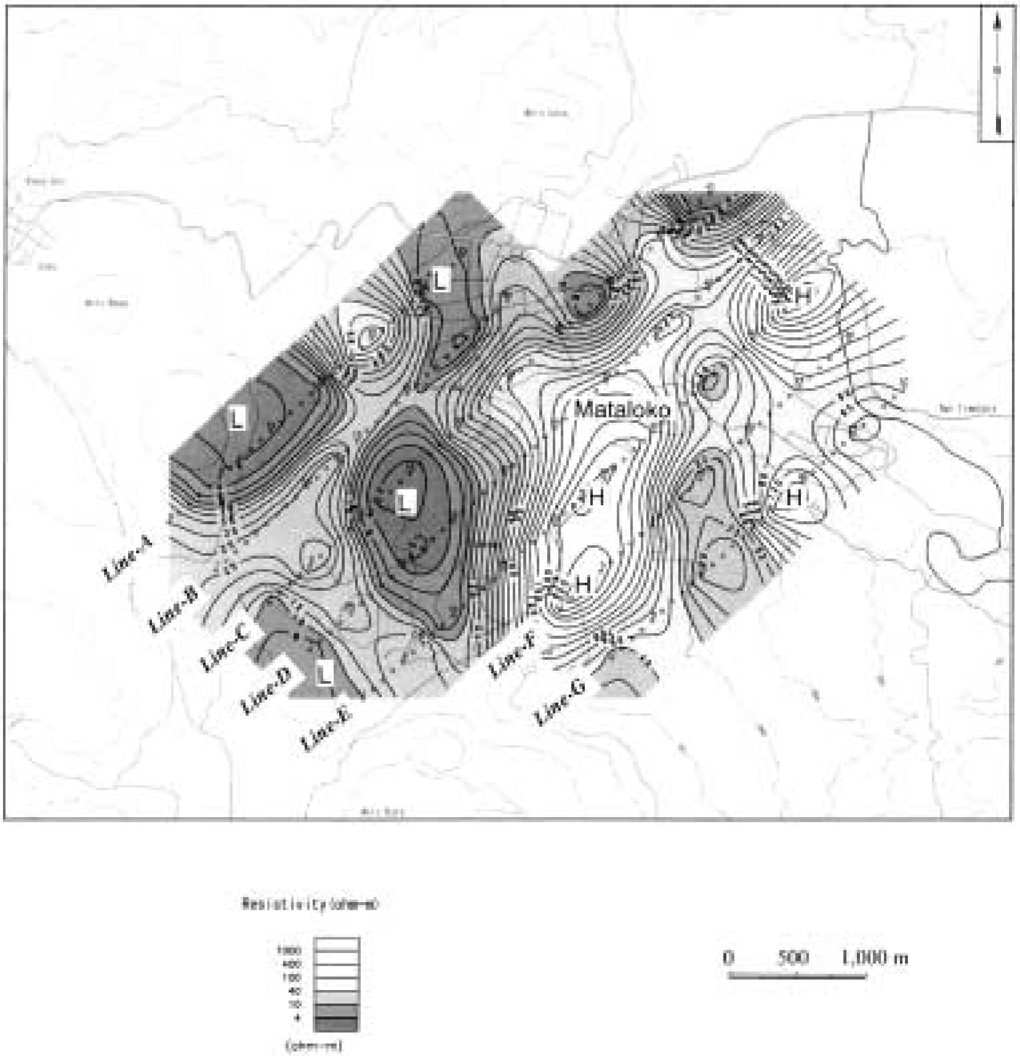

Fig. 6 Iso-resistivity map obtained from 2D analysis in the Mataloko geothermal field.

ASL 0 m depth in the Mataloko geothermal area. Apart from the resistivity distribution pattern in the previous figure, the resistivity distribution in Fig. 6 is much different from that of Fig. 5. The pattern of resistivity low and high anomalies is just the reverse compared with the shallow pattern. The geothermal system in the Mataloko geothermal field is thought to be associated with an uplift system deduced from the configuration of the electrical basement. The uplift configuration is recognized as resistivity discontinuities trending in the N-S direction from a steep gradient between high and low resistivity anomalies. Geothermal water behavior at depth is expected to be controlled by these N-S trending discontinuities (probable faults and associated fractures).

In the western part of Mataloko, low resistivity anomalies are also distributed with a N-S trend. A clear electrical discontinuity is seen in the N-S direction with a steep gradient trend from the resistivity contours. It is difficult to judge whether these deep low resistivity anomalies in the west are associated with the geothermal system because there are no remarkable thermal manifestations on the surface. Future exploratory well drilling is desired to confirm the N-S trending faults and associated fractures in the western part.

5.3. Resistivity sections

As shown in Fig. 7, resistivity sections are shown along seven traverse lines from A to G. From the recognition of successive similar resistivity distribution patterns, it is easy to find resistivity discontinuities that may extend deeper. Those discontinuities are expected to be associated with fault locations and permeable fractures.

The conductive layers lower than 10 Ωm are distributed from near the surface down to about 500 m ASL. However in the western part of the survey area from line A to D, the conductive layer is distributed down to almost 0 m ASL. This conductive layer in the east is relatively thicker than that in the Mataloko geothermal field. This indication is suggesting two possibilities. It may be due to only

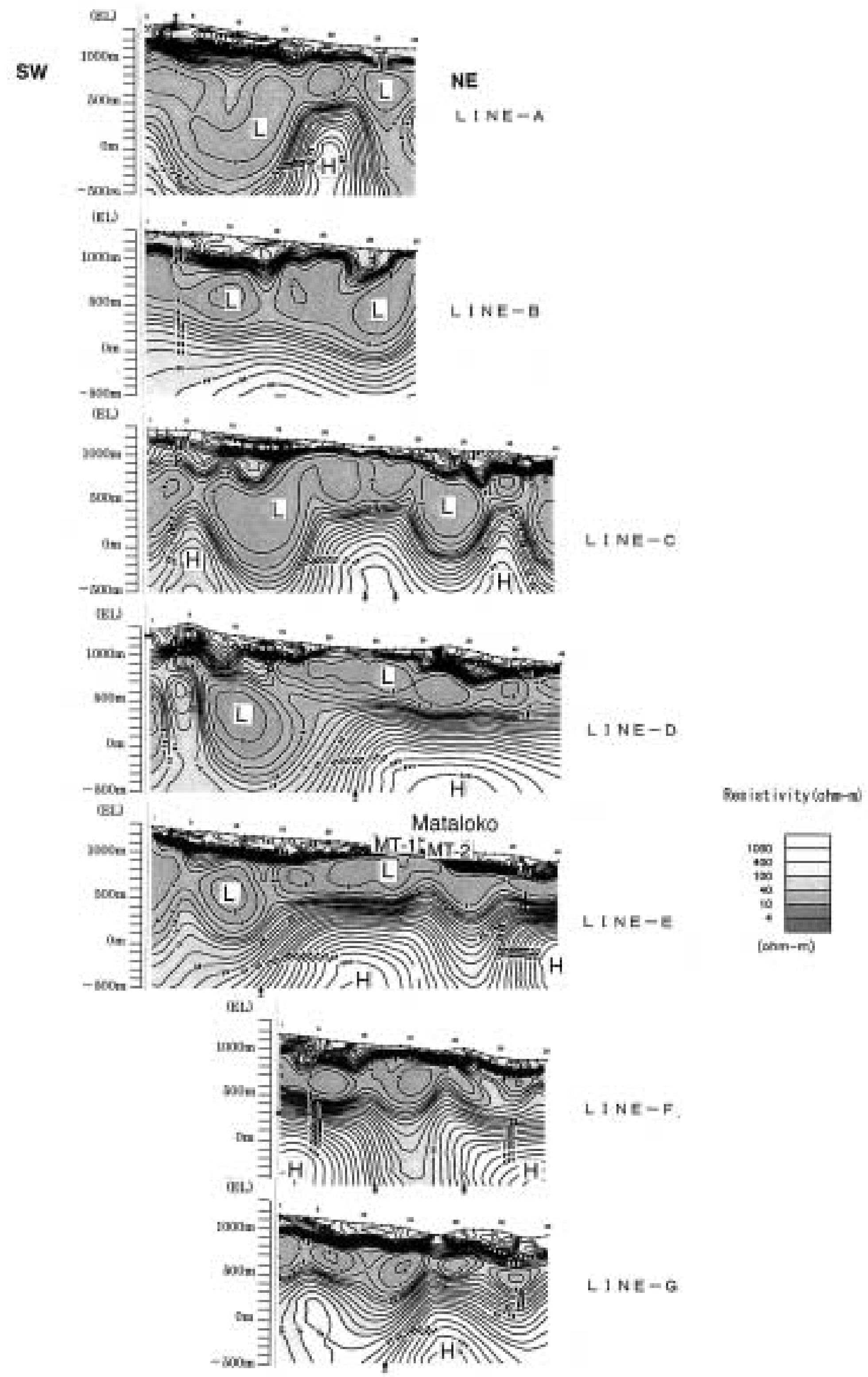

Fig. 7 Resistivity section obtained from 2D analysis in the Mataloko geothermal field.

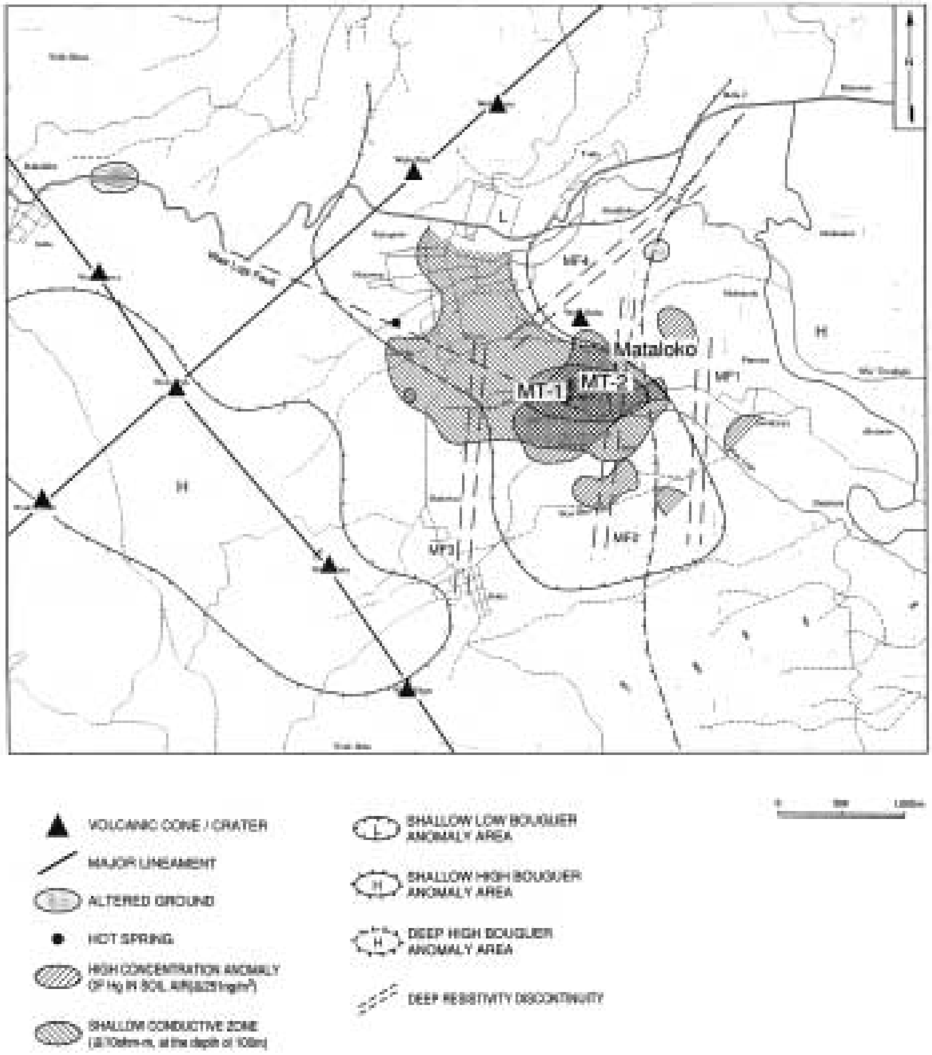

Fig. 8 Integrated gescientific survey results in the Mataloko geothermal field.

conductive layers like a sedimentary basin or deep seated geothermal reservoir.

6. Geothermal system

As previously described, the Mataloko geothermal field is located along the southeast margin of the Bajawa caldera, and geophysical lineaments and anomalies are concentrated coincidentally within the area (Fig. 8). In the region surrounding "the Project Area", the post-caldera volcanic cones are arranged in the NW-SE and NE-SW directions. The heat source of the geothermal system is considered to be residual magma under young volcanic cones. Resistivity discontinuities are found along the N-S directions. These lineaments are regarded to represent fracture zones or faults reaching to the depth.

In the Mataloko geothermal field, acidic alteration minerals are predominantly found showing that the hot water (about 100 ℃) had contributed to the generation process of hydrothermal alteration. From drilling results of the wells, MT-1 and MT-2, a steam-dominated reservoir was found at relatively shallow depth around 100 m. As recognized around Mataloko (MT-1 and MT-2) on Line-E of Fig. 7, the conductive layer less than 4 Ωm is distributed around depths from 300 m to 600 m and divides the shallow steam zone from a possible deep water-dominated reservoir. It is possible that the conductive layer may act as impermeable zones. Thus, the conductive layers detected from resistivity sections are considered to correspond to impermeable zones (Takahashi, 1995) and it is possible to divide the Mataloko geothermal system into two zones, a shallow steam dominated reservoir and a deep water-dominated reservoir. It is desirable to confirm the existence of Cl-type water-dominated geothermal reservoir at depth by drilling a deep well in the future.

7. Conclusion

The Wae Luja NW-SE fault trending can be estimated from a manifestation alignment at the surface and hydrothermal alteration trend as shown in Fig. 8. Since conductive zones at the shallow part are well coincident with the location of the Wae Luja fault, the shallow geothermal system in Mataloko seems to be controlled by the NW-SE fault system and associated fractures.

On the contrary, resistivity discontinuities (MF1, MF2 and MF3 shown in Fig. 8) delineated from the deep resistivity distribution in the Mataloko geothermal field are characterized to be trending in the N-S direction. From the regional trend by gravity-filtered map, a N-S trend is also estimated in this area. These show that the deep geothermal system in Mataloko may correlate to structures trending in the N-S direction.

To confirm a possible deep hot-water dominated reservoir that may be bounded by a conductive layer from the resistivity distribution, the target of a deep exploratory well is judged to select several points where N-S electrical discontinuities intersected the Wae Luja fault.

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マタロコ地熱地帯における
地質，熱水変質分布と重力，比抵抗分布との相関について

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要　旨

フローレス島中央部に位置するマタロコ地熱地帯他で，地熱構造を抽出する目的で地球科学的な調査を実施した．地上調査から，マタロコ，ウォロボボ，ウォロレアおよびゴウの各地熱地帯で種々のタイプの熱水変質帯が認められ，また，これらの地熱地帯は重力あるいは地形上から推定されるカルデラ状構造（"バジャワカルデラ"と仮称）内に位置していることが明らかになった．マタロコ地熱地帯は，バジャワカルデラの南東の縁部で北西－南東方向の延長 1,200 m の変質帯で特徴づけられ，これは，ほぼワエルジャ断層に沿って分布している．地表には主としてカオリン，アルナイトの変質鉱物が認められる．また，この変質帯の分布に一致して，低比抵抗ゾーンが広い範囲で分布し，その広がりの特徴から地表下に高温部の存在が予想された．さらに，重力，比抵抗調査から推定された南北系の線構造とワエルジャ断層との交点部付近は，深部に優勢な地熱貯留層が賦存することが推定される．